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GLOBAL FOODS - INNOVATIONS AND FUTURE PERSPECTIVES

Editor

Dr. Muhammad Imran

Associate Professor, Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

Dr. Muhammad Kamran Khan

Associate Professor, Department of Food Science, Faculty of Life Sciences, Government College University, Faisalabad, Pakistan

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REVIEW BASED BOOK CHAPTER

SUSTAINABLE AND ALTERNATIVE FOODS

Elena Narcisa Pogurschi[1], Nicoleta Ciocirlie[2]

[1]*Faculty of Animal Production Engineering and Management, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 071331, Romania*

[2]*Faculty of Veterinary Medicine, University of Agronomic Sciences and Veterinary Medicine of Bucharest, 050097, Romania*

For Correspondence
nicoleta.ciocirlie@fmvb.usamv.ro

Abstract

The term "sustainable food" defines food that is produced using methods that reduce environmental impact (lower carbon emissions, reduced water consumption, responsible use of resources, regenerative agriculture, etc.) while "alternative foods" define food sources that can substitute classic products (meat, milk, animal proteins), often being developed to respond to growing global demand and resource problems. Identifying foods that are both sustainable and alternative is a major challenge, an aspect that is discussed in the following paper. Globally, trends in sustainable and alternative foods show an accelerated growth of the market for plant-based and cultured proteins, supported by technological innovations such as modern fermentation and biotechnology, which reduce resource consumption and emissions. At the same time, governments are starting to play an active role through major investments in research and public policies – from the European Union's "Farm to Fork" strategy, to national plant-based food plans (e.g. Denmark, South Korea) and regulations for cultured meat (Singapore, USA, Israel). While some solutions, such as insect consumption, face cultural resistance and economic barriers, there is a growing consensus that transforming the global agri-food system is necessary to reduce climate impact, diversify food sources and ensure long-term food security. In order to outline an adequate response to these requirements, this paper aims to present the main categories of sustainable and alternative foods, to characterize them both from a nutritional and sustainability perspective, as well as to highlight the current regulatory framework applicable to their introduction on the market.

Keywords
Sustainable Foods, Zero Hunger, Alternative Proteins, Sustainable Diets, Food Acceptance

1. Introduction

The continuous growth of the world population represents one of the most pressing challenges of the 21st century, with direct implications for global food security [1]. According to United Nations projections, the world population is estimated to reach approximately 9.7 billion people by 2050 [2], which will lead to a significant increase in food demand. In this context, it is estimated that agricultural and livestock production would need to expand by 50–70% [3, 4] compared to current levels, given that natural resources (arable land, drinking water and biodiversity) are already under considerable pressure. According to the IPCC report (2019) [5], the food system is responsible for approximately 21–37% of global greenhouse gas emissions, a significant part of which comes from the livestock sector. In this framework, it is noteworthy that animal-based foods have, on average, a significantly higher carbon footprint than plant-based foods, due to the complex production processes, increased resource consumption and emissions associated with animal husbandry [6]. This discrepancy constitutes a major argument for intensifying efforts to identify and promote alternative and sustainable food sources, capable of meeting both nutritional requirements and environmental impact reduction objectives. Moreover, changes in consumption patterns, associated with urbanization and income growth, are leading to increased demand for animal products [7], thus intensifying the environmental impact and the need to identify sustainable and alternative food solutions. If, in addition to the major objectives of government policies regarding food security, the right to health and environmental protection, the improvement of the health status of the population is also added, then the approach can no longer be limited to the identification of "sustainable and alternative foods". In this context, the focus must be extended to the identification and promotion of "sustainable diets", which integrate both ecological sustainability criteria and nutritional and public health benefits. More precisely, according to FAO, sustainable diets are "diets with low environmental impacts that support food and nutrition security and healthy lives for present and future generations; they protect and respect biodiversity and ecosystems; are culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; and they optimize natural and human resources" [8]. Sustainable diets, characterized by a high intake of plant-based foods and whole grains and a low consumption of animal-based foods [9] will need to continue to meet the need for protein and essential amino acids. Animal-based foods (especially red meat and dairy) have the highest environmental impact within the food sector, yet at the same time they play an essential nutritional role. This creates the need for sustainable food alternatives (e.g., plant-based proteins, algae, insects, cultured meat). To this end, identified food alternatives must be nutritionally balanced and provide all the nutrients essential for a healthy diet. Thus, food policies acquire a complex dimension, simultaneously oriented towards protecting the environment and increasing the quality of life.

2. Types of Sustainable Food Alternatives

Many studies consider "alternative and sustainable foods" mainly as protein-providing foods and refer to them as "alternative proteins." The introduction of alternative and sustainable foods into diets is intended to address growing protein demand in the coming decades in a manner consistent with environmental protection and climate-change mitigation objectives, while also aligning with the 2030 UN Agenda for Sustainable Development, in particular the Zero Hunger goal [10].

Classification of sustainable alternative foods can be established according to their principal protein origin, which includes the following main categories:

1. Plant-based alternatives
2. Foods based on algae and aquatic plants
3. Edible insects (entomophagy)
4. Proteins derived from microorganisms
5. Cultured and innovative proteins.

The development of sustainable alternative protein sources is uneven, with plant-based proteins and microbial-derived products already widely commercialized algae and edible insects progressing at a moderate pace, and cell-based meat and dairy still in early experimental stages despite attracting the largest investments. Table 1 presents the main categories of sustainable alternative protein sources, highlighting their current stage of development, leading regions of research and commercialization, and estimated investment levels.

Table 1. Global development status and investment trends in sustainable alternative protein sources

Protein source	Development stage	Leading regions (R&D & commercialization)	Estimated investments / market size
Plant-based	Advanced, widely commercialized	North America, Western Europe, East Asia	Global market= 16,9 billion USD (2024) [11]
Algae	Emerging, niche use	East Asia (Japan, Korea, China), EU (France, Netherlands)	Investments ~1 billion USD (2022) [11]
Insects	Moderate, regional adoption	Southeast Asia, Africa, EU (Netherlands, France)	Investments >1 billion USD (2022) [12]
Microbial proteins	Growing, partly commercialized	UK, North America, Northern Europe	Investments 1.5 billion USD (2024) [13]
Cultivated meat/dairy	Early stage, pilot production	North America, Israel, Singapore, EU	Investments >2.5 billion USD (2023) [14]

2.1. Plant-based alternatives

Plant-based proteins represent one of the most widely available and sustainable sources of dietary protein, increasingly positioned as a viable alternative to animal-derived protein. Major sources include legumes such as soybeans, chickpeas, lentils, and peas, alongside cereals, nuts, seeds, and pseudocereals like quinoa and amaranth.

Nutritional profile of Plant-based alternatives

The protein content of plant-based foods is generally lower than that of animal-derived products. For example, 100 g of cooked lentils provides around 9 g of protein, compared with approximately 26 g in 100 g of cooked chicken breast. Similarly, soybeans and soy-derived products (such as tofu and tempeh) are among the richest plant protein sources, delivering between 10–20 g of protein per 100 g, which approaches the density found in certain animal proteins. Cereals such as rice and wheat, on the other hand, provide lower protein concentrations (typically 7–12 g/100 g uncooked).

The nutritional quality of dietary proteins is determined not only by their total content but also by their composition in essential amino acids (EAAs), which the human body cannot synthesize. Animal-derived proteins are generally considered of higher quality, as they provide all nine EAAs in sufficient amounts to support growth and metabolic functions.

In contrast, most plant-based proteins have an unbalanced amino acid profile, being limited in one or more EAAs. For example, cereals such as wheat and rice are typically deficient in lysine, whereas legumes like beans and lentils tend to be low in methionine and cysteine. This limitation affects both the biological value and the protein digestibility of many plant proteins, which are often lower compared to animal proteins. The essential amino acid content of the main plant proteins is presented in the Table 2.

Table 2. Essential amino acid content of the main plant protein sources [15] (g/100 g raw material)

Amino acid	Wheat	Soy	Rice	Pea	Beans	Lentils
Threonine	0.45	1.53	0.39	0.59	1.09	1.25
Methionine	0.13	0.41	0.17	0.21	0.18	0.19
Lysine	0.21	2.02	0.28	1.62	1.43	1.71
Tryptophan	0.10	0.41	0.10	0.21	0.28	0.23
Phenylalanine	0.45	1.53	0.39	0.59	1.09	1.25
Histidine	0.20	0.93	0.16	0.48	0.54	0.65
Valine	0.42	1.53	0.49	1.00	2.21	1.18
Leucine	0.64	2.46	0.57	1.48	1.67	1.82
Isoleucine	0.36	1.47	0.32	0.93	0.98	1.03
ΣEAA	2.95	12.29	2.87	6.11	9.87	9.31

The data presented in Table 2 highlight significant differences among major plant protein sources in terms of their essential amino acid (EAA) content. However, these values should be regarded as average estimates, since the protein composition of plants varies substantially with cultivar and agro-climatic conditions such as nitrogen fertilization, drought, or temperature during grain filling [16]. Year-to-year variability has also been documented, reflecting both environmental influences and long-term breeding effects on protein and amino acid profiles [17]. In addition, the amino acid pattern may differ between plant tissues or developmental stages, with germination leading to an increase in several EAAs while sometimes reducing valine [18, 19].

Processing and cooking methods exert a further impact: boiling can reduce the content of free amino acids due to leaching into the cooking water [20], while thermal treatments often lower lysine, tryptophan, sulfur-containing and aromatic amino acids [21]. Conversely, germination and fermentation may improve the EAA profile and digestibility by reducing antinutritional factors [22]. Beyond absolute amounts, the nutritional quality also depends on protein digestibility and the identity of the limiting amino acid, now assessed more accurately by the Digestible Indispensable Amino Acid Score (DIAAS) rather than Protein Digestibility-Corrected Amino Acid Score (PDCAAS) [23, 24]. Thus, the profiles in Table 2 provide a useful comparative reference, but should be interpreted in the light of natural variability and processing effects that influence the true nutritional value of plant proteins.

However, the concept of complementarity between different plant sources allows these deficiencies to be overcome. By combining foods with complementary amino acid profiles, such as legumes and cereals, diets based predominantly on plant proteins can provide adequate amounts of all EAAs. Some plant sources, including soy, quinoa, and amaranth, naturally contain a more balanced EAA profile and are therefore classified as "complete proteins," comparable in quality to those of animal origin.

A key strategy in improving the nutritional value of plant-based diets is the production of protein concentrates and isolates, as these provide a higher protein density and more effectively meet the essential amino acid requirements recommended by FAO [25]. In addition, the use of plant-based protein isolates in food formulations has recently gained interest not only because of their lower production costs, but also because they contribute to sustainability goals by reducing reliance on resource-intensive animal proteins [26].

The global market for plant-based protein isolates is currently dominated by soy protein isolate (SPI) and pea protein isolate, which are the most widely used ingredients due to their functional versatility and favorable cost profiles. SPI remains the leading category, particularly in the United States, where it is extensively incorporated into meat analogues, beverages, bakery products, and nutritional supplements. In parallel, pea protein isolate has experienced rapid growth in North America, Europe, and the Asia-Pacific region, driven by consumer demand for allergen-free and “clean label” alternatives. Both isolates are increasingly applied in plant-based meat alternatives, ready-to-drink beverages, protein bars, bakery products, and functional foods, where they contribute not only to nutritional fortification but also to improved texture, water-binding, and emulsification.

Although soy and pea protein isolates dominate the market, other plant-based isolates are also emerging. These include rice protein isolate, lupin protein isolate, fava bean protein isolate, and even oat protein isolate, which are gaining attention for their specific functional properties and their potential to diversify sources beyond soy and pea. While their market shares are still relatively small, these isolates are increasingly incorporated into specialized applications such as gluten-free bakery products, allergen-free formulations, sports nutrition, and novel plant-based dairy alternatives. Their development reflects a growing interest in broadening the portfolio of plant protein ingredients to meet consumer demands for variety, allergen management, and sustainability.

As shown in Table 3, a variety of plant protein isolates are utilized across diverse food categories, ranging from meat and dairy analogues to bakery products and nutritional supplements, illustrating their functional versatility.

Table 3. Major plant protein isolates and their main food applications

Protein isolate	Main food applications
Soy protein isolate	Meat analogues (burgers, sausages), plant-based dairy, protein powders, bakery products, nutritional bars, beverages
Pea protein isolate	Meat substitutes, plant-based beverages, protein shakes, snack foods, bakery items, sports nutrition products

Rice protein isolate	Gluten-free bakery products, infant formulas, sports nutrition powders, hypoallergenic foods
Fava bean protein isolate	Meat alternatives, plant-based cheeses, bakery products, soups and sauces
Oat protein isolate	Plant-based dairy (oat milk, yogurt), protein-enriched cereals, bakery goods

Sustainability

Plant cultivation generally requires considerably fewer natural resources compared to livestock production. Cereals and legumes, the primary raw materials for protein isolates, demand less arable land, consume significantly less water, and have a lower feed conversion ratio than animal-based protein systems. For example, producing 1 kg of soy protein requires up to 10 times less water than producing the same amount of beef protein (Table 4). This efficiency in resource use is one of the main reasons why plant protein isolates are increasingly promoted as sustainable alternatives.

Table 4. Comparative environmental impact of animal vs. plant protein sources

Protein source	GHG emissions ($kg\ CO_2$-eq / kg protein)	Water use (L / kg protein)	Land use (m^2 / kg protein)
Beef	~60	>15.0	~250
Pork	~20	~6.0	~45
Poultry	~10	~4.3	~25
Milk	~15	~1	~30
Soy protein	~4	~2	~15
Pea protein	~3	~1.5	~10
Lentil protein	~2	~1.25	~9

In terms of environmental impact, plant-based proteins also contribute to lower greenhouse gas (GHG) emissions. Livestock production is responsible for an estimated 14–18% of global anthropogenic GHG emissions, primarily methane and nitrous oxide, whereas legumes and other protein crops generate only a fraction of these values per kilogram of protein produced. The substitution of animal proteins with plant protein isolates therefore offers a viable pathway to reduce pollution and mitigate climate change, aligning with global sustainability targets.

Plant-based byproducts as protein sources

Agricultural and food industry byproducts represent an underutilized reservoir of proteins that can contribute both to nutrition and sustainability. Oilseed meals (from soy, rapeseed, sunflower), cereal brans (wheat, rice, corn), and legume hulls contain substantial amounts of proteins, often with favorable amino acid profiles. For example, rapeseed meal can contain up to 35–40% protein, while brewers' spent grain, a side stream of beer production, provides 20–30% protein along with valuable fibers. Similarly, fruit seed residues (such as pumpkin or grape seeds) and potato processing byproducts are being investigated as novel protein sources.

Soybean meal is predominantly directed to the animal feed sector: approx. 98% of global soybean meal output serves livestock feed purposes. Rapeseed meal demonstrates a favorable essential amino acid profile (notably in methionine and cysteine), and has been identified in several reviews as having good nutritional and functional potential for human food applications. Sunflower meal, obtained as a secondary product from sunflower oil processing, contains roughly one third protein on a dry matter basis and provides notable amounts of sulfur-containing amino acids. Because of this, it has been explored as an ingredient in fortified foods such as bakery items, infant formulations, and even analogues of meat and dairy. Nevertheless, its application in human nutrition is still relatively restricted, since it carries significant levels of phenolic compounds most notably chlorogenic acid that can impair both functionality and sensory properties of the proteins.

The recovery and valorization of proteins from such waste streams not only enhances protein availability but also reduces environmental burdens associated with waste disposal. This approach aligns with the principles of the circular bio-economy and supports the development of sustainable protein ingredients for use in bakery, beverages, meat analogues, and functional foods [27].

2.2. Foods based on algae and aquatic plants

Algae have served as a source of food since ancient times in various parts of the world, particularly in Asian regions where macroalgae (nori, wakame, kombu) have been part of traditional diets, as well as in Central America, where the Aztecs consumed Spirulina in the form of "tecuitlatl." Today, interest in algae as alternative and sustainable protein sources has grown significantly due to their high nutritional value and ecological potential. In Europe, this growing interest is reflected in market dynamics: the EU ranks among the top global importers of seaweed products, with imports valued at EUR 554 million in 2016. Demand is expected to rise further in line with health and sustainability trends, potentially reaching EUR 9 billion by 2030 [28].

Algae used in food can be broadly classified into two main groups:

1. Macroalgae (seaweeds): multicellular algae commonly consumed in Asian diets, including red (nori), brown (wakame, kombu), and green (ulva) species. These are typically eaten whole, dried, or processed as food ingredients, and are rich in minerals, dietary fiber, and certain bioactive compounds.

2. Microalgae: microscopic, unicellular species such as Spirulina (*Arthrospira*) and *Chlorella*. They are mainly consumed as powders, tablets, or incorporated into functional foods and beverages, valued for their high protein content (up to 60–70% dry weight), essential amino acids, and polyunsaturated fatty acids (EPA, DHA).

Algae can also be classified according to their dominant pigment:

1. Green algae (*Chlorophyta*) contain chlorophylls a and b, and are commonly used both as food and feed.

2. Brown algae (*Phaeophyceae*), characterized by the presence of fucoxanthin, include species such as *Laminaria* and *Undaria*, widely consumed in East Asia.

3. Red algae (*Rhodophyta*), rich in phycoerythrin, comprise economically important species like *Porphyra (nori)*, traditionally used in sushi.

4. Blue-green algae is the common term used for cyanobacteria, which are prokaryotic microorganisms and therefore not true algae; however, species such as Spirulina are widely cultivated and appreciated for their high protein content and diverse bioactive compounds.

It is important to note that both microalgae and macroalgae can be classified within the four pigment-based groups, meaning that color categories do not correspond exclusively to organism size or complexity; this relationship is illustrated in Figure 1.

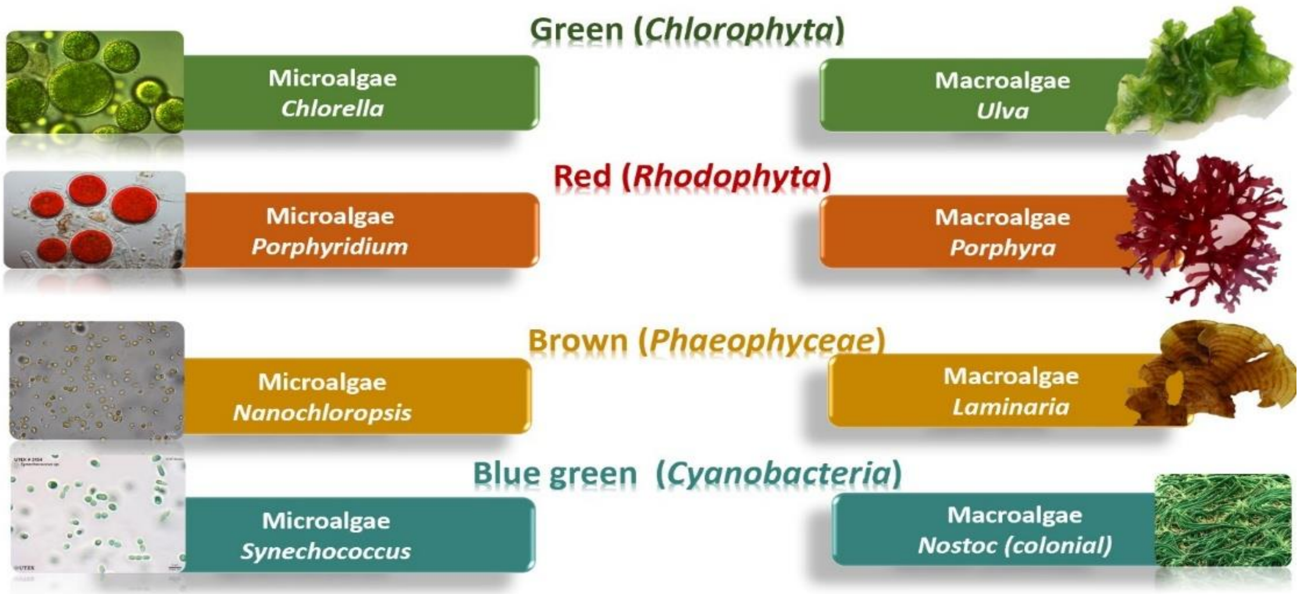

Figure 1. Pigment-based Algal Group vs Size (Micro/Macro)

According to recent studies [29, 30], algae surpass most land-based crops in terms of growth velocity, biomass productivity, and protein yield, attributes that strengthen their potential as a sustainable and scalable source of alternative proteins.

The interest in cultivating algae as a food source intensified in the aftermath of World War II, when several countries faced severe food shortages and malnutrition crises. In this context, microalgae such as *Chlorella* and *Spirulina* attracted scientific attention due to their exceptionally high protein content and rapid growth potential. Early research programs, particularly in Japan, Germany, and the United States, explored large-scale algal cultivation as a way to ensure food security and to provide an affordable, protein-rich alternative to conventional crops [31]. Despite the technological and economic barriers that limited widespread adoption at the time, these pioneering efforts provided the basis for the modern development of algae-based foods.

Although algae had long been harvested from natural environments for human consumption, large-scale utilization faced significant limitations. Natural algal blooms are difficult to harvest efficiently, and they often carry risks of contamination with toxins, pathogens, or heavy metals, making them unsuitable for reliable food production. To overcome these challenges, research after World War II focused on the development of controlled algal cultivation systems, allowing stable biomass yields, improved food safety, and standardization of nutritional quality. This transition from wild harvesting to dedicated cultivation marked the beginning of modern algal biotechnology.

The most widely consumed algae in Europe are microalgae such as *Spirulina* and *Chlorella*, primarily used in the form of dietary supplements, as well as several macroalgae, including *Alaria esculenta*, *Ascophyllum nodosum*, and *Chondrus crispus*, which are incorporated into food products or health-related applications. In 2024, European legislation expanded the Novel Food catalogue [32] by reclassifying several algae species as "non-novel," thereby authorizing their use as food or food ingredients without the need for further approval. This regulatory update reflects the growing acceptance of algae within the European market and is expected to facilitate their integration into both traditional food products and dietary supplements.

Nutritional profile of Algae and Aquatic plants

Algae are characterized by a diverse nutritional profile, providing proteins (10–70% dry weight, depending on species), carbohydrates (mainly dietary fiber, including soluble polysaccharides such as alginates, carrageenans, agar, lipids rich in polyunsaturated fatty acids, vitamins (vitamins A, C, E, and some B-vitamins, including B12 in certain species), minerals (notably iodine, iron, calcium, magnesium), and a wide range of bioactive compounds (carotenoids and phenolic compounds), which together contribute to their growing recognition as valuable food and supplement ingredients.

Microalgae, including species such as *Spirulina*, *Chlorella*, *Nannochloropsis*, and *Dunaliella*, are distinguished by their exceptionally high protein content, often ranging from 40% to 70% of dry weight. Their amino acid profile is generally well balanced, providing significant amounts of lysine, leucine, valine, isoleucine, and threonine. Among them, *Spirulina* and *Chlorella* are particularly valued for their completeness, although methionine and cysteine may be limiting in certain strains. Due to their high protein digestibility and the additional presence of essential fatty acids and pigments such as chlorophyll and carotenoids, microalgae are predominantly commercialized as dietary supplements.

Macroalgae, encompassing red, brown, and green seaweeds such as *Porphyra*, *Palmaria*, *Laminaria*, *Undaria*, and *Ulva*, display a more variable protein content, typically ranging from 10% to 35% of dry weight, with red species often reaching the higher end of this range. Their amino acid profile is dominated by glutamic and aspartic acid, which contribute to the characteristic umami taste, while essential amino acids such as leucine, valine, and lysine are also present, though at lower concentrations compared to microalgae. Beyond proteins, macroalgae provide valuable dietary fibers, minerals, as well as functional polysaccharides like alginates, carrageenans, and agar, making them important both as food ingredients and as sources of bioactive compounds with health-promoting properties.

To better highlight the differences between the two groups, Table 5 provides a comparative overview of the total protein content and essential amino acid composition of microalgae and macroalgae.

Table 5. Comparison between microalgae and macroalgae in terms of protein content and essential amino acids

Parameter	Microalgae (Spirulina, Chlorella, Nannochloropsis, Dunaliella)	Macroalgae (Porphyra, Palmaria, Laminaria, Undaria, Ulva)
Total protein content (dry wt)	40–70%	10–35% (red species up to ~35–40%)
Main essential amino acids	Lysine, leucine, valine, isoleucine, threonine; well-balanced profile	Leucine, valine, lysine; lower amounts compared to microalgae

Other notable amino acids	Methionine and cysteine sometimes limiting; good digestibility overall	High levels of glutamic and aspartic acid (umami flavor)
Nutritional role	High-quality protein, pigments, PUFAs; marketed as supplements	Moderate protein, rich in fibers, minerals and polysaccharides

The protein content of algae is highly variable, depending on factors such as geographic origin, season, and environmental conditions, as well as on specific cultivation and harvesting practices. Moreover, significant differences are observed among taxonomic groups: red and green algae generally contain higher levels of protein, while brown algae typically display lower concentrations [33, 34]. It is also worth noting that certain essential amino acids are present in lower concentrations depending on the algal group: red algae are relatively poor in leucine and isoleucine, while brown algae generally contain limited amounts of methionine, cystine, and lysine.

Despite their valuable amino acid composition, algal proteins are generally characterized by lower digestibility compared to animal-derived proteins. This reduced bioavailability is largely attributed to the presence of rigid cell walls, high polysaccharide content, and phenolic compounds that can interfere with protein hydrolysis and absorption. Consequently, although algae may serve as promising sources of essential amino acids, their effective nutritional contribution is often lower than that of proteins from meat, dairy, or eggs [35, 36].

Protein digestibility in algae has been reported at levels broadly comparable to those of many plant foods, though still lower than animal proteins. Red seaweeds generally show higher digestibility values, in the range of 83–87%, whereas brown species tend to be slightly lower, around 79–82% [37]. These figures align with the variability observed in grains, legumes, fruits, and vegetables, which typically fall between 68% and 92%. For microalgae, the data are more limited, yet available studies indicate digestibility coefficients of 88.0% for *Scenedesmus obliquus*, 77.6% for *Spirulina*, and 76.6% for *Chlorella*. By comparison, animal-derived proteins such as casein and egg display higher digestibility, reaching 95.1% and 94.2%, respectively [36].

Because of their rigid cell walls and high polysaccharide content, algae are seldom consumed directly in raw form. Instead, a variety of technological processes are applied to improve protein digestibility and nutrient release. These include mechanical disruption (e.g., milling, high-pressure homogenization), enzymatic hydrolysis, fermentation with microorganisms, thermal treatment, and protein extraction or fractionation. Such interventions weaken or break the structural barriers of the algal matrix, reduce antinutritional compounds, and make amino acids more accessible for human absorption, thereby increasing the overall nutritional value of algal proteins.

Sustainability

Unlike conventional agricultural crops, algae do not require arable land and use only minimal amounts of freshwater, as they can be cultivated in marine or diverse aquatic environments [38]. In addition, their ability to capture carbon dioxide and release oxygen contributes to lowering environmental impacts and supports global climate change mitigation strategies. With high biomass productivity and the capacity to supply proteins, lipids, and bioactive compounds, algae are increasingly recognized as a strategic resource in the development of more sustainable food systems. Based on data from FAO and USDA statistical databases, it is possible to calculate and compare the annual protein yield per hectare obtained from different crops and alternative sources. This comparison highlights the substantial variation in protein productivity across sources, ranging from traditional legumes and cereals to emerging alternatives such as insects and microalgae (Figure 2).

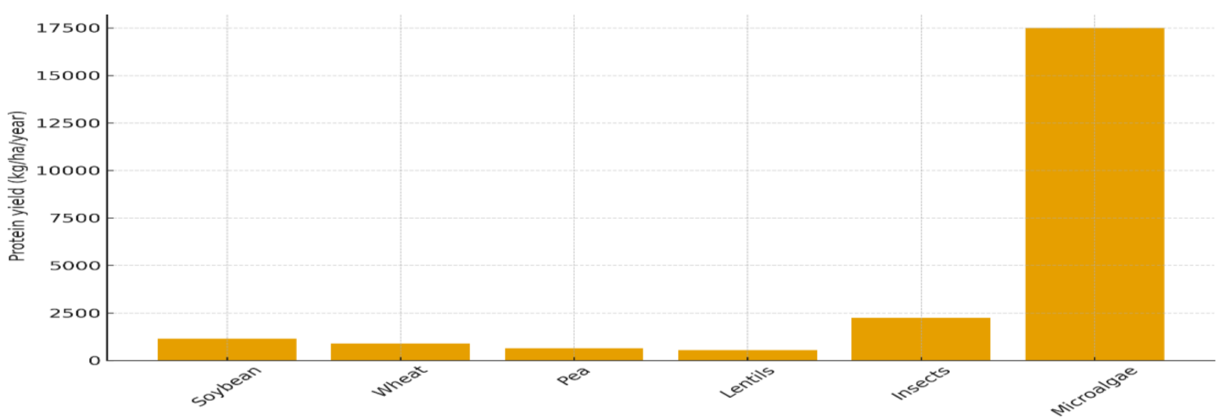

Figure 2. Annual protein productivity per hectare: crops, insects, and microalgae (FAO and USDA data)

Annual biomass productivity of algae has been estimated to exceed that of corn by a factor of 167 under equivalent land use conditions [39]. Although biomass production in algae involves nearly one ton of water for every kilogram produced (≈1,000 m^3/ton), this input remains considerably lower than that of many staple crops. For instance, soybeans and lentils require 2,145 and 5,874 m^3/ton, respectively, underscoring the relative advantage of algae in terms of water efficiency [40].

Recent studies have highlighted that whole algae protein has a substantially lower carbon and water footprint compared to animal-based proteins such as beef and whey, and performs similarly or even better than several plant-based alternatives (Table 6).

Table 6. Comparative carbon and water footprints of protein sources (per kg protein)

Protein source	Carbon footprint (kg CO2-eq/kg protein)	Water footprint (L/kg protein)	Sources
Beef	60	15.400	[41]
Whey	14-20	6.0- 7.0	[42]
Soy	6-10	2.1	[41]
Pea	4-5	1.8 - 2.0	[43]
Whole algae	2-4	1.0 -1.2	[44]

Furthermore, analyses of land use efficiency indicate that algae generate significantly more protein per hectare of cultivation area than conventional protein sources. These findings strengthen the case for algae as a sustainable ingredient, capable of providing high-quality nutrients while minimizing environmental burdens across multiple dimensions.

Evidence from scientific studies indicates a strong synergy between microalgae and conventional crops, demonstrating that integrated cultivation systems can improve both resource efficiency and protein yield. For instance, coupling sugar beet cultivation with mixotrophic algae production enables sucrose from beets to be converted into microalgal single-cell protein with very high efficiency. Such systems require considerably less land and water compared to soy protein production, while also offering an economically promising pathway for sustainable protein supply.

Seaweeds and microalgae contribute not only to food security but also to the protection of marine ecosystems. Through photosynthesis, they absorb significant amounts of carbon dioxide, thereby mitigating ocean acidification and contributing to climate regulation [45]. Moreover, many species are efficient biofilters, taking up excess nitrogen and phosphorus from surrounding waters and thus reducing the risk of eutrophication caused by agricultural run-off [46]. Large seaweed beds, such as kelp forests, provide critical habitats and nursery grounds for diverse marine organisms, supporting biodiversity and fisheries [47]. Importantly, seaweed farming requires no freshwater, arable land, or synthetic inputs, making it a low-impact activity that can be integrated into circular systems such as Integrated Multi-Trophic Aquaculture, where seaweeds improve water quality while supplying biomass for food and feed [48].

2.3. Insects

Beyond algae and mycoproteins, a wide range of emerging protein sources are gaining increasing attention from the food industry. These include plant-based proteins derived from legumes and cereals, as well as edible insects, which are being explored as novel, sustainable alternatives to traditional animal proteins [49, 50]. Edible insects, in particular, combine high nutritional value with efficient resource utilization, positioning them as one of the most promising protein sources for the future of sustainable diets [51].

Entomophagy, or the consumption of insects, is a long-standing tradition in many regions of the world. In Africa, Asia, and Latin America, more than 2,000 insect species are part of local diets, often prepared as delicacies or seasonal specialties. Their role in these cultures extends far beyond being a substitute food in periods of scarcity, as they are valued for their taste and embedded in culinary traditions. Globally, an estimated two billion people consume insects daily, with more than 1,900 species identified as edible [49]. On this global foundation, regional patterns of entomophagy reveal distinct traditions and species preferences across Africa, Asia, and Latin America. To illustrate the diversity of entomophagy practices worldwide, Table 7 summarizes the main regions where insects are traditionally consumed, along with examples of commonly eaten species.

Table 7. Regional diversity of edible insects and representative species

Region	Edible species	Representative species	Consumption patterns
Africa	>500	Mopane worm *(Gonimbrasia belina)*, Termites *(Macrotermes spp.)*, Grasshoppers *(Ruspolia differens)*	Seasonal delicacies, important for food security and household income
Asia	>300	Crickets (*Acheta domesticus*), Silkworm pupae *(Bombyx mori)*, Bamboo worms *(Omphisa fuscidentalis)*	Street food, traditional dishes, widely commercialized
Latin America	>300	Leafcutter ants (*Atta spp.*), Chapulines *(Sphenarium spp.)*, Palm weevil *(Rhynchophorus palmarum)*	Consumed as snacks, sauces, and festive foods
Oceania	Limited but present	Witchetty grubs *(Endoxyla leucomochla)*, Honey ants *(Camponotus inflatus)*	Part of traditional diets of Indigenous peoples
Europa	Emerging practice	Mealworms (*Tenebrio molitor*), Crickets (*Acheta domesticus*), Migratory locust (Locusta migratoria) Lesser mealworm (*Alphitobius diaperinus*)	Recent introduction under EU novel food regulations; growing consumer interest

In the European Union, initial efforts have been made to introduce insects into staple foods such as bread, with only four species (Figure 3) currently authorized as novel foods under Regulation (EU) 2015/2283: *Tenebrio molitor* (yellow mealworm, Implementing Regulation (EU) 2021/882), *Locusta migratoria* (migratory locust, Implementing Regulation (EU) 2021/1975), *Acheta domesticus* (house cricket, Implementing Regulation (EU) 2022/188), and *Alphitobius diaperinus* (lesser mealworm, Implementing Regulation (EU) 2023/58).

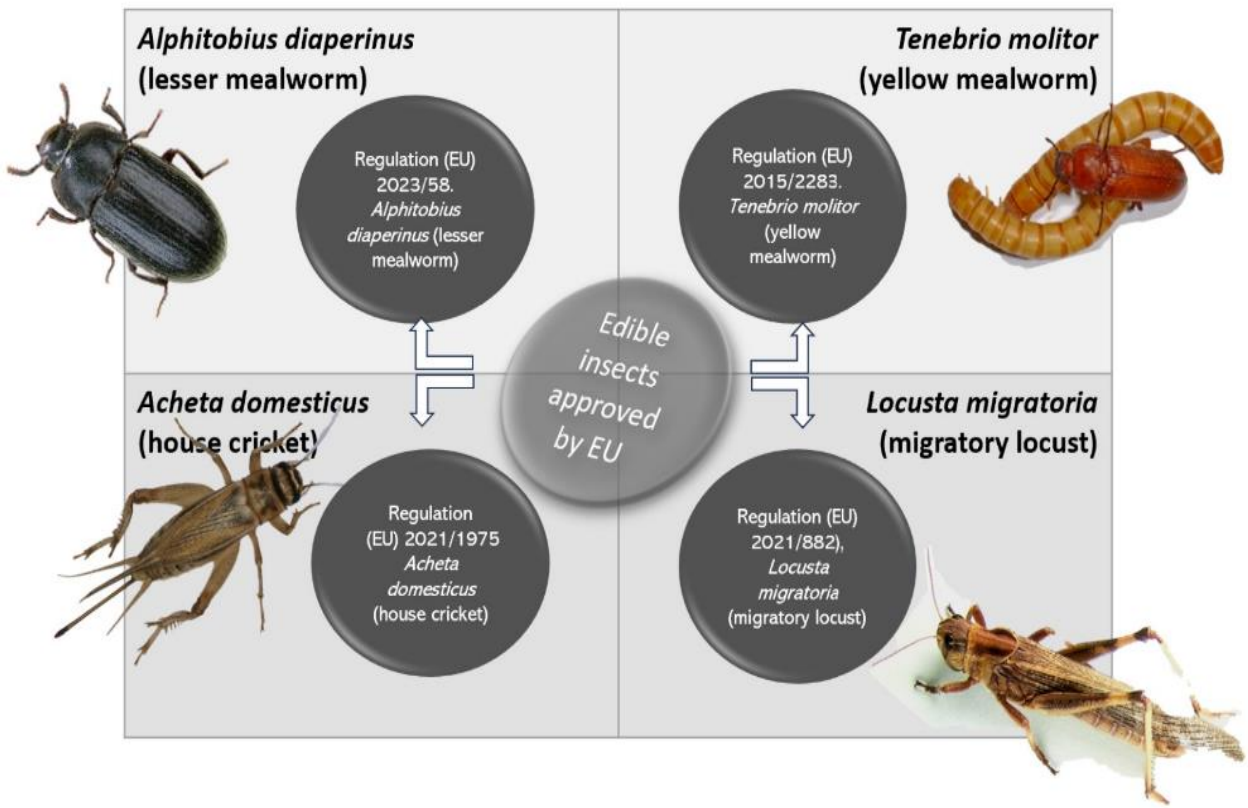

Figure 3. Currently authorized insect species for human consumption in the EU

Globally, the most widely consumed insects belong to the order Coleoptera (beetles), which account for about 31% of reported edible species, followed by Lepidoptera (caterpillars, 18%), Hymenoptera (bees, wasps, and ants, 14%), and Orthoptera (grasshoppers, locusts, and crickets, 13%) [49]. The stage of development at which insects are consumed varies by order: Coleoptera are eaten both as larvae and adults, Lepidoptera almost exclusively as caterpillars, and Hymenoptera mostly in their larval or pupal stages. By contrast, Orthoptera, Isoptera (termites), and Hemiptera (true bugs) are typically consumed in the mature stage. These patterns reflect cultural preferences, nutritional differences between life stages, and practical aspects such as availability and ease of harvest. In addition, the larval stage is particularly valued not only because of its widespread consumption but also due to its high nutritional density and ease of rearing.

Edible insects are consumed in a wide variety of forms across the world, reflecting both traditional practices and modern food innovations. In many regions of Africa, Asia, and Latin America, insects are commonly eaten fried, roasted, or boiled, often seasoned and served as snacks or incorporated into soups and stews [49]. Some species, such as crickets and grasshoppers, are sold as street food, while others, like caterpillars, are preserved by drying or smoking to ensure year-round availability [52]. In recent years, new processing methods have been developed, most notably the production of insect flours and powders, which can be incorporated into bakery products, pasta, energy bars, or protein shakes. This approach not only extends shelf life but also improves consumer acceptance by masking the insect's original appearance [51].

Nutritional profile of Insects

Edible insects are characterized by a rich and diverse nutritional profile, which varies across species but generally compares favorably with conventional protein sources. Protein content typically ranges from 35% to 70% of dry matter, with many species providing all essential amino acids in proportions comparable to meat, soy, or fish [51]. Among the species with the highest protein levels are crickets (*Acheta domesticus*) and grasshoppers (*Locusta migratoria*), which typically contain 60–70% protein, and yellow mealworms (*Tenebrio molitor*), which may reach up to 75% [53]. By contrast, species such as the giant water bug (*Lethocerus indicus*) or some termite species (*Macrotermes bellicosus*) have been reported with protein levels closer to 35–40% [51]. This wide nutritional range indicates that edible insects cannot be treated as a homogeneous group but rather as a highly diverse category of protein-rich foods, where some species rival conventional animal proteins in density, while others are closer to legumes.

Figure 4 compares the protein content of selected edible insects with that of conventional protein sources, expressed on a dry weight basis. As shown, crickets (*Acheta domesticus*), mealworms (*Tenebrio molitor*), and grasshoppers (*Locusta* *migratoria*) can provide 60–70% protein, which is equal to or even higher than beef, chicken, or fish. By contrast, plant-based sources such as soybean and lentils contain substantially lower levels, typically ranging from 25% to 45%.

The nutritional quality of insect proteins is largely determined by their essential amino acid profile and digestibility. Many edible insect species provide all nine essential amino acids, with levels that are comparable to or even exceed those found in conventional animal proteins. The amino acid composition of edible insects reveals a generally favorable profile, although with species-dependent variations. Brown mealworms (*Tenebrio molitor*) are particularly rich in leucine, phenylalanine, and threonine, which are crucial for muscle development and repair [54]. Crickets (*Acheta domesticus*) provide high levels of valine, isoleucine, and histidine, making their profile comparable to that of beef [55]. Rice grasshoppers (*Oxya spp*.) are notable for their lysine content, while mopane worms (*Gonimbrasia belina*) offer balanced amounts of methionine and cysteine, amino acids typically limited in cereal-based diets. Silkworm pupae (*Bombyx mori*) contribute substantial levels of serine and glycine, while black soldier fly larvae (*Hermetia illucens*) contain high concentrations of glutamic and aspartic acids, although their methionine content is relatively low [56].

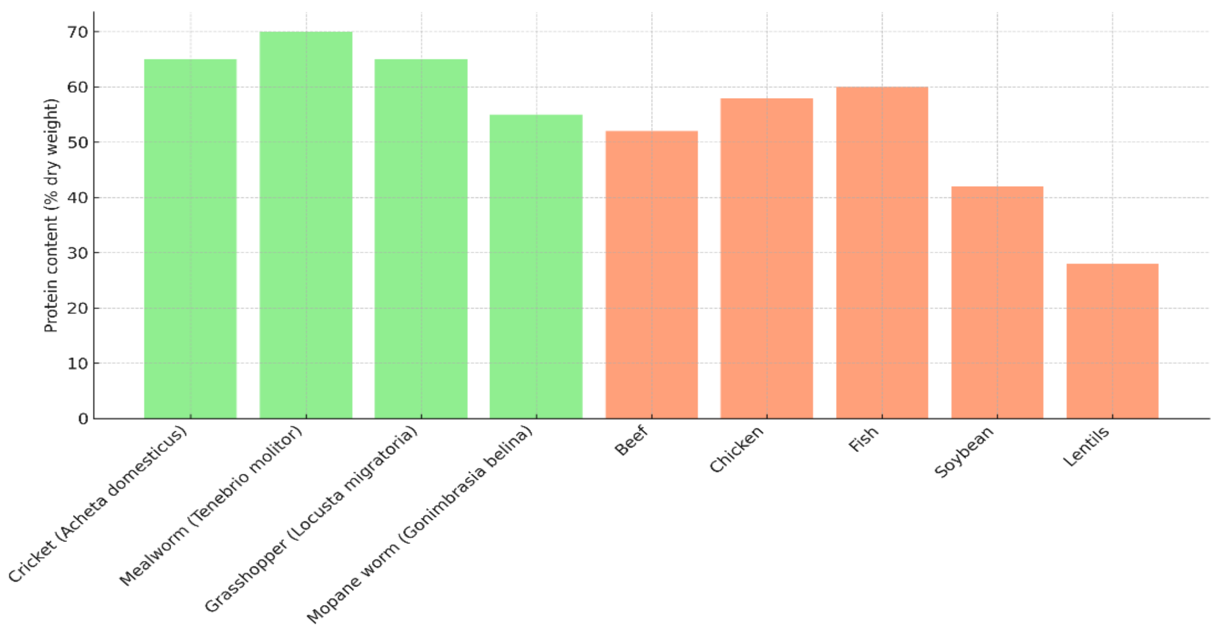

Figure 4. Protein composition of insects versus conventional animal and plant sources (%/dw)

The nutritional quality of insect proteins is not only determined by their amino acid composition but also by their digestibility. Reported values vary considerably, ranging from approximately 70% to over 90%, depending on the insect species and the processing method applied. A major factor influencing digestibility is the presence of *chitin* in the exoskeleton, which can hinder enzymatic access to proteins. However, technological processing, such as drying, grinding, protein extraction, fermentation, or enzymatic hydrolysis, substantially improves digestibility by reducing the chitin barrier and altering protein structure. For instance, proteins from *Tenebrio molitor* (yellow mealworm) have shown in vitro digestibility values between 76% and 90% [54], while *Acheta domesticus* (house cricket) exhibits similar levels, comparable to those of soy or egg proteins once processed. Hydrolyzed insect proteins can even reach digestibility values above 90%, placing them in the same range as milk or chicken [54]. Overall, insects display a digestibility profile that is comparable to or higher than many plant-based proteins, which underscores their potential as a high-quality alternative protein source.

In addition to proteins, insects are also rich in lipids, with some species containing high levels of polyunsaturated fatty acids, including omega-3 (a-linolenic acid) and omega-6 (particularly linoleic acid) [53]. Due to their high proportion of unsaturated fatty acids, insect lipids are frequently described as "insect oils", since they typically remain liquid at room temperature. Humans are unable to synthesize these essential fatty acids endogenously, which makes dietary intake indispensable. In this context, edible insects can serve as a functional food and a suitable dietary supplement to provide these vital fatty acids, thereby supporting physiological functions such as cell membrane integrity, growth, and immune response.

For insects to gain wider acceptance in regions where they are not traditionally consumed, it is essential to highlight their beneficial components for human nutrition. Among these, the lipid fraction plays an important role, as it not only contributes to the energy value but also provides essential fatty acids with proven health benefits. To illustrate this, table 8 presents the lipid profile of the four insect species currently approved as novel foods in the European Union.

Table 8. Lipid composition of the four insect species authorized as novel foods in the EU

Species	Stage	Fats (%)	SFA	UFA	MUFA	PUFA	n-3	n-6	Sources
Tenebrio molitor (yellow mealworm)	Larvae	24.70-43.08	25.35 30.12	-	43.27-66.77	3.11-31.37	1.61	29.68	[57]
Locusta migratoria (migratory locust)	Adult	30.52	46.70-56.85	43,15	25.70-28.00	17.45-25.20	6.74	10.71	[58]
Acheta domesticus (house cricket)	Adult	12.20-22.96	32.22-32.80	64.36-67.40	21.72-33.50	33.90-42.64	0.01-0.39	2.08-42.63	[58] [59]
Alphitobius diaperinus (lesser mealworm)	Larve	18.00-24.00	3.,2	-	40.66	27.16	1.11	25.1	[60]

It is important to emphasize that the chemical composition of insects is not fixed but can be modulated depending on the intended end use. Factors such as the feeding substrate, the developmental stage at harvest, and the processing method strongly influence their nutritional profile. Rearing conditions, including temperature and humidity, as well as the choice of insect strain, have also been shown to affect lipid and protein composition. This plasticity provides opportunities to tailor the nutritional characteristics of edible insects to specific dietary or industrial applications.

Insects are furthermore an important source of vitamins (such as B12, riboflavin, and folic acid) and minerals (including iron, zinc, magnesium, and calcium), which are essential for human health and often deficient in plant-based diets. Vitamin B12, which is naturally abundant in animal-derived foods, is often deficient in vegan and vegetarian diets. This deficiency can lead to neurological disorders and anemia, making adequate intake essential for maintaining nervous system function and healthy red blood cells. Edible insects represent a promising alternative source of vitamin B12, with certain products showing remarkably high concentrations. For instance, dried cricket powder has been reported to contain up to ten times more vitamin B12 than beef [62]. Thus, incorporating insect-based foods or supplements could help to balance nutrient intake and reduce the risk of vitamin B12 deficiency in populations following plant-based diets.

In addition to their macronutrients and vitamins, edible insects also contain a variety of bioactive compounds such as chitin [63], polyphenols, and bioactive peptides [64], which have been associated with antioxidant, antimicrobial, and immunomodulatory properties. These components further enhance the functional value of insects, positioning them not only as a source of essential nutrients but also as contributors to overall health promotion. This unique combination of macronutrients and micronutrients positions edible insects as a highly valuable food source in the context of global nutrition security.

Sustainability

Growing global concerns about climate change, biodiversity loss, and resource scarcity have positioned edible insects as one of the most promising environmentally friendly alternative food sources [49]. Compared to conventional livestock, insect farming presents several ecological advantages, including:

- Higher feed conversion efficiency,
- Reduced greenhouse gas emissions,
- Lower water and land requirements,
- the ability to valorize organic side streams, and
- Reduced pressure on biodiversity.

An important ecological benefit of edible insects, when compared to conventional livestock such as poultry, pigs, and cattle, lies in their superior ability to convert feed into body mass. Because they are poikilothermic, insects channel a larger share of ingested nutrients directly into growth rather than expending energy on maintaining body temperature, which results in markedly higher feed conversion efficiency [49, 65]. The feed conversion ratio (FCR) of mealworms has been shown to be approximately 2.2 (kg feed/kg fresh weight), which is comparable to that of broiler chickens (2.3), yet substantially lower than that of pigs (4.0) and beef cattle (ranging between 2.7 and 8.8). Crickets perform even better, requiring only 1.7 kg of feed to produce 1 kg of body weight gain [66]. These findings underline the superior feed conversion efficiency of insects compared to conventional livestock, reinforcing their role as a resource efficient protein source.

In addition to their favorable feed conversion ratios, insects also reproduce at a much faster rate than conventional livestock. Many edible insect species have short life cycles and high fecundity, allowing large populations to be reared within a relatively short period of time and on limited resources. For example, house crickets (*Acheta domesticus*) reach reproductive maturity in about 6–8 weeks, with females laying between 1.200 and 1.500 eggs over their lifetime. The eggs typically hatch within 7–10 days, and the nymphs reach market size in 5–7 weeks depending on rearing conditions. Similarly, mealworms (*Tenebrio molitor*) develop from egg to harvestable larvae within 8–10 weeks, and a single female may produce 300–500 eggs. The combination of high fecundity and short generation times allows insects to efficiently transform feed into successive generations, further improving production outcomes.

Another important aspect of feed conversion efficiency in insects is their ability to grow on low-value organic side streams derived from various agro-industrial sectors. Substrates such as fruit and vegetable residues, cereal by-products, brewery waste, or even food scraps can be used as feed for species like mealworms and black soldier fly larvae. By converting these residues into high-value protein and fat, insects not only reduce the demand for conventional feed resources but also contribute to circular economy models and the reduction of food waste [67].

Feed efficiency in insects is also enhanced by the high proportion of their body mass that is considered edible. For example, in crickets and mealworms, between 80% and 90% of the body can be consumed, compared with about 55% in chickens, 40% in pigs, and only around 40% in cattle, once bones and other inedible parts are removed. This larger edible fraction means that not only do insects convert feed more efficiently into biomass, but a higher share of that biomass is directly available as food for humans [49].

In contrast to conventional livestock, insect farming produces markedly lower greenhouse gas (GHG) emissions throughout the production cycle. Ruminant species such as cattle and sheep release large quantities of methane (CH_4) and nitrous oxide (N_2O) through digestive fermentation and manure decomposition, both identified as major contributors to global warming. Insects, on the other hand, do not rely on enteric fermentation and therefore lack methanogenic microorganisms in their digestive systems. This physiological difference results in negligible GHG emissions during growth and reproduction.

Quantitative assessments demonstrate that the global warming potential (GWP) of mealworm production ranges between 2 and 5 kg CO_2-equivalents per kilogram of edible protein, which is up to 100 times lower than that of beef (approximately 250–500 kg CO_2-eq/kg protein) and substantially lower than that of pork (55–90 kg CO_2-eq/kg protein) or poultry (35–40 kg CO_2-eq/kg protein) [68]. Similar findings have been reported for crickets, whose production emits up to 80% less total GHG compared with poultry farming [69].

When compared with other alternative protein sources, such as plant-based proteins and microalgae, insect farming maintains a competitive environmental profile. For example, soy protein isolate typically generates 3–10 kg CO_2-eq/kg protein, while pea protein falls within a similar range. Microalgal biomass can vary considerably depending on the cultivation system, ranging from 10 to 40 kg CO_2-eq/kg protein under phototrophic conditions to as low as 5–8 kg CO_2-eq/kg protein in optimized heterotrophic systems [70]. Despite these variations, insect-based proteins consistently demonstrate one of the lowest overall GHG footprints, particularly when by-products and organic residues are used as rearing substrates.

Beyond their reduced GHG footprint, insects also require significantly less water and land compared with conventional and alternative protein sources. The water footprint of insect protein has been estimated at 3,000–4,000 L per kg of edible mass, whereas chicken requires about 4,300 L, pork around 6,000 L, and beef nearly 15,000 L per kg of edible mass [70]. Microalgae show variable water demands depending on cultivation methods, ranging from 1,000 to 10,000 L/kg, while plant-based proteins such as soy require 2,000–5,000 L/kg.

In terms of land use, insect farming is highly space-efficient. Producing 1 kg of insect protein typically requires 30–70 m² of land, compared with 250–300 m² for soy protein, 450 m² for chicken, and over 2,000 m² for beef [71]. This compact production footprint allows insect farms to operate vertically and utilize agro-industrial by-products as feed substrates, further enhancing sustainability.

Overall, the combination of low GHG emissions, minimal water consumption, and reduced land use places insects among the most environmentally efficient protein sources available, bridging the sustainability advantages of plant-based systems with the high nutritional density of animal proteins.

2.4. Microbial proteins

Microorganisms such as bacteria, yeasts, and filamentous fungi have the remarkable ability to synthesize proteins and other high-value biomolecules, including vitamins, essential fatty acids, polysaccharides, pigments, and bioactive compounds. These microbial cells, when cultivated and harvested for their protein-rich biomass, are commonly referred to as single-cell proteins (SCP), also known as microbial proteins (MP), a term increasingly used to emphasize their biological origin and potential role as sustainable food and feed resources. For millennia, humans have relied on microorganisms to ferment, preserve, and enhance foods, often without understanding their biological nature. Today, these same microorganisms are at the forefront of innovation, being cultivated not only as tools of food processing but as primary sources of nutrition and sustainability.The concept of using microorganisms as a food and feed source emerged in the 1960s, initially motivated by the need to identify alternative protein sources that could support a growing global population with limited agricultural resources [72, 73].

A wide range of microorganisms can be exploited for the production of microbial proteins, including bacteria, yeasts, and filamentous fungi (Figure 5). Each group exhibits distinct metabolic characteristics, substrate preferences, and nutritional profiles, which determine their suitability for various applications in food and feed systems.

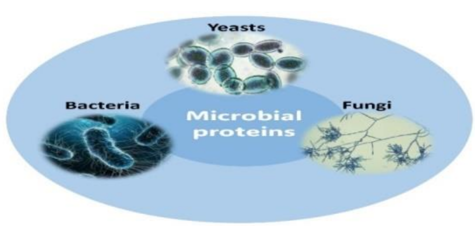

Figure 5. Overview of the main microbial sources of protein

Bacteria

Several bacterial groups have been identified as suitable for microbial protein production due to their high growth rates, elevated protein content, and metabolic versatility. Depending on their substrate utilization, they can be broadly classified into heterotrophic, methylotrophic, and hydrogen-oxidizing (autotrophic) bacteria.

Heterotrophic bacteria

These utilize organic carbon sources such as sugars, organic acids, or agricultural by-products. Species such as *Corynebacterium glutamicum*, *Bacillus subtilis*, and *Lactobacillus plantarum* have been investigated for SCP production because of their high nutritional value and established safety profiles (many being Generally Recognized as Safe — GRAS). These bacteria are particularly attractive for food applications, as they can grow on inexpensive substrates like molasses, whey, or starch hydrolysates.

Methylotrophic bacteria

These including *Methylophilus methylotrophus*, *Methylomonas methanica*, and *Methylococcus capsulatus*, can metabolize single-carbon compounds such as methanol or methane. This group gained prominence with the development of Pruteen, a bacterial protein product derived from *Methylophilus methylotrophus* in the 1970s, and more recently with FeedKind™, produced from Methylococcus capsulatus grown on natural gas.

Autotrophic bacteria

(Hydrogen-oxidizing bacteria) such as *Cupriavidus necator* (formerly Hydrogenomonas eutropha, *Alcaligenes eutrophus* and *Ralstonia eutropha*), *Xanthobacter autotrophicus*, and *Hydrogenobacter thermophilus* utilize hydrogen and carbon dioxide as energy and carbon sources, respectively. These bacteria are capable of converting inorganic carbon directly into protein, representing one of the most sustainable biological pathways for protein production.

These bacterial groups illustrate the diversity of metabolic strategies that can be harnessed for microbial protein production, from organic waste valorization to carbon recycling, highlighting bacteria as a cornerstone of future sustainable protein technologies.

Despite their nutritional potential, the large-scale use of bacterial proteins is still hindered by technical and practical limitations, such as the difficult recovery of small-sized cells, which requires costly flocculation and centrifugation steps, concerns regarding safety and public acceptance, and the excessive nucleic acid content of the dried biomass that necessitates additional processing to ensure consumer safety [72].

Yeasts

Yeasts have a long and well-documented association with food production. For millennia, these unicellular fungi have been employed in the fermentation of bread, beer, and wine, shaping dietary cultures worldwide. However, beyond their traditional role as processing agents, yeasts are now recognized as direct sources of nutrients, particularly proteins, vitamins, and bioactive compounds. The renewed scientific interest in yeasts as single-cell protein (SCP) or microbial protein (MP) sources began in the mid-20th century, when their rapid growth, high protein yield, and safety for human consumption positioned them as promising alternatives to conventional protein ingredients.

The most extensively studied and utilized yeast species include Saccharomyces cerevisiae, Candida utilis, and Yarrowia lipolytica, each exhibiting distinct metabolic capacities and nutritional characteristics.

Beyond their nutritional value, yeasts play an increasingly important role in food formulation due to their functional and technological properties. The sustainable production of yeast biomass provides a rich source of nutritional proteins that can be incorporated into a wide range of food products, including extruded foods [74], processed meat products [75], and emulsified preparations such as mayonnaise [76]. Yeast-derived ingredients contribute not only to the protein enrichment of foods but also to texture improvement, flavor development, and emulsifying stability. As a result, yeasts are now considered versatile biofactories capable of delivering both nutritional and functional benefits for human diets.

Despite their nutritional quality and long history of safe use, several factors limit the large-scale use of yeasts as direct protein sources for human food. A major drawback is the relatively high nucleic acid content (6–12% of dry weight) of yeast biomass, which, as in bacteria, can lead to excessive uric acid formation when consumed in large amounts. This requires additional processing steps, such as heat treatment or enzymatic degradation, to reduce nucleic acid levels [77]. Another limitation is related to cell wall composition, as yeasts possess a thick structure rich in β-glucans and chitin, which can decrease protein digestibility if the cells are not properly disrupted. Mechanical or enzymatic cell wall lysis is therefore needed to increase bioavailability of intracellular proteins.

From a technological perspective, downstream processing (drying, cell disruption, and nucleic acid removal) can be energy-intensive and costly, affecting the economic feasibility of large-scale production. Moreover, flavor and color attributes of yeast biomass may restrict its inclusion levels in certain food products, requiring refinement or blending with other protein sources [78]. Finally, consumer perception remains a barrier, as yeast-derived proteins are often associated with industrial fermentation rather than food-grade ingredients.

Filamentous fungi

Among the microbial sources of protein, this group of eukaryotic microorganisms has received increasing attention for its nutritional value and versatile applications. These fungi form multicellular mycelial structures, which give their biomass distinctive textural and functional properties compared to unicellular yeasts and bacteria. Their ability to grow efficiently on low-cost substrates, including agricultural residues and food-processing by-products, together with a high protein content (30–50% of dry weight), makes them an important component of the microbial protein sector [79].

The potential of filamentous fungi as food sources was recognized as early as the 1970s, when intensive research led to the development of mycoprotein, derived from *Fusarium venenatum* and later commercialized under the Quorn™ brand. This innovation established the technological and nutritional feasibility of fungal biomass for direct human consumption. Since then, species such as *Aspergillus oryzae*, *Rhizopus oligosporus*, and *Neurospora intermedia* have been explored for food and feed applications, owing to their balanced amino acid profiles, low fat content, and dietary fiber components such as chitin and β-glucans.

In addition to providing high-quality proteins, these microorganisms contribute to improved texture, flavor, and structure in fermented foods and meat analogues. Their ability to generate fibrous networks that mimic muscle tissue, together with the GRAS status of selected species, positions them as a key bridge between traditional fermentation and modern sustainable protein technologies.

Although fungal proteins are generally considered safe and nutritious, several factors may limit their broader acceptance and use in food. The most frequently reported issues are related to allergic or hypersensitivity reactions, occasionally occurring after consumption of Fusarium-derived mycoprotein products. Clinical and epidemiological studies have documented immediate-type allergic responses, including urticaria, angioedema, or gastrointestinal symptoms in susceptible individuals. Such reactions are thought to be linked to residual fungal cell wall components, such as chitin and β-glucans, or to fungal proteins capable of triggering IgE-mediated immune responses [80].

Another limitation concerns the digestibility of fungal biomass. Due to the rigidity of the mycelial cell wall, the bioavailability of intracellular proteins can be reduced unless the biomass is heat-treated or enzymatically disrupted before consumption [81]. Moreover, the nucleic acid content of fungal cells, although lower than that of bacteria, still requires attention and occasional processing to comply with nutritional recommendations

From a production perspective, fungal cultivation and downstream processing demand strict environmental control and energy input, which can influence production costs. In addition, consumer perception continues to represent a barrier, as products derived from fungal biomass are often associated with mold or industrial fermentation, which may hinder acceptance in certain markets.

Nutritional profile of Microbial proteins

Microbial proteins exhibit a broad spectrum of nutritional qualities depending on the producing organism: bacteria, yeasts, or filamentous fungi. However, all share the common advantage of high protein density and a balanced amino acid composition, which makes them valuable alternatives to conventional protein sources.

In general, the protein content of microbial biomass varies according to the producing organism, ranging from 60–80% of dry weight in bacteria, 45–55% in yeasts, and 30–50% in filamentous fungi, values that often exceed those of conventional plant-based sources such as soy or pulses. When compared to other alternative proteins, microbial biomass exhibits protein levels comparable to microalgae (40–70%) and often higher than those of edible insects (35–65%), while maintaining a more balanced amino acid profile and consistent composition due to controlled fermentation conditions. Microbial proteins generally contain two to three times more protein on a dry-weight basis than meat (60–80% vs. 20–25%), though their digestibility is slightly lower due to the presence of cell wall components such as chitin or glucans.

Microbial proteins provide a balanced amino acid profile that closely matches human nutritional requirements, with adequate levels of all essential amino acids, particularly lysine and threonine, which are often limiting in plant-based proteins.
In bacterial proteins, the concentration of methionine can reach about 3% of total amino acids, exceeding the FAO/WHO adult requirement of approximately 2.2 g per 100 g protein, while tryptophan remains comparatively lower, often approaching the lower limit of human nutritional needs. Yeast proteins exhibit a balanced amino acid profile, rich in lysine and threonine, with methionine and cysteine present at moderate levels that generally meet human dietary recommendations, making them suitable for use as complementary protein ingredients. Fungal proteins, by contrast, contain all essential amino acids, with notably high levels of lysine and threonine, yet are relatively low in methionine, which may limit their amino acid balance unless complemented by other protein sources. However, due to variations in amino acid bioavailability and the presence of structural cell wall materials, microbial biomass is typically not consumed directly as a bulk food but rather processed into purified or hydrolyzed protein ingredients. These refined microbial protein fractions are increasingly used to enrich or replace conventional proteins in formulated foods such as meat analogues, bakery products, or nutritional supplements.

Besides proteins, microbial cells contain variable amounts of lipids and carbohydrates, depending on the organism and cultivation conditions. The lipid content of microbial biomass generally ranges from 5–10% in bacteria, 6–15% in yeasts, and up to 20–25% in filamentous fungi, with composition varying according to species and cultivation conditions. In bacteria, lipids are predominantly phospholipids and membrane-associated fatty acids, mainly serving structural roles. Yeast lipids consist largely of mono- and polyunsaturated fatty acids, particularly oleic and linoleic acid, which enhance their nutritional quality. Fungal lipids, especially in oleaginous strains such as Fusarium or Mortierella, include significant amounts of storage triglycerides and long-chain polyunsaturated fatty acids (PUFAs), some of which resemble those found in higher plants or fish oils. When used as food or food ingredients, the lipid fraction of microbial biomass contributes both nutritional and functional value. These lipids are rich in unsaturated fatty acids, including oleic and linoleic acids, and in some fungal species, long-chain polyunsaturated fatty acids such as γ-linolenic or arachidonic acid. From a technological perspective, microbial lipids enhance emulsification, flavor retention, and mouthfeel, while nutritionally they provide essential fatty acids that are often limited in plant-based formulations. Their balanced fatty acid profile and oxidative stability make microbial lipids suitable for incorporation into a variety of food matrices as natural fat sources or functional ingredients.

The carbohydrate fraction of microbial biomass is mainly composed of structural polysaccharides such as β-glucans, mannans, and chitin or chitosan, whose proportions vary among species. In bacteria, carbohydrates represent a minor fraction (5–15% of dry weight), mostly in the form of peptidoglycan and exopolysaccharides. Yeasts contain 15–25% carbohydrates, largely as β-glucans and mannans forming the cell wall, compounds known for their prebiotic and immunomodulatory effects. Fungal biomass typically includes 20–30% polysaccharides, primarily chitin and β-glucans, which contribute dietary fiber and enhance the functional properties of food matrices by improving viscosity and water-holding capacity. These complex carbohydrates, while not major energy sources, provide valuable techno-functional and health-promoting attributes when microbial proteins are used as food ingredients.

Beyond their macronutrient composition, microbial proteins also contain a variety of bioactive compounds that contribute to their nutritional and functional value. These include vitamins (particularly B-complex vitamins such as B_{12}, B_2, and folate), antioxidant pigments like carotenoids [81] and melanin-like compounds, and cell-wall–

derived polysaccharides such as β-glucans and chitin, which exert immunomodulatory and prebiotic effects. Additionally, microbial cells can produce bioactive peptides with antihypertensive, antimicrobial, or antioxidant properties upon hydrolysis. The presence of these components enhances the nutraceutical potential of microbial biomass, making it not only a source of high-quality protein but also a functional ingredient capable of promoting health and improving food quality.

Sustainability

The production of microbial proteins represents one of the most promising strategies to decouple protein supply from conventional agricultural resources. Unlike livestock or even plant crops, microorganisms can be cultivated using minimal land and water, under controlled conditions that enable year-round production independent of climate or geography. Their conversion efficiency of substrates into biomass is exceptionally high, with some bacterial and yeast systems converting up to 80–90% of assimilated carbon into cellular protein. Moreover, microbial cultivation can utilize low-value or residual feedstocks, such as agricultural by-products, industrial effluents, or CO_2 and methane, thus contributing to a circular bio economy and reducing environmental burdens associated with food production.

In terms of land and water requirements, microbial protein production is considerably more efficient than both conventional livestock and most plant-based protein systems. Because microorganisms can be cultivated in closed and vertically integrated bioreactors, production is independent of arable land and can take place in non-agricultural or industrial areas. Studies consistently report that the land footprint of microbial protein is over 90% lower than that of soy and up to 99% lower than beef, while water use can be reduced by 80–95% through the recycling of culture media and the absence of irrigation needs [82]. For instance, mixotrophic cultivation of Chlorella on sugar beet sucrose was found to require only 0.23 ha per ton of protein, compared with 0.80 ha for soy and 5–10 ha for beef [83].

Microbial protein production requires substantially less freshwater than conventional animal or plant systems, with estimated water use of 20–50 m^3 per ton of microbial biomass, compared with approximately 2,000–2,500 m^3/t for soybeans, 1,800–2,000 m^3/t for wheat, and over 15,000 m^3/t of edible protein from beef. Moreover, microbial cultivation allows recycling of up to 90–95% of process water, further reducing net consumption and enabling production even in regions with limited freshwater availability.

When compared to conventional protein sources, microbial biomass exhibits a significantly lower greenhouse gas (GHG) footprint. Life cycle assessments report emissions in the range of 0.4–0.8 kg CO_2-eq per kg protein, whereas soybean meal releases about 2.5–3.0 kg CO_2-eq, and beef protein exceeds 25–30 kg CO_2-eq. The low emission intensity arises from the absence of enteric fermentation and manure management, coupled with the high carbon conversion efficiency of microbial systems, where up to 80–90% of assimilated carbon is retained as cellular biomass [83]. These advantages underline the potential of microbial proteins to reduce the carbon intensity of global protein production.

2.5. Cultured and innovative proteins

Within the broader field of cellular agriculture, several innovative food products are currently under development, including cultured meat, milk, and eggs. Among these, cultured meat has received the greatest scientific, industrial, and media attention due to its potential to fundamentally transform the global protein supply chain. While cell-based dairy and egg alternatives are generally perceived as more acceptable to consumers and have already reached early stages of commercialization, this section focuses primarily on cultured meat, the most emblematic and debated form of cellular protein innovation, given its rapidly expanding research base and its central role in discussions on sustainable and ethical protein production.

Cultured meat, also referred to as lab-grown, *in vitro* meat, cell-based or cultivated meat, represents an emerging branch of cellular agriculture that aims to produce animal muscle tissue directly from cells rather than by raising and slaughtering animals. The concept relies on isolating a small sample of animal stem or satellite cells, which are then proliferated and differentiated into muscle fibers under controlled conditions within a bioreactor. The final product mimics the structure and composition of conventional meat, offering a potentially more sustainable and ethical alternative to livestock farming [84].

The idea of producing meat through tissue culture was first proposed by Dutch researcher Willem van Eelen in the 1990s, but the field gained global attention in 2013 when the first cultured beef burger (developed by Professor Mark Post and his team at Maastricht University) was publicly presented in London. Since then, significant technological advances and private investments have driven rapid progress, reducing costs and expanding research beyond beef to poultry, pork, and seafood.

At present, only a few countries have granted regulatory approval for the commercialization of cultured meat. Singapore became the first nation to approve the sale of cultivated chicken in 2020, followed by the United States in 2023, where two companies (GOOD Meat and UPSIDE Foods) received clearance from the Food and Drug Administration (FDA) and the Department of Agriculture (USDA). The European Union and other regions are currently evaluating similar regulatory frameworks, while pilot production facilities have been established in Israel, the Netherlands, and Japan.

Cultured meat represents one of the most technologically advanced forms of alternative protein, obtained through the cultivation of animal cells under controlled laboratory conditions, thereby producing genuine meat without the need to raise or slaughter animals.

Compared with other alternative proteins, cultivated meat offers several distinct advantages:

- it replicates more closely the sensory properties of conventional meat;
- it is free from common allergens and antinutritional compounds that can be present in plant-derived proteins;
- it allows precise control over nutritional composition.

Relative to conventional livestock products, cultured meat provides additional benefits, including:

- a substantially lower environmental footprint in terms of greenhouse gas emissions, water, and land use;
- the elimination of animal slaughter, addressing ethical concerns;
- the possibility to tailor its nutritional value through cellular and biochemical modulation.

Despite its promising potential, the large-scale development of cultured meat remains limited by several technical, economic, and social challenges. Production costs are still considerable, largely driven by the high price of cell culture media, the operation of bioreactors, and the need to maintain sterile conditions throughout the process. Although it reduces land and water use, current production systems are energy-intensive, and their overall carbon footprint depends heavily on the source of electricity employed. Technological hurdles also persist in replicating the complex structure, texture, and flavor of conventional meat, which require sophisticated scaffolds and co-culturing of muscle and fat cells [85]. Moreover, many processes still rely on fetal bovine serum, emphasizing the need for serum-free or plant-based alternatives [86]. Beyond technological barriers, consumer acceptance and regulatory approval remain uncertain, as perceptions of unnaturalness and concerns over safety continue to shape public attitudes [87].

Nutritional profile of cultured meat

Beyond technological and economic challenges, an important aspect of cultured meat assessment concerns its nutritional composition and how it compares with that of conventional meat. Because the product is developed directly from animal cells, its macronutrient profile, particularly protein quality and amino acid composition, closely resembles that of traditional meat. However, the controlled culture environment provides opportunities to modulate its nutritional value, for example by adjusting the lipid profile, micronutrient content, or the ratio between muscle and fat cells [88].

In terms of macronutrient composition, cultured meat is designed to mirror conventional meat, containing comparable levels of high-quality proteins with a complete amino acid profile and high digestibility. The controlled culture environment allows fine-tuning of lipid content, particularly by increasing polyunsaturated fatty acids and reducing saturated fats, thereby improving the overall health profile of the product [88].

Regarding micronutrients, current prototypes still show variability. While the levels of essential minerals such as iron and zinc can be adjusted through the culture medium, the absence of organs and complex metabolism limits the natural synthesis of compounds like vitamin B12 and heme iron. Supplementation strategies are therefore being developed to ensure nutritional equivalence with traditional meat [89].

From a sensorial perspective, cultured meat closely resembles conventional meat in texture and appearance, though differences in color, juiciness, and flavor persist due to the absence of myoglobin maturation and intramuscular fat distribution [90]. Advances in co-culturing muscle and adipose cells, as well as the use of edible scaffolds, are progressively improving these sensory attributes.

Sustainability

The environmental sustainability of cultured meat remains one of the most debated aspects of this technology. Early assessments suggested that cell-based meat could significantly reduce land and water requirements and lower greenhouse gas emissions compared with conventional livestock production. By eliminating animal farming, the system theoretically removes major sources of methane and nitrous oxide emissions while drastically decreasing land occupation for feed crops or grazing. Although the production of cultured meat is often portrayed as environmentally friendly, owing to its potential to generate fewer greenhouse gas emissions, use less water, and require substantially less land compared with conventional livestock, especially ruminants, such comparisons should be interpreted with caution.

Many life cycle assessments are still based on preliminary or modelled data, and results vary depending on assumptions related to energy sources, production scale, and medium formulation. As highlighted by several authors, these evaluations may therefore be incomplete or biased, reflecting the early and experimental stage of the technology rather than its mature industrial reality [89, 91].

According to one of the earliest and most frequently referenced life cycle assessments, the production of cultured meat was estimated to generate 1.9–2.2 kg CO_2-eq of greenhouse gas emissions and to consume 26–33 MJ of energy per kilogram of product, depending on the production parameters [92]. The results indicated that cultured meat could require 7–45% less energy, emit 78–96% fewer greenhouse gases, and use 82–96% less water and about 99% less land than traditional meat production, under the assumption that cyanobacteria biomass would serve as the nutrient and energy source. It should be noted that this assessment was based on optimistic assumptions that no longer reflect the current stage of production technology. The use of cyanobacteria hydrolysate was proposed as a nutrient source in the growth medium, an ingredient that is not employed and remains technically unfeasible under present cultured meat production conditions. A few years later, in a follow-up study, the same research group refined their modelling approach and reaffirmed these trends, emphasizing that improvements in process design and renewable energy integration could further enhance the environmental performance of cultured meat [93].

In 2023, a non–peer-reviewed preprint [94] attracted significant media attention by suggesting that the carbon footprint of cultivated meat could exceed that of conventional beef by several times. Although the findings diverged sharply from most published life cycle assessments, the study was not accepted for publication and was later criticized for relying on preliminary and highly conservative assumptions regarding growth media and energy use. This episode highlighted the ongoing uncertainty and sensitivity of environmental estimates for cultured meat.

Recent analyses suggest that cultivated meat can provide higher energy and protein yields per unit of land compared with conventional livestock. Nevertheless, as production scales up, efficient management of wastewater and nitrogen recycling will be essential to ensure environmental sustainability. Findings reported in [95] indicate that cultivated meat systems could achieve greater protein and energy yields per unit of land than conventional animal farming, emphasizing their potential for spatial efficiency. At the same time, the research highlighted that wastewater management in cell-culture facilities may represent a greater environmental and economic challenge than manure handling, underlining the importance of nutrient recovery and medium recycling as production expands.

Since industrial-scale production of cultured meat has not yet been realized, only a limited number of studies have attempted to model its potential environmental performance using life cycle assessment (LCA) approaches [92, 93]. These analyses, based on simulated production systems and hypothetical input data, explore how different assumptions regarding growth media, energy sources, and process efficiency could affect the overall footprint. Although the predicted values vary widely, most scenarios indicate that the climate impact of cultured meat would likely be lower than that of beef, while comparisons with other animal proteins remain uncertain.

3. Conclusions

The global demand for protein continues to rise as population growth, urbanization, and income expansion increase the consumption of meat and animal-derived foods. At the same time, traditional livestock systems are placing unprecedented pressure on ecosystems, contributing to greenhouse gas emissions, intensive land occupation, and freshwater depletion. In this context, novel protein sources, derived from plants, microorganisms, algae, insects, or cultured animal cells, offer alternative pathways to produce nutritious and safe foods with a lower environmental footprint and improved ethical standards.

The large-scale introduction of alternative proteins into the human diet faces a combination of technological, regulatory, and social challenges. While awareness of sustainability is increasing, consumer acceptance still varies widely among different protein sources. In general, plant-based products are the most readily accepted, as they resemble familiar foods and align with established dietary habits. Microalgae and microbial proteins attract growing interest for their nutritional benefits and environmental advantages, yet their use remains limited by sensory characteristics and higher production costs. By contrast, insect-based foods face strong cultural resistance in many Western societies, despite their proven nutritional value and efficiency. Cultured meat is perceived as technologically promising but continues to raise skepticism related to naturalness, safety, and price.

From a regulatory perspective, the introduction of these novel foods requires thorough safety assessment before market approval. In the European Union, all such products fall under Regulation (EU) 2015/2283 on novel foods, which mandates toxicological evaluation, compositional analysis, and proof of nutritional equivalence. So far, only a few insect species and several plant-based ingredients have received authorization, while cell-based meat products are still under evaluation. Singapore remains the only country that has fully approved cultivated meat for sale, followed by the United States, which granted clearance for specific cell-cultured poultry products in 2023.

Ensuring food safety is another central concern. These products must demonstrate microbiological stability, absence of contaminants, and compositional consistency comparable to traditional foods. In the case of microbial or cultured proteins, potential allergenicity, residual growth medium components, and product shelf life require particular attention. Robust regulatory frameworks and transparent communication with consumers will therefore be essential to building public trust and enabling a gradual transition toward diversified, sustainable protein sources.

Clear and transparent communication with consumers is essential to promote informed choices and to highlight the potential benefits of alternative proteins, both for human health and for the environment. For this reason, the present work was conceived to emphasize the growing necessity of sustainable protein sources, their nutritional and functional characteristics, and the contribution they can make to reducing the environmental impact of future food systems.

Author Contributions

The authors had contributions throughout all sections, read, and approved the final manuscript.

Conflicts of interest

The authors declare that this work was carried out independently, without any commercial or financial interests that could be interpreted as potential conflicts of interest.

Generative AI statement

The authors declare that no generative artificial intelligence was employed in the conception, data analysis, or writing of the scientific content of this manuscript. AI-based tools were used solely to assist in the linguistic translation.

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