

Article

# Alternative Proteins from Filamentous Fungi: Drivers of Transformative Change in Future Food Systems

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## Abstract

Current food systems are highly complex, with interdependencies across regions, resources, and actors, and conventional food production is a major contributor to climate change. Transitioning to sustainable protein sources is therefore critical to meet the nutritional needs of a growing global population while reducing environmental pressures. Filamentous fungi present a promising solution by converting agro-industrial side streams into mycoproteins—nutrient-dense, sustainable proteins with a carbon footprint more than ten times lower than beef. This review evaluates the potential of mycoproteins derived from fungi cultivated on low-cost substrates, focusing on their role in advancing sustainable food systems. Evidence indicates that mycoproteins are rich in protein (13.6–71% dw), complete amino acids, fiber (4.8–25% dw), essential minerals, polyphenols, and vitamins while maintaining low fat and moderate carbohydrate content. Fermentation efficiency and product quality depend on substrate type, nutrient availability, and fungal strain, with advances in bioreactor design and AI-driven optimization enhancing scalability and traceability. Supported by emerging regulatory frameworks, mycoproteins can reduce reliance on animal-derived proteins, valorize agricultural by-products, and contribute to climate-resilient, nutritionally rich diets. Integration into innovative food products offers opportunities to meet consumer preferences while promoting environmentally sustainable, socially equitable, and economically viable food systems within planetary boundaries.

**Keywords:** mycoprotein; filamentous fungi; sustainable production and consumption; future food systems; agro-industrial side-streams



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## 1. Introduction

By 2050, the global population is projected by United Nations to reach 10 billion, intensifying the demand for protein-rich foods and putting pressure on existing food system. This surge in demand, driven by diverse dietary needs, and amplified by urbanization, and aging populations, is straining land and natural resources. The global food system is now undergoing a major transition, making it essential to accelerate the shift toward healthier, more ethical, and environmentally sustainable protein sources [1].

Concerns about global protein shortages have grown since the 1960s, prompting research into alternatives to conventional animal-sourced proteins [2]. Currently, around one billion people worldwide do not consume sufficient protein [3]. Food insecurity is driven by persistent inequalities, weaknesses in food systems, and the impacts of climate change, including extreme weather that reduces crop yields. Given these challenges,

developing sustainable and resilient food systems is essential to achieve global hunger reduction targets, highlighting the need for alternative protein and food production [4].

Simultaneously, a rising number of conscious consumers are reducing or eliminating meat intake through vegetarian or vegan diets, which is often tied to religious, philosophical, or ethical beliefs. If these diets are not properly balanced, they can lead to protein deficiencies and related nutritional issues. Both the public health and environmental concerns of meat consumption increased the demand for meat substitutes. Thus, promoting sustainable land use, reducing the global environmental impact of protein production, and addressing the challenges of meeting future protein demand are essential. Shifting from high-impact animal proteins, to alternative proteins such as plant-based, fungal, microbial, algal, or insect proteins [5], can substantially reduce land demand and environmental impact, helping to create more efficient and sustainable food systems.

Filamentous fungi have recently attracted considerable interest in research due to their potential for innovative applications in various food products, particularly for their well-recognized use as alternative protein sources [6–9]. Mycoprotein production by filamentous fungi does not depend on agricultural land or specific climatic conditions and has a carbon footprint up to ten times lower than that of animal protein. It also requires fewer resources than traditional animal or plant proteins. Filamentous fungi offer significant benefits by biotransforming agricultural by-products and side-streams from agri-food industries into protein-rich fungal biomass. This process helps address food security and waste management challenges while promoting recycling and enabling resource recovery in line with circular-economy principles [10].

Currently, microbial protein serves as a valuable source of nutrition in the food industry. Fungal-based proteins are attracting increasing interest due to their highly efficient production processes, which function independently of agricultural inputs and climatic constraints, as well as their favorable amino acid compositions [5]. When added to food products, especially meat analogues, mycoprotein improves their quality, functional properties, and culinary value. Moreover, mycoprotein is a nutrient-dense food, providing a complete amino acid profile in the level required by FAO standards [11]. In addition, they provide good sources of dietary fiber ( $\beta$ -glucan), healthy fats, essential minerals, vitamins, and bioactive compounds [10]. These nutritional and functional properties establish mycoprotein as a recognized sustainable protein source [5].

Various edible fungal species and substrates have been explored for biotechnological applications in both food (e.g., nuggets, ready-to-eat sausages, salami, and burgers) and animal feed (for calves, pigs, poultry, and fish) [12]. Quorn™ is a notable commercial mycoprotein derived from *Fusarium venenatum*. There are other fungal species considered for use as mycoprotein including *Aspergillus*, *Rhizopus*, *Trichoderma*, and *Neurospora* [5,13]. However, the feasibility, regulatory hurdles, production technologies, and consumer acceptance of fungal proteins remain key challenges for their integration into European and global food systems and commercialization.

This review introduces a new perspective by situating filamentous fungi within the broader transformation of global food systems, emphasizing their capacity to meet rising protein demands while staying within planetary boundaries. Although filamentous fungi are increasingly recognized for their ability to convert low-value agro-industrial streams into nutrient-dense mycoproteins, most existing reviews center on conventional production strategies and overlook emerging technological innovations. To address this gap, this work integrates recent advances in fungal strain bioengineering, process optimization, food structuring, and AI-driven fermentation system, offering a comprehensive synthesis of these rapidly evolving domains. By examining the latest scientific and regulatory developments, this review highlights the significant potential of fungal biomass to reduce

environmental burdens, support circular-economy principles, and contribute to resilient and equitable food systems. It further identifies emerging opportunities for fungal proteins in next-generation food applications and delineates key challenges related to compositional attributes, safety, sensory quality, and regulatory compliance. This integration of emerging fungi-based foods and specialized compounds with novel processing technologies establishes a foundation for developing high-quality, consumer-oriented fungal products that promote sustainable diets, strengthen food security, and alleviate environmental pressures.

1.1. Sustainability of Protein-Rich Food Production Systems

Sustainability is a fundamental element and prerequisite for food security, while nutrition underpins the availability, stability, accessibility, and utilization of food. The rapid increase in production driven by population growth and high meat consumption has raised concerns about environmental degradation, public health, ethics, and resource management [4]. Population growth drives increased food demand, production, and consumption, while simultaneously generating larger amounts of agri-food waste rendering current global food systems and consumption patterns unsustainable.

Nearly all agri-food production requires substantial land, with approximately 50% of the world’s habitable land currently devoted to agriculture (Table 1).

**Table 1.** Breakdown of global habitable land used for agri-food production and its contribution to protein and calorie supply. Data source: Our World in Data [14].

Category	Subcategory	% of Category	Area (Mln km <sup>2</sup> )
Earth’s Surface	Land	29%	141
	Ocean	71%	369
Land Surface	Habitable land	76%	107
	Glaciers	10%	14
	Barren land <sup>1</sup>	14%	20
Habitable Land	Agriculture	45%	48
	Forests	38%	40
	Shrub	13%	14
	Urban and built-up land <sup>2</sup>	1%	1
	Freshwater bodies <sup>3</sup>	2%	2
Agricultural Land	Livestock (meat, dairy)	80%	38 (6 Mln km <sup>2</sup> cropland for feed + 32 Mln km <sup>2</sup> grazing land)
	Crops for food	16%	8
	Non-food crops <sup>4</sup>	4%	2
Global Calorie Supply <sup>5</sup>	From meat & dairy	17%	—
	From plant-based food	83%	—
Global Protein Supply <sup>5</sup>	From meat & dairy	38%	—
	From plant-based food	62%	—

<sup>1</sup> Deserts, salt flats, beaches, dunes. <sup>2</sup> Includes settlements and infrastructure. <sup>3</sup> Lakes, rivers, coastal bodies. <sup>4</sup> Biofuels, cotton, etc. <sup>5</sup> Includes fish and seafood from aquaculture production, which uses land for feed. If wild fish catch is also included, animal products would provide 18% of calories and 40% of protein.

Livestock production dominates agricultural land use, occupying roughly 80% (~38 million km<sup>2</sup>) of total agricultural land, while crops occupy only 16% (~10 million km<sup>2</sup>), despite providing a smaller share of global protein (38% from livestock and 62% from crops) [14]. The allocation of land strongly influences food system operations and has direct implications for land quality, water resources, and climate [4]. This disproportionate alloca-

tion highlights the inefficiency of land use in traditional animal-based protein production and underscores its environmental implications.

Comparison of environmental impacts across various protein production systems average values for land and water use per 100 g of protein, as well the average value for greenhouse gas (GHG) emissions per 100 g of protein, expressed as kg CO<sub>2</sub>-equivalent (Table 2). Data include traditional animal-based proteins (beef, lamb, pork, chicken, eggs, milk, cheese), seafood (farmed fish, shrimp/prawns), plant-based proteins (beans, peas, grains, nuts, groundnuts), and alternative proteins (insect, microalgal, bacterial, mycoprotein, cultured meat).

**Table 2.** Comparison of environmental impacts across various protein production systems average values per 100 g of protein.

Category	Land (m <sup>2</sup> )	Water (L)	GHG (kg CO <sub>2</sub> -eq)	Reference
Beef	164	728	25	
Lamb & mutton	185	901	20	
Pork	11	1110	6.5	
Chicken	7	381	4.3	
Eggs	6	521	3.8	
Milk	27	1904	1.4	
Cheese	40	2539	8.4	
Farmed fish	3.7	1619	3.5	
Farmed shrimp/prawns	2	2380	10	
Beans	7.3	203	0.65	[15–20]
Peas	3.4	178	0.36	
Nuts	7.9	2531	−0.8	
Groundnuts	3.5	708	0.4	
Grains	4.6	3167	0.2	
Insect protein	0.35	200	0.82	
Microalgal protein	0.35	500	12.9	
Bacterial protein	0.04	36.4 <sup>1</sup>	0.44	
Mycoprotein	0.082	53.9	0.58	
Cultured meat	0.2	445	2.05	

<sup>1</sup> Bacterial protein is estimated to use up to 20 times less water than animal-based (beef) proteins. GHG: greenhouse gas emissions.

Land requirements per 100 g of protein vary widely across protein sources, with beef and lamb exhibiting the highest land use (164–185 m<sup>2</sup>), while plant-based proteins such as peas and beans require far less land (3–7 m<sup>2</sup>), and alternative proteins like insect, mycoprotein, and microalgal protein are particularly land-efficient (≤0.35 m<sup>2</sup>).

Agriculture accounts for approximately 70% of global freshwater consumption according to FAO’s AQUASTAT. Water requirements per 100 g of protein follow patterns similar to land use: beef and lamb are the most water-intensive (728–901 L), followed by pork and dairy products (381–1110 L), while plant-based proteins generally require considerably less water (178–708 L). Among alternative proteins, mycoprotein (54–78 L), insect protein (~200 L), and microalgal protein (~500 L) demonstrate substantial water-use efficiency compared to conventional meats. Studies consistently show that replacing animal-based foods with nutritionally equivalent plant-based foods significantly reduces the water footprint (WF) of diets, with reductions ranging from 15 to 41% depending on the region and dietary shift [21]. These findings emphasize that shifts toward plant-based or alternative proteins could significantly reduce pressure on freshwater resources while maintaining protein supply.

Greenhouse gas (GHG) emissions associated with protein production vary markedly depending on the source and production system. Protein-rich foods vary widely in their

greenhouse gas emissions per 100 g of protein, with significant implications for sustainable diets. Animal-derived proteins typically exhibit the highest carbon footprints. Beef and lamb are the most GHG-intensive, emitting approximately 25 and 20 kg CO<sub>2</sub>-eq per 100 g of protein, respectively. Other animal-based protein products, including cheese, pork, chicken, and eggs, also contribute substantially to GHG emissions, ranging from 3.8 to 8.4 kg CO<sub>2</sub>-eq per 100 g of protein. Farmed fish has intermediate emissions (3.5 kg CO<sub>2</sub>-eq), and higher emissions has farmed shrimp release (10 kg CO<sub>2</sub>-eq) per 100 g of protein. In contrast, plant-based proteins such as beans, peas, and grains have much lower carbon intensities, with GHG emissions ranging from 0.36 to 0.65 kg CO<sub>2</sub>-eq per 100 g of protein, and nuts, which can even have negative emissions (−0.8 kg CO<sub>2</sub>-eq) due to carbon sequestration in tree crops. This reflects their relatively efficient resource use and lower dependence on energy- and methane-intensive production systems. Alternative protein sources, including insects, microalgae, bacteria, and mycoprotein from filamentous fungi, present a promising pathway to reduce the dietary carbon footprint. Among these, bacterial protein exhibits the lowest emissions (0.44 kg CO<sub>2</sub>-eq per 100 g of protein), while microalgal protein shows higher GHG emissions (12.9 kg CO<sub>2</sub>-eq per 100 g), due primarily to energy-intensive cultivation and processing. Mycoprotein represents a low-impact microbial option, with emissions of 0.58 kg CO<sub>2</sub>-eq per 100 g of protein, indicating its potential as a sustainable alternative to traditional animal-based proteins.

Conventional protein production uses water, soil, fertilizers, and energy, which can harm biodiversity and the environment. Animal-based proteins use the most resources, causing habitat loss, water stress, and environmental damage. Transitioning from high-impact animal proteins to alternative proteins that need less land, and water can reduce environmental burden of protein production globally and help create a more sustainable food system.

### 1.2. Sustainability in Dietary Protein Patterns from Conventional to Revolutionary

A sustainable diet is "... a dietary pattern that promote all dimensions of individuals' health and wellbeing, have low environmental pressure and impact; are accessible; affordable; safe and equitable; and are culturally accessible" [22]. This dietary pattern emphasizes ecological consumption, focusing on modifying food choices to minimize negative environmental impacts. Reducing the intake of meat and other animal-based foods provides dual benefits for health and the environment, contributing to climate change mitigation. Lucas et al. [23] found that about one-third of the health gains are linked to lower dietary risks, while two-thirds arise from reduced production impacts. Transitioning from a flexitarian to a vegan diet can cut greenhouse gas emissions by 54–87%, freshwater use by 2–11%, cropland uses by 8–11%, and fertilizer use (nitrogen and phosphorus footprints) by 41–46%. Furthermore, antibiotic and drug use in livestock and agriculture carries adverse environmental and health impacts. On average, producing 1 kg of animal protein requires about 6 kg of plant protein, and these supply chains contribute approximately 14.5% of global greenhouse gas emissions, along with increased carbon footprints and water pollution [4]. Such production systems place substantial pressure on the environment, underscoring the urgent need for sustainable alternatives.

Transforming current dietary patterns is essential to mitigate climate change, supporting global and regional initiatives such as the UN SDGs [24] and the European Green Deal [25]. These initiatives aim to eradicate hunger, ensure food security, improve nutrition, and promote sustainable agriculture, particularly through the "Farm to Fork" strategy and the adoption of sustainable dietary guidelines across EU countries [26]. Shifting from meat to alternative protein sources, such as mycoprotein, offers a practical pathway to achieve these goals by reducing environmental impacts while providing high-quality nutrition.

Realizing this transition requires collaboration among the food industry, regulatory agencies, and the scientific community to drive innovation, implement sustainable production strategies, and support policy development [27].

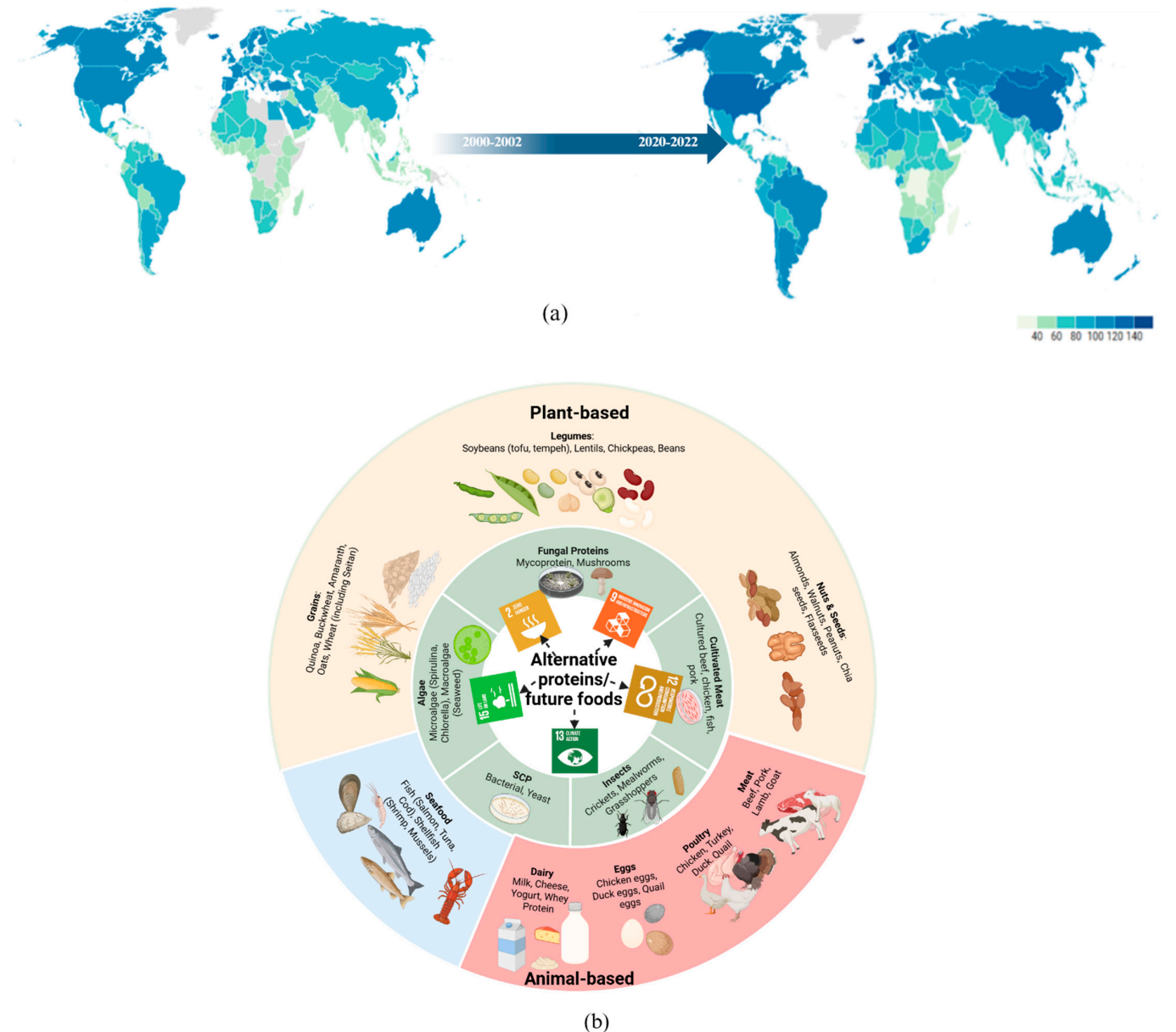
Evidence shows that sustainable consumption is linked to reduced meat intake, increased plant-based food consumption, and improved nutritional quality, alongside growing openness to emerging protein sources. Overall, these trends suggest that consumers are increasingly integrating ecological and sustainable principles into their diets. However, to address the 'diet–environment–health' trilemma for present and future generations, it is essential to promote sustainable and ethically justified alternative foods to conventional meat [4].

Animal-based proteins remain the dominant source of dietary protein worldwide, with global production and consumption projected to reach nearly 470 million tons by 2050 and average per capita meat intake rising from 40 kg to 52 kg annually [28]. Data from the Global Dietary Database reveals substantial disparities in animal-source food consumption. Between 1990 and 2018, mean global intakes of unprocessed red meat (51 g/day), processed meat (17 g/day), seafood (28 g/day), eggs (21 g/day), milk (88 g/day), cheese (8 g/day), and yoghurt (20 g/day) varied by country, education, and urbanization [29], with persistent disparities between low- and high-income countries. The global minimum protein intake declined from 36 g/capita/day in 2000–2002 to 29.6 g/capita/day in 2020–2022 (FAOSTAT), while the maximum increased from 124.3 g/capita/day to 150.6 g/capita/day, reflecting a widening range of consumption (Figure 1a).

Addressing this trajectory requires a systemic shift toward sustainable protein sources, including plant-based, fungal, single-cell, insect, and cultivated proteins, guided by integrated nutritional, environmental, and socio-economic frameworks to ensure that future protein systems are both nutritionally adequate and environmentally resilient [30].

Emerging alternative proteins will be the base protein ingredient of future foods (Figure 1b). Plant-based proteins, derived from sources such as soy, peas, legumes, nuts, oats, wheat, quinoa, amaranth, and beans, are widely utilized in products including burgers, sausages, nuggets, tofu, tempeh, and plant-based milk and meat alternatives, contributing to reduced reliance on conventional meat. Microalgae, including *Spirulina*, *Chlorella*, and *Nannochloropsis*, are incorporated into protein powders, shakes, fortified pasta, snacks, and functional foods, offering nutrient-dense options. Edible insects, such as crickets, mealworms, and locusts, serve as efficient protein sources in biscuits, crackers, breads, meat pies, and sausages. Cultivated meat, produced from animal muscle cells in vitro, replicates the nutritional and sensory properties of conventional meat. Fungal proteins, derived from mushrooms and mycoprotein (*Fusarium venenatum*, used in Quorn™ products), are employed in protein-rich snacks and meat analogs. Finally, single-cell proteins (SCPs) from bacteria and yeast are processed into protein powders, fermented foods, and fortified baking ingredients, providing nutrient-rich and climate-resilient protein sources [4].

Furthermore, alternative protein sources support several SDGs: goal 2 (zero hunger) by providing affordable, high-quality protein; goal 9 (industry, innovation, and infrastructure) by fostering sustainable fermentation and green industrial growth; goal 12 (responsible consumption and production) by using significantly less land and water than conventional meat and promoting circular bioeconomy practices; goal 13 (climate action) by reducing greenhouse gas emissions; and goal 15 (life on land) by minimizing land use and preventing deforestation and soil degradation [17].



**Figure 1.** (a) Global choropleth map showing the 3-years average protein supply per capita per day over the last 20 years (average values between 2000–2002 and 2020–2022). Darker shades indicate higher per capita protein availability (range 29.6–150.6 g/cap/day), while grey areas represent countries with no available data. Data sourced from: Global Dietary Database and FAOSTAT database. (b) Protein sources supply in our food systems: conventional animal-based and plant-based proteins and emerging alternative proteins for future food systems supporting UN SDGs.

## 2. Materials and Methods

A comprehensive literature review was conducted to analyze scientific publications on sustainable food production, dietary patterns, and alternative protein sources derived from filamentous fungi. Literature was retrieved from the Web of Science. The search strategy combined several keywords, including sustainable food production, sustainable diet, alternative protein sources, mycoproteins, production, applications, safety, regulation, consumer acceptance, market penetration, side-stream valorization, and fermentation.

The search was further limited to open access articles, published between 2020 and 2025, written in English, and classified under the research areas of Food Science & Technology, Biotechnology & Applied Microbiology, and Microbiology. A total of 7062 relevant

publications were selected for detailed analysis. The final dataset was exported in plain text format and analyzed using VOSviewer software (version 1.6.18, Leiden University, Leiden, The Netherlands) to identify major research clusters, co-occurrence patterns, and emerging trends in fungal-derived alternative protein research. A co-occurrence map-based analysis, based on the title and abstract fields with full counting and a minimum occurrence threshold of 30 terms, resulted in 3917 terms that met the threshold. These terms were further refined using a thesaurus to remove irrelevant terms, resulting in the identification of five main thematic clusters comprising 333 items.

Other data extracted from publicly available databases (FAOSTAT <https://www.fao.org/faostat/en/#data>, accessed on 28 October 2025, AQUASTAT <https://www.fao.org/aquastat/en/>, accessed on 31 October 2025, PATENTSCOPE <https://patentscope.wipo.int/search/en/search.jsf>, accessed on 2 November 2025, Global Dietary Database <https://globaldietarydatabase.org/>, accessed on 1 November 2025, and Our World in Data <https://ourworldindata.org/>, accessed on 5 October 2025), for visualization were imported into Origin software version 2025b and into Datawrapper 2025 for choropleth map creation. In parallel, illustrations were created using BioRender.

### 3. Results and Discussion

#### 3.1. Production Platforms of Filamentous Fungi Proteins and Bioactive Compounds for Sustainable Food Systems

Fungi represent one of the most biodiverse kingdoms of life, with over 97,000 species described to date, estimated to comprise only about 6% of their total global diversity. Among them, filamentous fungi stand out for their exceptional metabolic versatility and offer a promising biotechnological solution. Filamentous fungi, particularly Mucoromycota (formerly Zygomycetes): *Actinomucor elegans*, *Amylomyces rouxii*, *Mucor circinelloides*, *Mucor hiemalis*, *Mucor racemosus*, *Rhizopus oryzae*, *Rhizopus oligosporus*, *Rhizopus azygosporus*; and Ascomycota such as *Aspergillus oryzae*, *Aspergillus sojae*, *Aspergillus tamarii*, *Fusarium venenatum*, *Geotrichum candidum*, *Monascus purpureus*, *Monascus ruber*, *Neurospora crassa*, *Neurospora intermedia*, *Neurospora sitophila*, *Paecilomyces variotii*, *Penicillium nalgiovense*, *Penicillium roqueforti*, offer multiple advantages in food systems by providing high-quality protein, producing enzymes, natural colorants, and bioactive compounds, and converting diverse substrates into a wide range of value-added food ingredients (Table 3).

**Table 3.** Proteins and bioactive compounds from filamentous fungi with industrial and nutritional relevance for food systems.

Compound Category	Filamentous Fungi (GRAS Species)	Fungal Metabolites	Industrial Application	Growing Substrate	References
Mycoprotein	<i>Fusarium venenatum</i> , <i>Aspergillus</i> spp. ( <i>oryzae</i> , <i>sojae</i> ), <i>Rhizopus</i> spp. ( <i>oryzae</i> , <i>delemar</i> ), <i>Amylomyces rouxii</i> , <i>Neurospora</i> spp. ( <i>intermedia</i> , <i>crassa</i> , <i>sitophila</i> ), <i>Mucor</i> spp. ( <i>circinelloides</i> , <i>miehei</i> , <i>azygosporus</i> ), <i>Paecilomyces variotii</i>	Proteins (>40%)	Meat alternatives, protein-rich foods, fortified and functional foods	Plant and industrial side streams (potato starch and liquor, whey, bread, pea, oat, grape marc, wine lees, vinasse, olive mill water, Oncom substrate)	[15,31–37]

Table 3. Cont.

Compound Category	Filamentous Fungi (GRAS Species)	Fungal Metabolites	Industrial Application	Growing Substrate	References
Bioactive peptides	<i>Aspergillus</i> spp. ( <i>oryzae</i> , <i>sojae</i> ), <i>Monascus</i> spp. ( <i>purpureus</i> , <i>pilosus</i> ), <i>Neurospora intermedia</i> , <i>Rhizopus oligosporus</i> , <i>Fusarium venenatum</i> , <i>Cordyceps militaris</i>	Cordymin and other bioactive peptides	Functional foods and nutritional fortification through bioactive peptides with multiple health-promoting activities (antihypertensive, antioxidant, antidiabetic, anticancer, antithrombotic, and immunomodulator)	Koji, rice, corn, pea by-products, bread leftovers, semi-synthetic media, grain-based substrates, silkworm pupae	[36,37]
Lipids	<i>Mucor</i> spp. ( <i>circinelloides</i> , <i>miehei</i> , <i>azygosporus</i> ), <i>Rhizopus oryzae</i> , <i>Geotrichum candidum</i>	Triglycerides, polyunsaturated fatty acids ( $\gamma$ -linolenic acid)	Nutritional lipids, functional lipids	Whey, plant substrates, industrial residues	[31,38–40]
Polysaccharides/ dietary fibers/ prebiotics	<i>Mucor rouxii</i> , <i>Rhizopus</i> spp., <i>Aspergillus</i> spp., <i>Neurospora</i> spp., <i>Fusarium venenatum</i> , <i>Cordyceps militaris</i> , <i>Paecilomyces variotii</i>	$\beta$ -glucan, chitin, chitosan, chitooligosaccharides, fructooligosaccharides (FOS)	Functional foods and prebiotics with potential health benefits: promoting gut microbiota, anticancer, antidiabetic, immunomodulatory, antioxidant, and antitumor effects	Rice, wheat, plant flours, grain-based substrates, silkworm pupae, semi-synthetic media, agro-industrial residues (potato liquor, whey, bread leftovers, spent coffee grounds, vinasse, olive mill water, fish industry residues)	[34,37,41,42]
Essential minerals	<i>Neurospora intermedia</i> , <i>Aspergillus oryzae</i> , <i>Rhizopus</i> spp.	Iron (Fe), Zinc (Zn), Calcium (Ca), Copper (Cu), phosphorus (P)	Mineral-enriched foods, enhances micronutrient intake, and mineral accessibility	Grape marc, wine lees, vinasse, stale bread, brewers' spent grain, mineral-enriched media	[33,43,44]
Bioactive compounds/ Polyphenols	<i>Aspergillus</i> spp., <i>Rhizopus</i> spp., <i>Actinomucor elegans</i> , <i>Amylomyces rouxii</i> , <i>Monascus</i> spp., <i>Mucor</i> spp., <i>Neurospora</i> spp., <i>Fusarium</i> spp., <i>Cordyceps militaris</i>	Caffeoylquinic acid, ellagic acid, quercetin and kaempferol glycosides, flavones, hydroxycinnamic acids, carotenoids, ergosterol, $\gamma$ -aminobutyric acid, L-carnitine, cordycepin, adenosine	Functional foods, antioxidant-rich, natural preservatives, nutraceuticals with anti-inflammatory, antihypertensive, antidiabetic, anti-fatigue, and antitumor properties	Koji, rice, corn, wheat, Oncom substrate, bread leftovers, silkworm pupae, grain-based substrates, semi-synthetic media	[36,37,39,45–47]

Table 3. Cont.

Compound Category	Filamentous Fungi (GRAS Species)	Fungal Metabolites	Industrial Application	Growing Substrate	References
Vitamins	<i>Ashbya gossypii</i> , <i>Neurospora intermedia</i> , <i>Rhizopus oryzae</i> , <i>Aspergillus oryzae</i>	Riboflavin (Vitamin B2), Vitamin E, Vitamin D2, B-group vitamins (B1, B2, B3, B6)	Vitamin-enriched food and nutritional fortification	Glucose media, stale bread, brewers' spent grain	[43,48,49]
Enzymes	<i>Aspergillus</i> spp., <i>Rhizopus</i> spp., <i>Trichoderma reesei</i> , <i>Mucor</i> spp., <i>Neurospora intermedia</i>	Proteases, amylases, lipases, cellulases, hemicellulases, $\beta$ -glucosidase, feruloyl esterase, endo-1,4- $\beta$ -xylanases (GH10, GH11), and other hydrolytic enzymes	Food processing applications, proteolysis and protein modification (soft, cheese-like gels), starch and fiber hydrolysis, prebiotic production, bread and beverage improvement, olive oil hydrolysis.	Koji, Tempeh, Oncom, Sufu, plant flours, bread leftovers, buckwheat, quinoa, ginseng, tangerine peel, oat, semi-synthetic media, Adams' medium	[31,36,37,39,50]
Organic acids	<i>Aspergillus</i> spp., <i>Rhizopus</i> spp., <i>Neurospora intermedia</i> , <i>Monascus</i> spp., <i>Fusarium venenatum</i> , <i>Cordyceps militaris</i>	Lactic, fumaric, citric, gluconic, and kojic acids	Food acidification, flavor enhancement, antioxidant and preservative effects, prebiotic potential	Koji, rice, corn, Oncom substrate, bread leftovers, wheat bran, tomato pomace, fruit/vegetable by-products, industrial residues, semi-synthetic media	[31,36,37,39,50]
Aroma & Flavor Compounds	<i>Geotrichum candidum</i> , <i>Penicillium</i> spp. ( <i>roqueforti</i> , <i>camemberti</i> , <i>nalgiovense</i> , <i>chrysogenum</i> ), <i>Rhizopus oryzae</i> , <i>Neurospora crassa</i>	Proteolytic and lipolytic metabolites, glutamate, methionine, cysteine, volatile aroma compounds (smoky, cheesy, floral notes)	Enhances aroma and umami flavor in fermented dairy, meat, and soybean products, improving sensory appeal.	Whey, cheese, meat, soybean substrates	[31,51]
Pigments/bio-colorants	<i>Monascus</i> spp., <i>Neurospora intermedia</i>	MonAzPs pigments, yellow (monascin, ankaflavin), orange (rubropunctatin, monascorubrin), red (rubropunctamine, monascorubramine); carotenoids (neurosporaxanthin)	Natural red, orange, and yellow food bio-colorants with high-yield production from low-cost substrates; suitable for commercial use.	Rice, rice flour, corn molasses, Oncom substrate	[37,39,50,52,53]

While traditional fungal fermentation processes include the production of soy sauce, sake, rice vinegar, koji, oncom, and miso, as well as the fermentation of soybeans, mold-ripened cheeses, and various beverages, the targeted use of fungi for mycoprotein production represents a relatively recent innovation. The selection and optimization of strain is pivotal as it can have a significant impact on the substrate conversion efficiency, fungal biomass productivity, morphology, nutritional value, flavor and color [6]. In the food

industry, microbial protein is generally obtained in two main forms: whole fungal biomass or protein extracted from the biomass.

Filamentous fungi are not only a source of high-quality protein but also produce a wide range of bioactive compounds and specialized metabolites with industrial and nutritional relevance. They are prolific producers of bioactive peptides, including cordymin and other functional peptides, generated by *Aspergillus oryzae*, *A. sojae*, *Monascus purpureus*, *M. pilosus*, *Neurospora intermedia*, *Rhizopus oligosporus*, *Fusarium venenatum*, and *Cordyceps militaris*. These peptides exhibit antihypertensive, antioxidant, antidiabetic, antithrombotic, anticancer, and immunomodulatory activities, supporting their growing use in functional foods and nutraceuticals [36,37].

Advances in fungal biotechnology continue to enhance the versatility of GRAS filamentous fungi as robust cell factories. Several species, such as *Mucor circinelloides*, *M. miehei*, *M. azygosporus*, *Rhizopus oryzae*, and *Geotrichum candidum*, efficiently synthesize oleic and  $\gamma$ -linolenic acid, making them promising sources of nutritional lipids for functional foods and supplements [31,38–40]. Filamentous fungi can be enriched in lipids without compromising protein content through culture medium modification and high-lipid yeast immobilization, offering a sustainable and promising alternative to traditional meat for the food industry [54]. New and improved fungal strains are being developed for precision fermentation, including oleaginous species that accumulate specific lipids or fatty acids [9].

Fungi metabolic diversity extends to polysaccharides and dietary fibers, including  $\beta$ -glucans, chitin, chitosan, chitoooligosaccharides, and fructooligosaccharides (FOS), produced by *Mucor rouxii*, *Rhizopus* spp., *Aspergillus* spp., *Neurospora* spp., *Fusarium venenatum*, *Cordyceps militaris*, and *Paecilomyces variotii*. These compounds demonstrate immunomodulatory, antioxidant, antitumor, and antidiabetic activities [34,37,41,42], function as prebiotics and can improve gut health [9].

Filamentous fungi also contribute to micronutrient enrichment. Species such as *Neurospora intermedia*, *Aspergillus oryzae*, and *Rhizopus* spp. accumulate essential minerals (iron, zinc, calcium, copper, phosphorus), enabling the development of mineral-fortified foods aimed at mitigating micronutrient deficiencies [33,43,44]. In addition, species such as *Ashbya gossypii*, *Neurospora intermedia*, *Rhizopus oryzae*, and *Aspergillus oryzae* serve as capable producers of riboflavin (vitamin B<sub>2</sub>), vitamin E, vitamin D<sub>2</sub>, and B-group vitamins (B<sub>1</sub>, B<sub>2</sub>, B<sub>3</sub>, B<sub>6</sub>), supporting applications in nutritional fortification [43,48,49]. Application of UV irradiation has enhanced vitamin D<sub>2</sub> content, by converting ergosterol naturally present in mycelia, with potential to offer a supplement base to produce fortified food products/ready-to-eat processed foods [55].

Fungi play a pivotal role in applied biotechnology, particularly in the production of enzymes and organic acids for food and beverage applications. Species such as *Aspergillus* spp., *Rhizopus* spp., *Trichoderma reesei*, *Mucor* spp., and *Neurospora intermedia* produce broad enzyme suites, including proteases, amylases, lipases, cellulases, hemicellulases,  $\beta$ -glucosidase, feruloyl esterase, and endo-1,4- $\beta$ -xylanases (GH10, GH11), which are employed in protein modification, starch and fiber hydrolysis, bread and beverage improvement [31,36,37,39,56–58]. Similarly, filamentous fungi such as *Aspergillus* spp., *Rhizopus* spp., *Neurospora intermedia*, *Monascus* spp., *Fusarium venenatum*, and *Cordyceps militaris* synthesize organic acids, such as lactic, fumaric, citric, gluconic, and kojic acids, used for food acidification, flavor enhancement, and providing antioxidant and preservative benefits [31,36,37,39,51].

Additionally, *Aspergillus* spp., *Rhizopus* spp., *Actinomucor elegans*, *Amylomyces rouxii*, *Monascus* spp., *Mucor* spp., *Neurospora* spp., *Fusarium* spp., and *Cordyceps militaris* produce polyphenols and other secondary metabolites, including caffeoylquinic acid, ellagic acid, quercetin and kaempferol glycosides, flavones, hydroxycinnamic acids, carotenoids (e.g., neu-

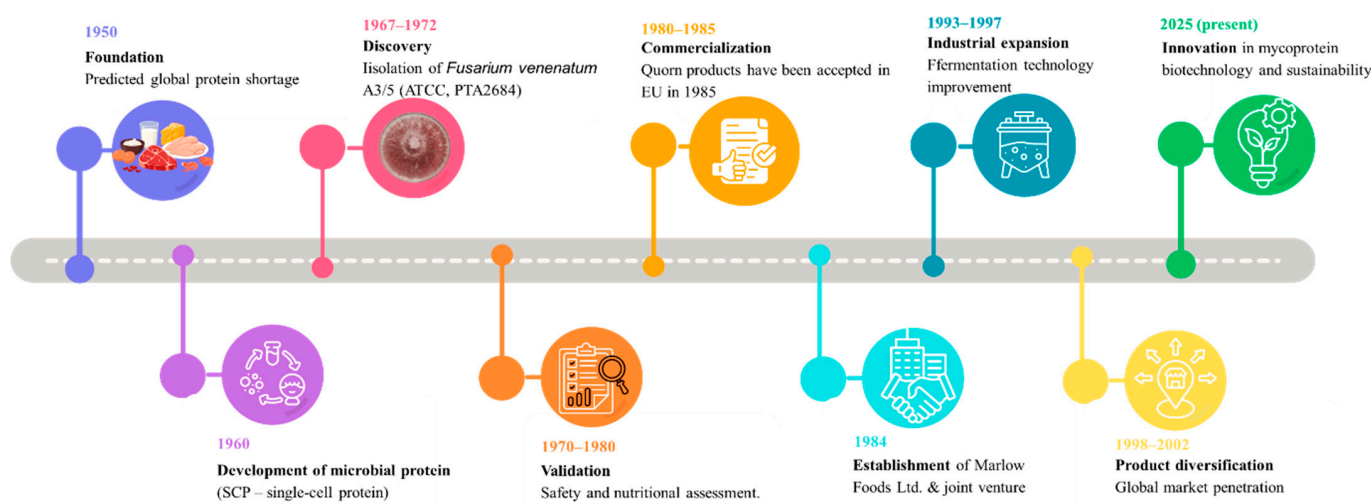
rosporaxanthin), ergosterol, GABA, L-carnitine, cordycepin, and adenosine, with antioxidant, anti-inflammatory, antibacterial, antidiabetic, and anti-fatigue benefits [36,37,39,45,46].

### 3.1.1. History of Mycoprotein

From ancient Asian fermentations to modern fungal-based proteins, the production of fungal ingredients for food has evolved significantly. Traditional foods like Koji, fermented with *Aspergillus oryzae* [59]; Tempeh, with *Rhizopus oligosporus* [60]; Sofu, with *Actinomucor elegans*, *Mucor* spp., or *Rhizopus* spp. [61] and Oncom, with *Rhizopus oryzae* [62] and *Neurospora intermedia* [63], harnessed filamentous fungi to convert plant-based substrates and agro-industry side streams into protein-rich products. In European gastronomy, filamentous fungi such as *Penicillium nalgiovense*, *P. chrysogenum*, *P. camemberti*, and *P. roqueforti* have long been essential for ripening and preserving meats and cheeses, contributing to their characteristic flavors, textures, and microbial stability. Today, these same species are also used in fungal-fermented vegan cheeses, reflecting a growing trend to adapt traditional fermentation techniques for sustainable, plant-based foods [61].

Building on these fermentation traditions, in the 1960s–70s the filamentous fungus *Fusarium venenatum* (strain A3/5, ATCC PTA-2684) was isolated and selected for its ability to convert glucose (or other carbon sources) and ammonia into a fibrous, protein-rich biomass [13,64]. From the early 1970s through the 1980s, intensive work was carried out to scale up fermentation processes (e.g., continuous or air-lift fermenters), reduce RNA content and ensure robust safety and nutritional profiles of the fungal biomass [65]. After thorough safety evaluation on toxicology, allergenicity, nutritional aspects and production processes, the Ministry of Agriculture, Fisheries and Food in the United Kingdom in 1984, mycoprotein derived from *F. venenatum* was approved for human consumption [66]. The first commercial mycoprotein product was launched in the UK in 1985 by Quorn [64], and is now permitted for sale across all EU member states. Around 2002 was approved in the U.S. by the FDA, and other regulatory approvals were obtained in Switzerland, Australia, Japan, Thailand, Malaysia, and Canada.

Figure 2 shows the progress in mycoprotein production and commercialization, highlighting key technological, regulatory, and market milestones that underpin its potential to contribute to transformative change in global food systems by 2050.



**Figure 2.** Seventy-five years of progress in mycoprotein production and commercialization toward transformative change in global food systems by 2050.

Quorn™ offers an extensive lineup of products including meat-free mince, burgers, sausages, and even ready-to-eat meals. The brand and technology were scaled up and with continuous processes for mycoprotein-based product formulations [65].

Beyond the original product, new companies are developing different strains, substrates, and bioreactor configurations, aiming to broaden the commercial footprint of fungal-based proteins. In the culinary setup, mycoprotein products are incredibly versatile. Chefs and home cooks alike are incorporating them into a myriad of dishes, from classic comfort foods like shepherd's pie and meatloaf to international cuisines such as curries and stir-fries [2].

### 3.1.2. Fungal Cultivations and Fermentation Modes

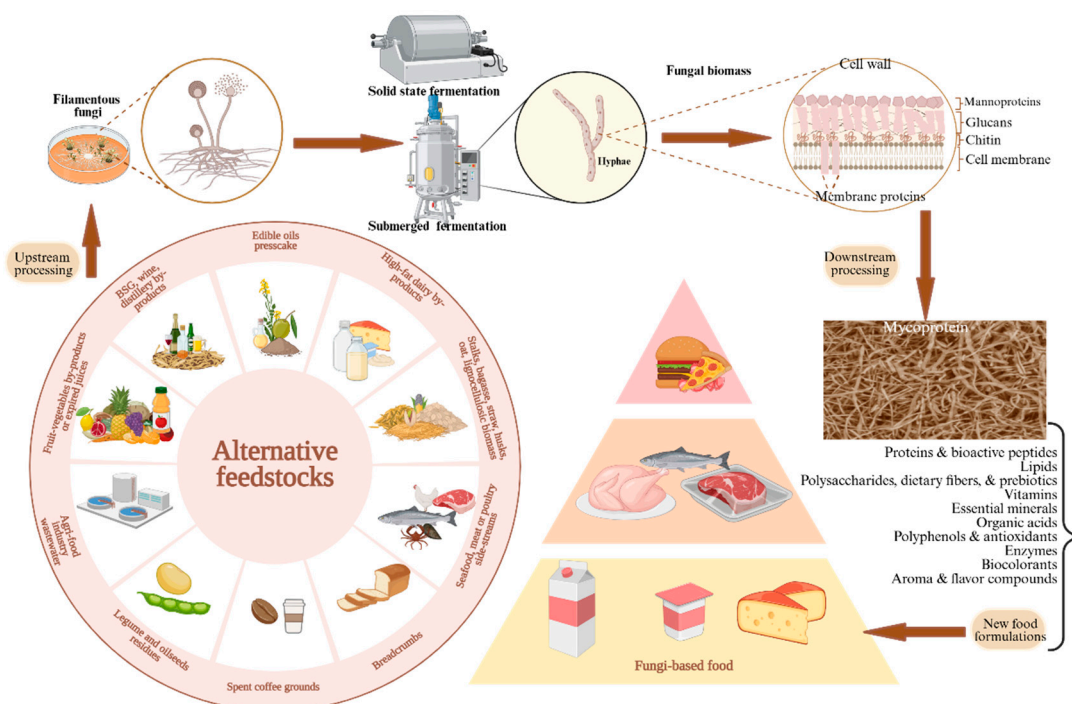
The production of fungal proteins involves two main steps: fermentation and extraction, both of which have seen significant innovation in recent years. Fungal fermentation in carbon-rich media supplemented with nitrogen and essential micronutrients [67] under aerobic conditions can proceed via submerged or solid-state modes, ultimately yielding fungal biomass. Submerged fermentation (SmF) involves cultivating microorganisms in nutrient-rich liquid media, typically within stirred-tank or airlift bioreactors. This method enables efficient microbial growth, precise process control, and scalability. Beyond fungal biomass production, SmF is widely employed in the manufacture of enzymes, organic acids, antibiotics, vitamins, flavoring agents, biopesticides, animal feed, and bioplastics. SSF, in contrast, supports fungal growth on moist, solid substrates. Under favorable conditions with improved oxygen availability, SSF promotes mycelial germination and enzyme synthesis. It offers several advantages, including high productivity, low energy and water consumption, and minimal wastewater generation. SSF is increasingly recognized for its potential in fungal biomass and secondary metabolite production; however, its large-scale application remains limited by challenges in process control, substrate heterogeneity, and heat and mass transfer. Recent advances have demonstrated the synergistic combination of SSF and SmF, known as the sequential fermentation method, has proven effective in enhancing fungal adaptability and productivity while optimizing resource use, making it a valuable approach for industrial biotechnology. However, this dual-mode strategy remains limited, and further technological innovation and process engineering are needed to address operational and scale-up challenges [28].

Controlling bioprocess parameters in submerged or solid-state fermentation is crucial, as these variables directly influence fungal growth and metabolism, ultimately affecting both the yield and quality of the final product. The bioreactor functions as a controlled system designed to support the growth and metabolic activity of microorganisms. It enables the efficient transfer of nutrients and oxygen to the culture medium while allowing precise regulation of key parameters such as mixing, agitation, temperature, and humidity, all of which collectively enhance process efficiency and product yield. Most fungi are known to grow well at temperatures between 20 and 30 °C and prefer a neutral pH of medium. Aeration is crucial in fungal fermentation to supply oxygen, dissipate metabolic heat, and prevent excess moisture and CO<sub>2</sub> accumulation, while agitation can enhance mass transfer. For large-scale industrial applications SmF is the preferred method, due to precise control of pH, temperature, aeration, and dissolved oxygen [28].

Advanced bioreactor technologies with integrated real-time monitoring have greatly improved fermentation processes by tracking pH, temperature, oxygen, and biomass without sampling, reducing contamination and enhancing batch consistency [68]. Additionally, when combined with software models, they enable smart control, process prediction, and automation, optimizing growth conditions and ensuring reliable, high-quality production [69].

### 3.1.3. Alternative Feedstock and Biovalorization Strategies

To support sustainability a transformative change from farm to waste is required in actual food production and consumption models. Agri-food industries generate substantial volumes of organic side streams, including peels, seeds, slaughterhouse wastewater, dairy effluents, and residues from edible oil production, which, if not properly managed, can contribute to environmental pollution and increase waste management costs. Traditional valorization approaches of agri-food industries side streams include their use as animal feed or fertilizers. These materials are typically rich in organic matter and often exhibit high biochemical oxygen demand and chemical oxygen demand. Their composition and biodegradability vary considerably, reflecting differences in C/N ratio, lignin, cellulose, hemicellulose, protein, phenolic content, and the presence of potential inhibitory compounds. Improper handling of these side streams can lead to the formation of toxic substances, pathogen proliferation, and environmental degradation. Filamentous fungi can grow on a wide range of feedstocks (Figure 3), including fruit and vegetable pomaces, cereal husks and brans, brewery spent grain, coffee grounds, edible oil cakes, potato peels, fish and poultry by-products, winery and distillery residues, molasses, vinasse, and combinations thereof, making them versatile platforms for sustainable bioprocessing [11,28].



**Figure 3.** Production platforms of filamentous fungi proteins and bioactive compounds for food systems. General overview of the alternative feedstocks plant-based or food and beverage industry side-streams and agro-industrial residues, and their biotransformation through submerged fermentation or solid-state fermentation into mycoprotein rich in bioactive compounds for new fungi-based foods formulation.

The utilization of nutrient-rich, waste-derived feedstocks can markedly reduce the environmental footprint of fungal mycoprotein production by lowering greenhouse gas emissions, water and land use, and eutrophication potential compared with conventional animal-based protein production systems. Integrating these side streams into fungal biorefineries provides a sustainable strategy to produce value-added products such as protein-rich fungal biomass, enzymes, hydrocolloids, dyes, citric acid, xanthan gum, and other high-value products [70–72].

Dairy wastes, particularly whey which contain 5–6% lactose, 1% protein, fat, serve as excellent substrates for fungal fermentation [72,73]. Legume and oilseed byproducts, including oilseed cakes, soybean okara, and legume husks, are nutrient-dense and provide ample proteins and carbohydrates for fungal growth [74]. Likewise, fruit and vegetable by-products, rich in sugars, proteins, cellulose, hemicellulose, lignin, pectin, minerals, and phenolic compounds, can support diverse fungal fermentations [72]. Cereal-derived residues such as wheat, rice, and corn straw, corn stover, cereal bran and oat are abundant lignocellulosic materials rich in cellulose, hemicellulose, lignin, proteins, and phenolic compounds [75,76]. Several lignocellulosic agricultural residues can serve as cost-effective feedstocks for fungal fermentation [77]. Sugarcane bagasse, a fibrous residue with high cellulose (26–50%) and hemicellulose (24–34%) content, is also a promising feedstock for fungal bioconversion [78]. Additionally, brewer's spent grain (BSG) containing ~64.9% polysaccharides, ~22.6% proteins and ~15.7% lignin has shown potential when integrated in fungal biorefinery with multiple products [79], also winery and distillery by-products (grape marc, wine lees, and vinasse) are rich in organic matter, contain proteins, minerals, and phenolic compounds that support fungal fermentation [32,33]. Spent coffee grounds are an abundant agro-industrial residue rich in carbon and phenolic compounds, offering significant potential as a substrate for fungal fermentation to generate value-added bioproducts under both submerged and solid-state conditions [80]. Seafood, meat, and poultry processing generate millions of tons of protein-rich by-products annually, offering significant potential for valorization through fungal fermentation. Wasted bread, containing 52.5% starch, 4.9% crude fat, 2.3% total nitrogen, and 2.4% ash, has potential for valorization through scalable fermentation using Zygomycete fungi [81]. Agro-industrial effluents are rich in organic matter and phenolics, and filamentous fungi can effectively remediate through diverse bioremediation mechanisms [82]. Olive pomace is highly acidic, polyphenol-rich with antimicrobial activity and fatty acids, and organically loaded matrix [83]. Filamentous fungi are capable to degrade lipids of these residues into glycerol and fatty acids, which are likely metabolized or stored within the fungal cells. Collectively, these substrates demonstrate the remarkable adaptability of fungi and their key role in advancing circular and low-waste bioprocessing systems [11,28].

However, industrial adoption of agri-food side stream biovalorization is limited by challenges such as cleaning heterogeneous residues and navigating [28]. Another concern is the presence of contaminants, heavy metals, or pesticide residues in the substrate, which further limits its suitability for mycoprotein production. Additionally, substrates may contain compounds that either stimulate or inhibit fungal growth; for example, essential oils in lemon, orange, or grapefruit peels have antimicrobial properties that can reduce biomass yield [84].

#### 3.1.4. Upstream and Downstream Processes

Substrate pretreatment is a critical step that could significantly enhance the efficiency of the process, based on physical, chemical, and biological methods. Agro-industrial substrates undergo various pretreatments to enhance fungal fermentation, including acid precipitation, thermal denaturation, physical grinding, soaking, dilute acid or alkali treatment, organosolv, hydrothermal processing, enzymatic hydrolysis, defatting, extrusion, hot water washing, steam explosion, and detoxification via liquid–liquid extraction, or a combination of methods [28].

The complex and regulated process of protein production consists of three phases, synthesis, modification, and secretion [85]. As the fungus grows and synthesizes protein, the cultivation period is a critical factor in determining optimal protein content. Variations in total protein content during fungal fermentation are influenced by the specific interaction

between the substrate and the fungal strain. Mycoprotein is derived from the mycelium, the vegetative part of the filamentous fungus. The mycoprotein produced contains dietary fiber, composed of approximately one-third chitin and two-thirds  $\beta$ -1,3 and  $\beta$ -1,6 glucans derived from the mycelial cell walls.

After fermentation, filamentous fungal biomass is harvested and can undergo downstream processing steps such as washing, cell disruption, the fermenter broth is heated to stop growth and also to reduce the amount of RNA in the mycoprotein (approximately 1% *w/w*) through the action of natural nuclease enzymes in the mycelium, followed by vacuum chilling [86], protein extraction, purification, and drying [11].

Extraction of fungal proteins involves careful consideration of safety and efficiency. Nucleic acid reduction through heat, chemical, or enzymatic treatments ensures safe consumption, while effective cell disruption techniques, including high-pressure homogenization, ultrasound, enzymatic degradation, and autolysis, maximize intracellular protein release [87]. Crude protein separation is achieved using ultrafiltration, salinization, isoelectric precipitation, or graded solvent extraction, with optimization via response surface methods enhancing yield and quality [88]. Fine purification is performed using chromatography, molecular sieves, electrophoresis, crystallization, or recrystallization, and extracellular enzymes can be directly isolated from culture media [89]. Modern extraction technologies, including ultrafine grinding, cavitation-assisted extraction, microwave-assisted extraction, and pulsed electric fields, improve efficiency while influencing protein functional properties, highlighting the need for careful control and further systematic studies on the relationship between extraction conditions, protein structure, and functionality [90].

### 3.2. Biotechnological Innovations of Filamentous Fungi in Food Applications

Over the last 15 years, 115 patents have been published on alternative proteins, with plant-based proteins dominating (72 patents), followed by microorganism-based proteins (31 patents) and insect-based proteins (10 patents) [91]. The number of patents has increased notably in the last five years, reflecting concentrated investment, technological development, and consumption in North America, Europe, and the Asia-Pacific region. This growth may be driven by the WHO promotion of sustainable protein alternatives and the growing interest of scientists and nutritionists in novel sources such as plants, insects, and microalgae [92]. The predominance of alternative protein patents also reflects greater consumer familiarity and acceptance of meat-free products [93].

This study analysis was conducted using the WIPO database via the PATENTSCOPE, considering patents published between 2020 and 2025 that included the keywords “mycoprotein” “mycelium”, “filamentous fungi” and “food.” The results enabled the recovery of 22 patent records that utilize mycoprotein as a primary component for the invention. Between 2020 and 2025, a total of 21 product-related patents concerning mycoprotein and filamentous fungi were identified across 13 applicants from six countries. The majority originated from Europe (Sweden, The Netherlands, UK, Germany, Switzerland) and China, reflecting global innovation in sustainable food biotechnology. Patent activity peaked in 2024, with 12 applications focusing on fermentation optimization, structured mycoprotein foods, and dairy alternatives (Table 4). Emerging technologies include AI-assisted fermentation monitoring, solid-state bioprocess control, and functional mycoprotein ingredients for health-oriented foods (Figure 4a).

In addition to analyzing patents, the recent literature (2020–2025) was reviewed using the Web of Science Core Collection to identify scientific publications related to sustainable food production and alternative protein sources derived from filamentous fungi (Figure 4b). Network analysis of mycoprotein research reveals a highly interconnected landscape comprising five main thematic clusters. The green cluster focuses on filamentous fungi

biomass, encompassing fermentation processes and biotechnological applications in food, including quality, sensory properties, and consumer acceptance.

**Table 4.** Summary of recent patents (2020–2025) related to mycoprotein derived from filamentous fungi in food applications. Data source: WIPO’s PATENTSCOPE database.

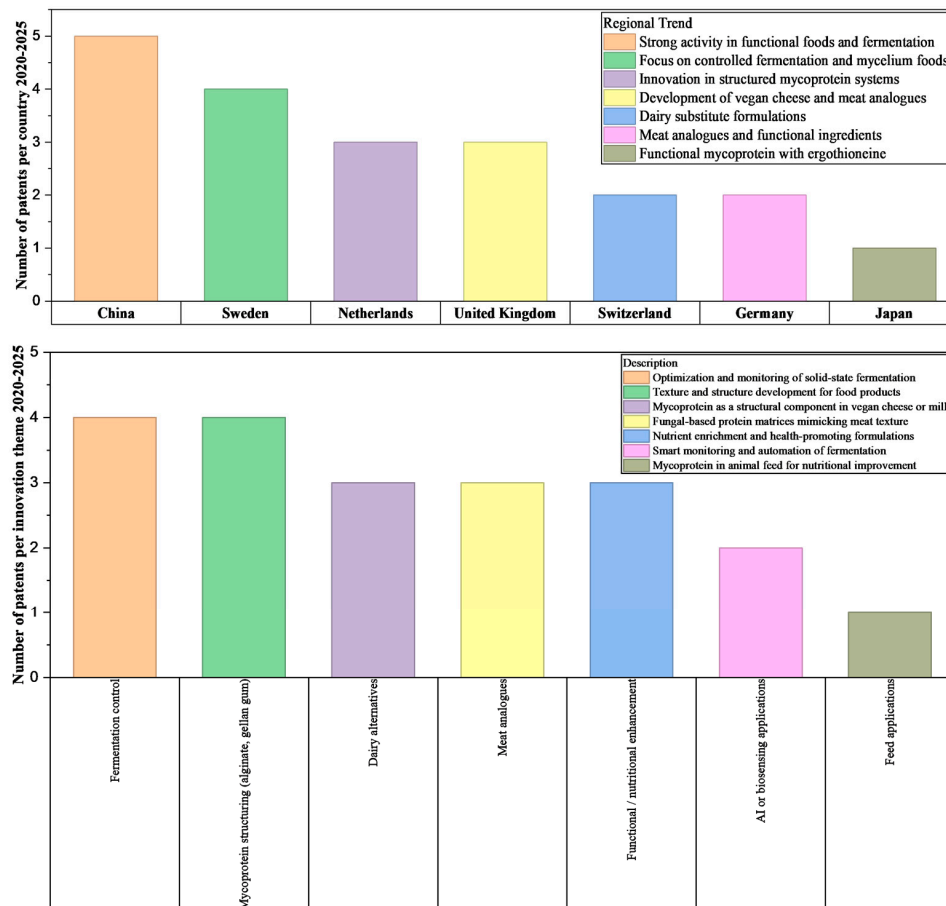
Country	Applicant	Product Application	Biotechnological Innovation
2025			
Sweden (EP)	Millow Holding AB	Edible mycelium-based products	Application of electrical, static magnetic, and low electromagnetic fields in solid-state fermentation of non-mushroom filamentous fungi to enhance production.
Sweden (EP)	Millow Holding AB	Mycelium-based food and feed	AI- and NIR spectroscopy-assisted method to monitor and control high-solid fermentation of edible filamentous fungi.
Netherlands (EP)	Meatless B.V.	Structured food product	Mycoprotein–alginate system forming fibrous textures via calcium-induced curing
Netherlands (EP)	Meatless B.V.	Cheese alternative	Mycoprotein (fungal hyphae) as structural component in vegan cheese formulations
Japan	Kikkoman Corporation	Fermented koji mold product	High ergothioneine-content mycoprotein fermented material for functional foods
2024			
Sweden (US)	Millow Holding AB	Protein-rich biomass	Solid-state fermentation of edible filamentous fungi under controlled conditions (temperature, humidity, pH, light, gas flow) to produce protein-rich biomass.
Sweden (EP)	Millow Holding AB	Protein-rich biomass	Controlled solid-state fermentation of edible filamentous fungi with environmental parameter monitoring for optimized biomass.
United Kingdom	Marlow Foods Ltd.	Hard vegan cheese	<i>Fusarium venenatum</i> mycoprotein with starch and vegetable oil, formulated with low hydrocolloid content.
United Kingdom	Marlow Foods Ltd.	Soft vegan cheese	<i>Fusarium venenatum</i> mycoprotein and oil–starch system creating smooth texture with minimal hydrocolloid.
Switzerland (WO)	Planetary SA	Dairy substitute	Mycoprotein dispersed in water with high-acyl gellan gum, providing milk- or cream-like texture.
Switzerland (EP)	Planetary SA	Milk/cream substitute	Mycoprotein dispersed in water/oil for dairy-like sensory profile
Germany (WO)	Nosh.Bio GmbH	Mycoprotein-based meat analogue	Filamentous fungal biomass processed to achieve desired texture and dry-matter characteristics.
Germany (WO)	Nosh.Bio GmbH	Functional mycoprotein ingredient	Alkali-treated and homogenized fungal biomass enhancing functional properties.

**Table 4.** *Cont.*

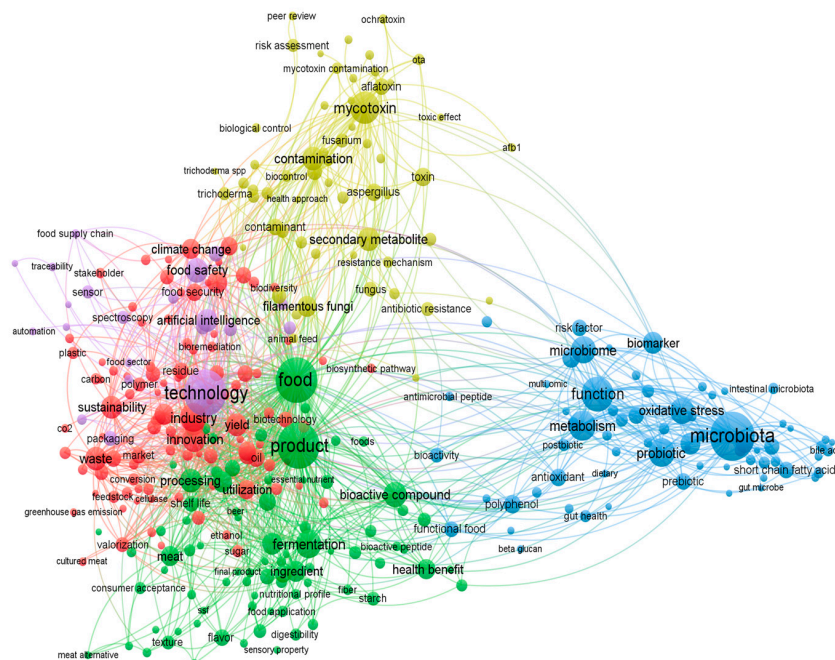
Country	Applicant	Product Application	Biotechnological Innovation
China	Qingdao Qian Dikang Functional Foods Co., Ltd.	Fermented detox food	Mycoprotein–probiotic formulation promoting detoxification and health restoration.
China	Qingdao Qian Dikang Functional Foods Co., Ltd.	Tianjin Institute of Industrial Biotechnology, Chinese Academy of Sciences	Fermented mycoprotein fried chicken nuggets
China	Qingdao Qian Dikang Functional Foods Co., Ltd.	Guizhou Hongqi Biotechnology Co., Ltd.	Plant amino-acid mycoprotein
Netherlands (EP)	Meatless B.V.	Structured food product	Mycoprotein–alginate hydrocolloid premix forming skin-cured texture through calcium crosslinking.
Netherlands (WO)	Meatless B.V.	Structured food product	Mycoprotein-based premix using alginate hydrocolloid curing (earlier patent family).
2022			
Sweden (WO)	Millow Holding AB	Protein-rich biomass	Early method for high-solid fermentation of edible filamentous fungi with continuous monitoring of environmental parameters to produce protein-rich biomass.
2021			
United Kingdom	Marlow Foods Ltd.	Meat-free food product	Mycoprotein ( <i>Fusarium venenatum</i> ) blended with potato and plant proteins; vegan meat analogue
China	Zhongxiang Xingli Food Co., Ltd.	Edible fungus soluble protein product	Mycoprotein-enriched fermented product with improved digestibility and nutrient availability.
2020			
China	Suqian Yibai Feed Co., Ltd.	River crab feed	Feed formulation containing 1–4% mycoprotein to improve nutrition and growth performance.

WO: World Intellectual Property Organization Publication, EP: European Patent; US: United States Patent.

The red cluster emphasizes technological innovations aimed at enhancing production efficiency and process optimization, and is closely associated with the purple cluster, which highlights the application of biosensors, artificial intelligence, and deep learning for scalable mycoprotein production, real-time monitoring, and traceability. The literature also highlights emerging trends including circular economy approaches for by-product valorization, the expansion of alternative protein research driven by sustainable consumer demand, and ongoing optimization of fermentation and enzymatic processes to improve yield and functionality. The yellow cluster addresses food safety concerns, such as mycotoxin-producing fungi, contamination, and allergenicity, emphasizing monitoring, regulatory compliance, and impacts on animal and public health, thereby underscoring broader food safety and biocontrol strategies. The blue cluster reflects a growing body of research investigating the health-promoting properties of mycoprotein, particularly its effects on gut microbiota and other health benefits. The collected evidence highlights the multidimensional nature of mycoprotein research, encompassing advances in biotechnology, food safety, health benefits, and consumer-centered innovation.



(a)



(b)

**Figure 4.** (a) Number of published patents by country and regional innovation trends related to mycoprotein derived from filamentous fungi in food applications between 2020 and 2025. (b) Network visualization of recent research on mycoprotein derived from filamentous fungi (2020–2025) generated using VOSviewer.

### 3.3. Novel Process Development for Fungi-Based Foods

#### 3.3.1. Emerging Fungi-Based Foods

While mycoprotein-based foods have been available since the 1980s, recent developments in mycelium-structured meat alternatives and precision fermentation are rapidly reshaping the alternative protein sector and expanding the range of fungal-based products. Over the past decade (2015–2025), numerous companies focused on fermentation-enabled alternative proteins have emerged, with several developing product pipelines based on filamentous fungi [9]. Driven by growing interest and investment, the global fungal protein market is projected to reach USD 6.7 billion by 2034, growing at a compound annual growth rate (CAGR) of 6.1% [94], underscoring strong demand for fungal-based products.

Fungal applications in food biotechnology have expanded well beyond traditional fermentation to include mycoprotein-based meat alternatives, self-structured mycelium whole cuts, and precision-fermented ingredients, offering sustainable replacements for conventional animal products. Species such as *Fusarium venenatum*, *Aspergillus oryzae*, *A. sojae*, *Rhizopus oryzae*, *R. delemar*, *Amylomyces rouxii*, *Neurospora intermedia*, *N. crassa*, *N. sitophila*, *Mucor circinelloides*, *M. miehei*, and *Paecilomyces variotii* produce over 40% protein, supporting applications in alternative meats, chicken patties, sausages, burgers, fungi-based steak, bacon, and fortified foods [6,15,31–37].

Fungal proteins serve as clean-label ingredients, with remarkable functional properties including solubility, foaming, emulsifying, water- and oil-holding capacities, and gelation [95]. They enhance nutritional value, texture, flavor, shelf-life, and sensory attributes while providing health benefits including digestive regulation and metabolic support [96]. Fungal-derived fats, muscle-like textures, pigments, and flavor compounds can transform dairy and meat alternatives, enhancing sensory qualities without relying on artificial additives [97].

Recent innovations are exploring diverse applications of fungi in fermented beverages (e.g., low-sugar, rich in protein, fiber, and mono- and polyunsaturated fats), high-protein milk analogs, dairy-free cheeses and yogurts, fat replacers, and functional ingredients enriched with bioactive compounds that may support gut health and immunity [6,98]. Similarly, *Pleurotus albidus* mycoprotein has been employed to replace wheat flour in cookies, significantly enhancing protein, dietary fiber, and phenolic content, while also modifying texture and color [6]. In chiffon cakes, replacing up to 40% of low-gluten flour with mycoprotein powder from *Fusarium venenatum* not only increases protein and fiber content but also improves water and oil retention and preserves desirable crumb structure and sensory quality; however, higher substitution levels lead to increased batter viscosity, resulting in denser, darker cakes [99]. Protein bars formulated with 10–30% mycoprotein, showed that modest amounts enhance nutritional value and sensory quality, whereas higher levels accelerate hardening during storage and reduce protein digestibility [100]. Furthermore, mycoprotein could be used in hybrid products, meat and protein blends, fish/seafood analogues, pet food [64].

Additionally, fungal foods are emerging in clinical nutrition and personalized diets, with studies exploring their bioactive compounds for supporting metabolic health, immune function, and cognitive performance [97]. Such advantages positioning fungi as adaptable ingredients in food processing that tackle environmental and energy pressures while supporting the rising demand for nutritious, healthy and eco-friendly foods.

#### 3.3.2. Bioengineered Fungal Strain to Advance Fungal Food Fermentations

Filamentous fungi have emerged as powerful platforms for strain engineering owing to their rapid growth, metabolic versatility, and increasingly sophisticated genetic toolkits. Recent advances integrate random mutagenesis, targeted genetic transformation, and modern genome-editing systems to enhance traits relevant to food, fermentation, materials,

and metabolite production. Chemical and irradiation-based mutagenesis remain effective for generating phenotypic diversity and improving stress tolerance, secretion capacity, and metabolite yields [101].

Precision fermentation is transforming fungal-based foods by using genetically optimized strains to produce targeted proteins, pigments, enzymes, fats, and bioactive compounds with high specificity [98,102,103]. It is increasingly applied to generate enzymes, pigments, fungal-derived fats and volatile flavor compounds that replicate the taste and aroma of animal-based foods [104,105]. Fungal enzymes, in particular, are known to enhance sensory attributes and improve texture. Filamentous fungi are also explored as biofactories for natural food additives, such as exopolysaccharides, including  $\beta$ -glucans and galactomannans, which function as thickeners, emulsifiers, and stabilizers [106]. Mycotechnologies, commercial mycelial fermentation platforms, have advanced in production of flavor modulators and sweeteners that improve umami, reduce bitterness, and enhance protein digestibility [61].

As new molecular tools and systems biology approaches advance, the metabolic capabilities of these organisms will continue to expand. Innovations such as clustered regularly interspaced short palindromic repeats associated protein (CRISPR/Cas) technologies, high-throughput screening, and global transcription machinery engineering are enhancing substrate conversion efficiency, leading to increased production of enzymes, organic acids, and specialized metabolites [9,107]. CRISPR/Cas9 now allows precise, predictable modifications, accelerating engineering of pathways involved in biomass formation, pigment production, and cell-wall biosynthesis [108,109].

To improve in situ nutritional content, the synthetic-biology toolkits provide an emerging route to overproduce desirable nutrients or cofactors, e.g., pathways for heme, vitamins, or enzymes that increase substrate conversion to desirable metabolites [103].

Increasingly, strain-engineering strategies target cell-wall-integrity pathways that regulate hyphal morphology and mechanical properties, critical determinants for optimizing fungal biomass for food applications, bioprocessing performance, and emerging bio-based materials [110].

Furthermore, multi-omics integration with UHPLC-ESI-MS/MS enables the identification and optimization of high-value bioactives, positioning filamentous fungi as key producers of industrially relevant biomolecules [111,112]. Additionally, advances in metabolic and morphological engineering continue to support the discovery and characterization of novel bioactive metabolites, reinforcing their industrial and nutritional significance [113].

Combined with modern processing methodologies, these genetic tools can enhance productivity across the fungi-based product value chain by improving protein, fiber, and lipid profiles, increasing functionality, and enabling removal of allergenic or undesirable genes, thereby accelerating industrial adoption. However, the integration of genetically modified filamentous fungi into food systems remains constrained by complex regulatory requirements and the cost and design challenges associated with large-scale production facilities [9].

### 3.3.3. Next-Generation Smart Fermentation Systems

The digitalization of biomanufacturing is accelerating next-generation smart fermentation systems that integrate continuous data acquisition, machine learning (ML)-based prediction and intelligent decisions, biosensor feedback, and adaptive automated control. These tools enable adaptive, data-driven processes for fungi-based production, with artificial intelligence (AI) models optimizing environmental conditions to improve reliability and productivity, and low energy consumption and processing time. Such technologies could support more efficient large-scale manufacturing of fungal proteins while preserving nutritional quality [114–116]. Furthermore, a smart fermentation approach supports

multiple UN SDGs by advancing innovation, improving nutrition and health, promoting sustainable economic growth, and reducing environmental impact through more efficient and responsible food production [117].

The growing availability of affordable internet of things (IoT) devices and open digital platforms is also transforming the landscape of fungi-based food production. Moreover, predictive modeling enables the design of digital twins: virtual versions of the fermentation process that can be used to explore alternative conditions and fine-tune variables without interfering with ongoing production [118].

Electronic (E)-noses and E-tongues use sensor arrays to monitor aroma and taste in fermentations, including fungal-based foods. E-noses detect volatile compounds in the headspace, while E-tongues profile dissolved taste compounds such as acidity, sweetness, and umami. These systems enable real-time monitoring of fermentation, detect off-odors or taste changes before humans can, and help standardize flavor development in products like tempeh, miso, and mycelium-fermented foods [119,120].

Additionally, integration of AI with synthetic biology hold promise for more precise metabolic control, higher yields, and tailored sensory and nutritional profiles, advancing scalable, functional fungal ingredients for fungi-based and hybrid foods [121]. Wang et al. (2026) presented the framework as a “blueprint for intelligent (precision) fermentation in filamentous fungi” [122]. This AI-driven fermentation framework, a combination of machine learning with Raman spectroscopy and metabolic-network analysis, boosted production of a fungal enzyme ( $\alpha$ -amylase) by ~46% over conventional control, and shortened fermentation time by 28 h. Furthermore, ML applications in metabolic engineering facilitate more efficient strain development and optimization of metabolic flux [123].

Smart fermentation technologies introduce new possibilities for fungi-based food production. These systems can reduce waste, minimize batch to batch variability, and boost biocontrol, while enabling efficient large-scale manufacturing of fungal proteins and preserving their nutritional quality. They also hold significant potential to drive innovation and enhance sustainability across the sector. Despite these benefits, the adoption of AI- and automation-driven approaches in fungi-derived food production remains limited, hindered by economic constraints, technical complexity, insufficient standardization, and regulatory barriers [12,98,124–126].

Future innovations integrating AI-driven bioprocess optimization with synthetic biology are expected to accelerate the development of fungal-based functional foods and enhance their nutritional value. However, translating these innovations into reliable, large-scale production poses significant technical and operational challenges, as industrial-scale manufacturing requires precise environmental control, strict regulatory compliance, and substantial initial investment.

#### 3.3.4. Advanced Structuring Technologies for Fungi-Based Foods

Filamentous fungi are an emerging and promising resource for future foods. Beyond traditional mycoprotein applications, their use is expanding to emulate challenging textures such as steak and bacon, and to develop beverages, baked goods, and other novel food products.

Fungal proteins have been successfully integrated into 3D printing technologies, offering additional potential to enhance or tailor the texture and nutritional profiles of these products. 3D food printing is an emerging area of research and commercial interest, offering precise control over the shape and composition of final food products. Commercial entities are exploring extrusion-based 3D printing to produce plant-based steak and pork alternatives [127]. Recently, 3D printing has been explored using fungal biomass specifically for food applications [128]. In these studies, substrates derived from agricultural waste were

inoculated with edible fungi and printed into defined shapes and sizes, while preserving the biological activity of the fungi. This suggests potential for developing 3D-printed fungal foods with 'probiotic' or 'biologically active' properties, opening opportunities for functional and health-promoting food products. However, printing fungal biomass presents several challenges, including nozzle clogging, poor print quality, contamination, and potential loss of fungal activity. Many knowledge gaps remain, such as optimizing environmental conditions for fungal colonization, mixing protocols, operational parameters during printing, and post-printing processes like drying or additional processing. Although still in its infancy, 3D printing of fungal foods holds promise for precisely shaping and tailoring products, with future applications potentially focusing on replicating or enhancing the characteristics of conventional foods [129,130].

The use of shear-cell technology for structuring filamentous fungal biomass in food applications remains largely unexplored. Recent research has focused on hybrid meat analogues that combine fungal mycelium with plant-derived proteins. Mandliya et al. [131] applied twin-screw extrusion to low-moisture meat analogues formulated with up to 30% *w/w* mycelium (*Pleurotus eryngii*) and pea protein isolate (PPI), resulting in a fibrous, porous microstructure with enhanced water and oil absorption and improved rehydration and solubility properties.

Another innovative approach involves cultivating fungal mycelium within engineered hydrogel frameworks, whose composition and architecture can be tailored to specific requirements. Santhapur et al. [132] showed that incorporating mycelial hyphae into a potato protein matrix generated hybrid gels with stronger gelation, superior rheological and textural characteristics, and a fibrous microstructure compared to potato-protein gels alone. These hydrogel-based frameworks support controlled nutrient distribution and growth patterns, while integration with 3D printing allows precise control over texture, shape, and mouthfeel. Such strategies offer exceptional ability to design high-quality mycelium-based meat alternatives with customized structural and sensory properties [61].

#### 3.4. Nutritional Value, Sensory and Textural Advantages of Mycoprotein

Dietary proteins, whether of plant, animal, or microbial origin provide essential amino acids necessary for human growth and health. Their role in promoting healthy aging and maintaining a balanced diet is increasingly recognized. Most dietary protein recommendations are based on the assumption of high-quality protein intake, in other words, the essential amino acid composition in food proteins should be close to the human body's need [133]. In this context, incorporating microbial protein into human diets offers a viable strategy to address global protein insufficiency [11].

Microbial proteins can match or even surpass animal-based foods in terms of nutritional value, digestibility, and processing properties [5]. During fermentation, fungal biomass can achieve a relatively high protein content, reaching up to 76% in *Fusarium venenatum*. Mycoprotein, is increasingly recognized as a high-quality alternative protein source due to its favorable nutritional profile, health-promoting properties, and sustainability. Mycoprotein is particularly valuable viable to replace both animal- and plant-based proteins and as a meat alternative because. It supports satiety, metabolic function, and overall nutrition.

Mycoproteins demonstrated high nutritional value, with crude protein content ranging from 13.6% to 71% dry weight (dw) and a complete amino acid profile. It boasts a complete amino acid profile, ensuring it provides all essential amino acids necessary for dietary needs. Commercially available wet products, such as Quorn™, provide 11.25 g protein, 6.25 g fiber, 3.25 g fat, and 85 kcal per 100 g [134]. The protein quality of mycoprotein is high, with a PDCAAS of 0.996 which is comparable to that of high-quality animal

proteins [135], and excellent net protein utilization. It is also rich in BCAAs, including leucine, isoleucine, and valine, which support muscle protein synthesis and metabolic health [136], making it a viable option for supporting anabolic responses in both young and older adults [135]. However, mycoprotein has lower protein content compared to animal protein sources, and individuals with high protein needs may necessitate larger portion sizes or supplementation with other protein-rich foods to meet dietary requirements.

It is valued for its high fiber content (4.8–25% dw), predominantly insoluble (88%) with 12% soluble fiber, consisting of a chitin and glucan matrix, which are known to aid fat metabolism and boost immune function that is beneficial for intestinal health. Consumption has been associated with reductions in LDL and total cholesterol by 4–14%, highlighting cardiovascular benefits [66]. The fungal biomass contains moderate levels of carbohydrates (>5.0% dw). Interestingly, mycoprotein fibrous matrix promotes satiety, regulate blood sugar, the glucose homeostasis, and insulin sensitivity, and contributes to lipid metabolism and offer several other nutritional benefits [1].

Mycoprotein lipid content typically ranges from 2 to 3.5%, and the fatty acid profile of the fungal biomass more closely resembles that of plants rather than animal fat. It is rich in mono- and polyunsaturated fatty acids contains less than 1.5 g of both long- and short-chain saturated fatty acids per 100 g. The ratio of unsaturated and saturated fatty acids ranges from 2:1 to 3.5:1 in *F. venenatum* biomass [6].

Additionally, mycoprotein is a good source of several water-soluble B vitamins, including pyridoxine (0.1 mg), folate (114 µg), and cobalamin (0.72 µg). It is particularly rich in essential minerals including calcium, potassium, sodium, magnesium, sulphur, zinc, phosphorus, iron [11,32,33]. Additionally, total polyphenol content exceeded 0.14% dw, and may produce secondary metabolites like statins and L-carnitine, enhancing their functional properties as food ingredients [32,33,36]. Moreover, studies indicate that regular consumption of these foods enhances short-chain fatty acid (SCFA) production, which supports intestinal barrier integrity and helps reduce inflammation [137].

Fungi-based food properties, including flavor, texture, color and nutritional profile, should align with the expectations of regional markets, culturally tailored products that align with growing consumer demand for sustainable protein alternatives. From a sensory and textural perspective, mycoprotein offers a distinct advantage due to its meat-like fibrous structure and neutral taste. This makes it particularly suitable for meat alternatives such as Quorn™, which closely replicates the chewiness and mouthfeel of animal protein [1]. Variations in composition and sensory attributes are influenced by substrate type and concentration, nutrient availability, and the fungal strain employed.

Filamentous fungi also contribute significantly to aroma and flavor development. *Geotrichum candidum* and *Penicillium* spp. (*P. roqueforti*, *P. camemberti*, *P. nalgiovense*, *P. chrysogenum*) generate volatile compounds and proteolytic/polytic metabolites essential to the sensory characteristics of cheeses, cured meats, and fermented soy products [31,51]. The flavor of fungi-based food is largely determined by the choice of fungal strain and the cultivation medium [6]. Sensory properties of mycoprotein-based foods are generally described as mild and umami, but a subtle earthy or mushroom-like taste may be off-putting for some consumers [66].

Texture is critical for consumer acceptance of fungi-derived foods, and fungal morphology strongly influences it: large pellets can form hollow, low-density cores, while smaller pellets promote uniform biomass distribution. Post-cultivation treatments, such as pressing, extrusion, or the addition of binders (e.g., albumin in Quorn™), can further enhance fibrous structure [6]. In contrast, whole self-structured mycelium foods leverage the natural filamentous growth of species such as *Rhizopus*, *Ganoderma*, and *Pleurotus* to produce whole-cut meat alternatives without mechanical processing or binders. The dense,

interlacing hyphae, combined with the inherent fiber-like structure resulting from the fibrous chitin–glucan matrix and water- and fat-retention properties of filamentous mycelia, naturally create rich, meat-like textures, and a fibrous mouthfeel that closely mimic animal tissues [138]. Emerging whole-cut meat analogs use fungi to replicate traditional meat and seafood textures. While there is potential for products such as steak-like cuts (*Hericium erinaceus*), bacon and scallop substitutes (*Pleurotus eryngii*), and chicken-like textures (*Pleurotus ostreatus*), challenges remain in scaling production, maintaining consistent quality, and optimizing sensory and nutritional properties to satisfy consumer expectations [61].

Many filamentous fungi produce natural pigments and biocolorants. *Monascus* spp. synthesize a range of MonAzPs pigments, including yellow (monascin, ankaflavin), orange (rubropunctatin, monascorubrin), and red pigments (rubropunctamine, monascorubramine), while *Neurospora intermedia* contributes carotenoids [37,39,50,52,53]. Color is influenced by the fungal strain and cultivation media, types of C and N sources and C:N ratio, the presence of organic acids and minerals, and on fermentation strategy used [139]. Further color can be affected by the organism's own pigments, enzymes, or other metabolic products [6]. Depending on the desired application of fungi-based foods, the colors and pigments can be modified during or after cultivation of the fungal biomass [140], while encapsulation of the fungal pigment into chitosan microsphere have been shown to be efficient application for food industry [141].

Overall, mycoprotein represents a nutritionally valuable and environmentally sustainable protein source with multiple potential health benefits, particularly in relation to lipid metabolism, muscle protein synthesis, and appetite regulation. However, its lower protein density, potential allergenicity, digestive considerations, and processing requirements highlight the need for careful dietary integration. Further long-term clinical studies are warranted to fully establish the health outcomes associated with regular mycoprotein consumption and to optimize its formulation for broader consumer acceptance.

### 3.5. Safety, Regulatory Issues and Consumer's Acceptance of Mycoprotein

Ensuring safety is paramount when introducing novel proteins into the food supply. From a safety perspective, the use of filamentous fungi in food production requires comprehensive risk assessments to protect consumers. Evaluations include analyses of chemical composition, production controls, digestibility, toxicology. Clinical studies are essential to demonstrate that can be effectively digested and metabolized by humans prior to broader market introduction. The primary concern associated with mycoprotein is allergenicity. Although data are limited, adverse reactions have been reported in individuals with a history of mold allergies, individuals sensitive to chitin or  $\beta$ -glucans [16]. In 2018, an analysis of self-reported adverse events from 1752 individuals consuming Quorn™ products, produced using *Fusarium venenatum* A3/5, found that the majority involved allergic reactions (e.g., hives and anaphylaxis) or gastrointestinal symptoms (e.g., vomiting and diarrhoea) [142]. Although a small number of mycoprotein-specific allergic cases have been reported in the clinical literature [143], systematic reviews and market surveillance indicate that its overall allergenic potential is very low compared with common food allergens [135]. Several promising fungal species for food have also been explored, demonstrating low toxicity, genotoxicity, pathogenicity, and allergenic potential [5].

Concerns regarding RNA content, potentially linked to purine-related hyperuricemia, are mitigated by heat treatment, reducing RNA from nearly 10% to below 2% [13]. Additionally, mycotoxin contamination may be a concern when alternative carbon sources (other than highly refined glucose syrup) are used for fungal growth, and heavy metals, pesticides, contaminants may be present if fermentation substrates are derived from agri-food industry

side streams. The occurrence of such adverse effects may also depend on the type of fungus strain and the substrate [16,144].

The introduction of new fungal species or production processes into the European food system is strictly regulated by the EFSA. Under the Novel Food Regulation (Regulation (EU) 2015/2283), all novel food products must undergo comprehensive safety evaluations before commercialization. Products such as Quorn™ have been subjected to rigorous safety assessments prior to market authorization in multiple countries, including the U.S., Canada, Australia, and EU member states [13]. However, clear and harmonized frameworks for assessing fungi-based proteins and fermentation-derived ingredients are still lacking [145]. In the United States, for instance, the FDA may grant GRAS status to ingredients, including microbial proteins, based either on a documented history of safe use or on scientific evidence demonstrating safety. This regulatory inconsistency continues to pose a major challenge to the global commercialization of mycoprotein, creating uncertainty for manufacturers and slowing the broader market adoption of fungi-based proteins within future food systems.

Recent studies suggest that consumer acceptance of mycoprotein remains uneven and strongly dependent on familiarity, product format. A large cross-national survey (N = 4088) found that key drivers of willingness to try or pay a premium for mycoprotein were perceived healthiness, nutritional benefits, safety, and sustainability. By contrast, taste, texture, and smell of conventional meat often reduced willingness to replace meat with fungi-based alternatives [146]. Disgust and perceived naturalness remain central to acceptance of mycelium [124]. Furthermore, a 2022–2023 European survey found that consumers with greater familiarity were more willing to try mycoprotein, while sensory attributes (taste, texture, smell) and associations with mould or fungi remained key barriers to acceptance [147].

Despite the long history of some brands, many consumers remain unfamiliar with mycoprotein (especially outside Europe and North America). Wider adoption will require education about benefits, cooking versatility, taste, and reassurance about safety and naturalness [148].

The successful integration of mycoproteins into modern diets continues to be constrained by consumer acceptance, which is shaped by intricate social, psychological, and cultural factors. Compared with conventional animal proteins, alternative protein sources are often perceived as less appealing due to concerns about taste, texture, and nutritional quality, as well as skepticism surrounding their processing methods and safety. These perceptions are largely influenced by food neophobia, perceived naturalness, cultural attitudes and familiarity toward novel protein sources [91].

Targeted education and awareness initiatives, along with co-creation approaches and persuasive communication, can enhance consumer understanding of the advantages and limitations of mycoproteins or fungi-based foods. Efforts in product design, packaging, branding and transparent labelling strategies can further foster broader acceptance of mycoprotein and other sustainable protein sources [149]. Compared to emerging protein sources, mycoprotein stands out for broader consumer acceptance due to its favorable taste, texture, and versatility in everyday foods [1].

### *3.6. Future Opportunities and Challenges of Mycoprotein*

Since its commercialization, it has established itself as a safe, nutritious, and widely accepted vegetarian alternative for individuals seeking to reduce or eliminate meat consumption. In recent years, interest in mycoprotein has surged, with numerous companies introducing innovative products, exploring diverse fungal species, and adopting novel cultivation techniques. Despite these advances, questions remain regarding the sustainability

and robustness of mycoprotein production, as well as its potential for continued global market expansion.

Recent scientific literature confirms that mycoprotein, derived via fungal fermentation, remains one of the most promising alternative proteins for a sustainable, nutritious, and potentially health-promoting diet. Given the current evidence, the next decade could see mycoprotein evolving from a niche meat substitute to a core component of a sustainable and diversified protein supply, provided certain conditions are met.

Production must be scaled up using waste-derived and lignocellulosic feedstocks. This approach would help optimize yield, minimize biomass losses, and ensure consistent quality while maintaining safe contaminant and toxin profiles. In addition, the strain portfolio should be broadened beyond the traditional *Fusarium venenatum* to exploit fungi with high protein yield, robust growth on varied substrates, and favorable nutritional profiles. Long-term clinical and epidemiologic studies are also needed to assess health outcomes, including metabolic health, gut microbiome modulation, and allergy potential across diverse populations.

Active engagement with the food industry, including ingredient suppliers, alternative-protein manufacturers, and regulatory bodies, is essential to integrate mycoprotein into mainstream food supply chains. This integration can occur as ingredients, analogues, or hybrid products that meet cost, safety, taste, and nutritional standards.

Despite these opportunities, substantial challenges remain. Scaling production economically and safely, ensuring consistent quality, and achieving broad consumer acceptance are critical hurdles. As research intensifies and technology advances, mycoprotein has the potential to play a central role in shaping a more sustainable global protein supply.

#### 4. Conclusions

This comprehensive review highlights the significant potential of filamentous fungi as a safe, high-quality protein suitable for diverse dietary patterns, emphasizing their contributions to sustainable food systems, healthy diets, and the promotion of environmental protection and circular bioeconomy principles. Mycoprotein, in particular, offers a complete amino acid profile, high digestibility, and functional properties that make it suitable for diverse food applications. It is also environmentally sustainable, providing the opportunity to address global protein deficiencies, reduce reliance on animal-derived proteins, and support resilient, sustainable diets.

Biotechnological innovations are transforming filamentous fungi into versatile platforms for next-generation foods. Leveraging strain bioengineering, combined with precision fermentation and smart fermentation systems integrating AI, IoT, and synthetic biology, can enhance production efficiency, metabolic control, nutritional content, flavor, functional properties and biosafety. Meanwhile, advanced structuring technologies, such as 3D printing, hydrogel frameworks, and extrusion, enable the creation of fungal foods with textures and functionalities that closely replicate conventional products, supporting scalable, sustainable, and innovation-driven protein solutions for future foods.

Successful integration of fungi-based food into global food systems will require the development of new value chains, alongside careful attention to feasibility, scalability, food safety, consumer acceptance, and harmonized regulatory frameworks. Future studies should explore personalized nutrition solutions tailored to individual dietary needs, along with the long-term health impacts of fungal-based diets, particularly regarding microbiome modulation, metabolic function, and immune responses. With these foundations, fungi-based foods can play a pivotal role in building sustainable and consumer-focused future food systems.

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## Abbreviations

The following abbreviations are used in this manuscript:

UN	United Nation
SDGs	Sustainable Development Goals
WIPO	World Intellectual Property Organization
GHG	Greenhouse gas emissions
FAO	Food and Agriculture Organization
WHO	World Health Organization
FDA	Food and Drug Administration
EFSA	European Food Safety Authority
EU	Europe
U.S.	United States
RNA	Ribonucleic Acid
GRAS	Generally Recognized as Safe
AI	Artificial intelligence
ML	Machine learning
IoT	Internet of things
PDCAAS	Protein Digestibility-Corrected Amino Acid Score
BCAAs	Branched-chain amino acids
SCFA	Short-chain fatty acid

## References

- Mundhe, S.; Pawase, P.A.; Bashir, O.; Pathare, A.M.; Mudgal, S.; Spandana, K.; Ahmad, M. Investigative studies on protein quality, absorption pathways, and techno-functional comparison of mycoprotein, insect, and algal proteins for global food security and sustainability. *Food Res. Int.* **2025**, *221*, 117469. [CrossRef]
- Ray, S.; Suri, S. Culinary Applications and Consumer Acceptance. In *The Sustainable Plate: Unveiling the Science of Meat Substitutes and Impact on Global Health*; Ray, S., Suri, S., Eds.; Springer Nature: Cham, Switzerland, 2025; pp. 79–99, ISBN 978-3-031-94604-2.
- FAO; IFAD; UNICEF; WFP; WHO. *The State of Food Security and Nutrition in the World 2024. Financing to End Hunger, Food Insecurity and Malnutrition in All Its Forms; The State of Food Security and Nutrition in the World (SOFI)*; FAO: Rome, Italy, 2024; ISBN 978-92-5-138882-2.
- Gil, M.; Rudy, M.; Duma-Kocan, P.; Stanisławczyk, R.; Krajewska, A.; Dziki, D.; Hassoon, W.H. Sustainability of Alternatives to Animal Protein Sources, a Comprehensive Review. *Sustainability* **2024**, *16*, 7701. [CrossRef]
- Wang, B.; Shi, Y.; Lu, H.; Chen, Q. A critical review of fungal proteins: Emerging preparation technology, active efficacy and food application. *Trends Food Sci. Technol.* **2023**, *141*, 104178. [CrossRef]
- Barzee, T.J.; Cao, L.; Pan, Z.; Zhang, R. Fungi for future foods. *J. Future Foods* **2021**, *1*, 25–37. [CrossRef]

7. Dupont, J.; Dequin, S.; Giraud, T.; Le Tacon, F.; Marsit, S.; Ropars, J.; Richard, F.; Selosse, M.-A. Fungi as a Source of Food. *Microbiol. Spectr.* **2017**, *5*. [[CrossRef](#)] [[PubMed](#)]
8. Pouris, J.; Kolyva, F.; Bratakou, S.; Vogiatzi, C.A.; Chaniotis, D.; Beloukas, A. The Role of Fungi in Food Production and Processing. *Appl. Sci.* **2024**, *14*, 5046. [[CrossRef](#)]
9. Strong, P.J.; Self, R.; Allikian, K.; Szewczyk, E.; Speight, R.; O'Hara, I.; Harrison, M.D. Filamentous fungi for future functional food and feed. *Curr. Opin. Biotechnol.* **2022**, *76*, 102729. [[CrossRef](#)]
10. Elhalis, H. Exploring Fungal Mycelium for Sustainable Food Solutions: From Biomass Utilization to Byproduct Innovation. *Food Rev. Int.* **2025**, 1–33. [[CrossRef](#)]
11. Pobiega, K.; Sękul, J.; Pakulska, A.; Latoszewska, M.; Michońska, A.; Korzeniowska, Z.; Macherzyńska, Z.; Pląder, M.; Duda, W.; Szafraniuk, J.; et al. Fungal Proteins: Sources, Production and Purification Methods, Industrial Applications, and Future Perspectives. *Appl. Sci.* **2024**, *14*, 6259. [[CrossRef](#)]
12. Amara, A.A.; El-Baky, N.A. Fungi as a Source of Edible Proteins and Animal Feed. *J. Fungi* **2023**, *9*, 73. [[CrossRef](#)]
13. Ahmad, M.I.; Farooq, S.; Alhamoud, Y.; Li, C.; Zhang, H. A review on mycoprotein: History, nutritional composition, production methods, and health benefits. *Trends Food Sci. Technol.* **2022**, *121*, 14–29. [[CrossRef](#)]
14. Ritchie, H.; Roser, M. Half of the World's Habitable Land Is Used for Agriculture. *Our World Data*. 2019. Available online: <https://ourworldindata.org/global-land-for-agriculture> (accessed on 25 October 2025).
15. Derbyshire, E.J. Is There Scope for a Novel Mycelium Category of Proteins alongside Animals and Plants? *Foods* **2020**, *9*, 1151. [[CrossRef](#)] [[PubMed](#)]
16. Hadi, J.; Brightwell, G. Safety of Alternative Proteins: Technological, Environmental and Regulatory Aspects of Cultured Meat, Plant-Based Meat, Insect Protein and Single-Cell Protein. *Foods* **2021**, *10*, 1226. [[CrossRef](#)]
17. Muazzam, A.; Samad, A.; Alam, A.N.; Hwang, Y.-H.; Joo, S.-T. Microbial Proteins: A Green Approach Towards Zero Hunger. *Foods* **2025**, *14*, 2636. [[CrossRef](#)]
18. Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360*, 987–992. [[CrossRef](#)]
19. Ritchie, H. Less Meat Is Nearly Always Better than Sustainable Meat, to Reduce Your Carbon Footprint. *Our World Data*. 2020. Available online: <https://ourworldindata.org/less-meat-or-sustainable-meat> (accessed on 25 October 2025).
20. Shahid, M.; Shah, P.; Mach, K.; Rodgers-Hunt, B.; Finnigan, T.; Frost, G.; Neal, B.; Hadjikakou, M. The environmental impact of mycoprotein-based meat alternatives compared to plant-based meat alternatives: A systematic review. *Future Foods* **2024**, *10*, 100410. [[CrossRef](#)]
21. Mekonnen, M.M.; Gerbens-Leenes, W. The Water Footprint of Global Food Production. *Water* **2020**, *12*, 2696. [[CrossRef](#)]
22. FAO; WHO. *Sustainable Healthy Diets: Guiding Principles*; Food and Agriculture Organization (FAO): Rome, Italy; World Health Organization (WHO): Geneva, Switzerland, 2019.
23. Lucas, E.; Guo, M.; Guillén-Gosálbez, G. Low-carbon diets can reduce global ecological and health costs. *Nat. Food* **2023**, *4*, 394–406. [[CrossRef](#)]
24. United Nations. *The Sustainable Development Goals Report 2022*; United Nations: New York, NY, USA, 2022.
25. European Commission The European Green Deal Striving to be the First Climate-Neutral Continent. Available online: [https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal\\_en](https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en) (accessed on 1 November 2025).
26. Schulze, M.; Janssen, M. Self-determined or non-self-determined? Exploring consumer motivation for sustainable food choices. *Sustain. Prod. Consum.* **2024**, *45*, 57–66. [[CrossRef](#)]
27. Onyeaka, H.; Anumudu, C.K.; Okpe, C.; Okafor, A.; Ihenetu, F.; Miri, T.; Odeyemi, O.A.; Anyogu, A. Single Cell Protein for Foods and Feeds: A Review of Trends. *Open Microbiol. J.* **2022**, *16*, e187428582206160. [[CrossRef](#)]
28. Khatami, K.; Qazanfarzadeh, Z.; Jiménez-Quero, A. Fungal fermentation: The blueprint for transforming industrial side streams and residues. *Bioresour. Technol.* **2026**, *440*, 133426. [[CrossRef](#)] [[PubMed](#)]
29. Miller, V.; Reedy, J.; Cudhea, F.; Zhang, J.; Shi, P.; Erndt-Marino, J.; Coates, J.; Micha, R.; Webb, P.; Mozaffarian, D.; et al. Global, regional, and national consumption of animal-source foods between 1990 and 2018: Findings from the Global Dietary Database. *Lancet Planet. Health* **2022**, *6*, e243–e256. [[CrossRef](#)]
30. Lumsden, C.L.; Jagermeyr, J.; Ziska, L.; Fanzo, J. Critical overview of the implications of a global protein transition in the face of climate change: Key unknowns and research imperatives. *One Earth* **2024**, *7*, 1187–1201. [[CrossRef](#)]
31. Barolo, M.I.; Castelli, M.V.; López, S.N. Antimicrobial Activity of Fungal Endophytes Associated with *Peperomia argyreia* (Piperaceae). *Appl. Microbiol.* **2024**, *4*, 753–770. [[CrossRef](#)]
32. Hoxha, L.; Lennartsson, P.R.; Taherzadeh, M.J. Grape marc biotransformation to protein-rich food ingredients using fungal fermentation. *Food Chem. Adv.* **2025**, *8*, 101058. [[CrossRef](#)]
33. Hoxha, L.; Wang, R.; Taherzadeh, M.J.; Undeland, I. In vitro protein digestion and mineral accessibility of edible filamentous fungi cultivated on winery and distillery by-products. *Food Biosci.* **2025**, *73*, 107711. [[CrossRef](#)]

34. Hyttinen, E.; Pajumo, M.; Valtonen, A.; Ritala, A.; Uusitalo, J.; Nordlund, E. Potato and dairy industry side streams as feedstock for fungal and plant cell cultures. *Biocatal. Agric. Biotechnol.* **2024**, *61*, 103367. [[CrossRef](#)]
35. Pranoto, Y.; Christia, A.; Sardjono. Effect of Fermentation by *Rhizopus oligosporus* or *Amylomyces rouxii* on In-Vitro Starch and Protein Digestibility of Decorticated Red Sorghum (*Sorghum bicolor* L. Moench). *Int. J. Adv. Sci. Eng. Inf. Technol.* **2020**, *10*, 2362–2366. [[CrossRef](#)]
36. Rousta, N.; Ferreira, J.A.; Taherzadeh, M.J. Production of L-carnitine-enriched edible filamentous fungal biomass through submerged cultivation. *Bioengineered* **2021**, *12*, 358–368. [[CrossRef](#)]
37. Starzyńska-Janiszewska, A.; Stodolak, B.; Fernández-Fernández, C.; Mickowska, B.; Verardo, V.; Gómez-Caravaca, A.M. Phenolic Profile, Antioxidant Activity and Amino Acid Composition of Moringa Leaves Fermented with Edible Fungal Strains. *Foods* **2022**, *11*, 3762. [[CrossRef](#)]
38. Fazili, A.B.A.; Shah, A.M.; Zan, X.; Naz, T.; Nosheen, S.; Nazir, Y.; Ullah, S.; Zhang, H.; Song, Y. *Mucor circinelloides*: A model organism for oleaginous fungi and its potential applications in bioactive lipid production. *Microb. Cell Factories* **2022**, *21*, 29. [[CrossRef](#)]
39. Labuda, R.; Bacher, M.; Gratzl, H.; Doppler, M.; Parich, A.; Aufy, M.; Lemmens-Gruber, R.; Schuhmacher, R.; Rychli, K.; Wagner, M.; et al. Luteapyrone, a Novel  $\gamma$ -Pyrone Isolated from the Filamentous Fungus *Metapochonia lutea*. *Molecules* **2021**, *26*, 6589. [[CrossRef](#)]
40. Wu, C.; Jiang, N.; Wang, R.; Jiang, S.; Yuan, Z.; Luo, X.; Wu, J.; Shi, H.; Wu, R. Linoleic acid enrichment of cheese by okara flour and *Geotrichum candidum* overexpressing  $\Delta 12$  fatty acid desaturase. *J. Sci. Food Agric.* **2023**, *103*, 2960–2969. [[CrossRef](#)]
41. Choukade, R.; Kango, N. Purification of *Aspergillus tamarii* mycelial fructosyltransferase (m-FTase), optimized FOS production, and evaluation of its anticancer potential. *J. Food Sci.* **2022**, *87*, 3294–3306. [[CrossRef](#)]
42. Šelo, G.; Planinić, M.; Tišma, M.; Tomas, S.; Koceva Komlenić, D.; Bucić-Kojić, A. A Comprehensive Review on Valorization of Agro-Food Industrial Residues by Solid-State Fermentation. *Foods* **2021**, *10*, 927. [[CrossRef](#)] [[PubMed](#)]
43. Gmoser, R.; Fristedt, R.; Larsson, K.; Undeland, I.; Taherzadeh, M.J.; Lennartsson, P.R. From stale bread and brewers spent grain to a new food source using edible filamentous fungi. *Bioengineered* **2020**, *11*, 582–598. [[CrossRef](#)] [[PubMed](#)]
44. Wikandari, R.; Nisrina, H.; Setiowati, A.D.; Millati, R. Enhanced Bioaccumulation of Essential Minerals in Filamentous Fungal Biomass During Cultivation to Produce High Quality Vegan Food. *Pol. J. Food Nutr. Sci.* **2025**, *75*, 274–282. [[CrossRef](#)]
45. Abd Razak, D.L.; Abd Rashid, N.Y.; Jamaluddin, A.; Abd Ghani, A.; Abdul Manan, M. Antioxidant activities, tyrosinase inhibition activity and bioactive compounds content of broken rice fermented with *Amylomyces rouxii*. *Food Res.* **2021**, *5*, 65–72. [[CrossRef](#)]
46. Brück, W.M.; Erismann, Y.; Andlauer, W. Fermentative Liberation and Transformation of Bioactive Compounds: Ellagic Acid from Nut Press Cake Ellagitannins. *Appl. Sci.* **2024**, *14*, 1141. [[CrossRef](#)]
47. Hameed, A.; Hussain, S.A.; Nosheen, S.; Muhammad, Z.; Wu, Y.; Ullah, S.; Suleria, H.A.R.; Song, Y. Microencapsulation of microbial antioxidants from *Mucor circinelloides*, their physico-chemical characterization, in vitro digestion and releasing behaviors in food. *Appl. Biol. Chem.* **2020**, *63*, 28. [[CrossRef](#)]
48. Averianova, L.A.; Balabanova, L.A.; Son, O.M.; Podvolotskaya, A.B.; Tekutyeva, L.A. Production of Vitamin B2 (Riboflavin) by Microorganisms: An Overview. *Front. Bioeng. Biotechnol.* **2020**, *8*, 570828. [[CrossRef](#)] [[PubMed](#)]
49. Dianatdar, F.; Etemadifar, Z.; Taherzadeh, M.J. Production of B vitamins and carotenoids as active biomolecules by edible filamentous fungus *neurospora intermedia*. *Food Biosci.* **2025**, *69*, 106850. [[CrossRef](#)]
50. Pimenta, L.P.S.; Gomes, D.C.; Cardoso, P.G.; Takahashi, J.A. Recent Findings in Azaphilone Pigments. *J. Fungi* **2021**, *7*, 541. [[CrossRef](#)]
51. Chin, X.H.; Soh, R.; Chan, G.; Ng, P.; Thong, A.; Elhalis, H.; Yoganathan, K.; Chow, Y.; Liu, S.Q. Modulating the aroma and taste profile of soybean using novel strains for fermentation. *Curr. Res. Food Sci.* **2025**, *10*, 100933. [[CrossRef](#)]
52. Chen, D.; Xu, Y.; Li, H.; Zhu, X. Optimization of *Monascus purpureus* Culture Conditions in Rice Bran for Enhanced *Monascus* Pigment Biosynthesis. *Fermentation* **2025**, *11*, 505. [[CrossRef](#)]
53. Da Silva, V.L.; Ienczak, J.L.; Moritz, D. Agro-industrial residues for the production of red biopigment by *Monascus ruber*: Rice flour and sugarcane molasses. *Braz. J. Microbiol.* **2021**, *52*, 587–596. [[CrossRef](#)]
54. Oviedo-Albarracín, C.; Chacón-Navarrete, H.; Cámara-Martos, F.; Bermúdez-Luque, A.; Koysuren, B.; Nitin, N.; Fotidis, I.; Yan, Y.; Moreno-García, J. Increasing the Lipid Content of Filamentous Fungi: Potential Alternatives to Conventional Meat through Culture Medium Modification and High-Lipid Yeast Immobilization. *Food Bioprocess Technol.* **2025**, *18*, 10789–10805. [[CrossRef](#)]
55. Singh, U.; Gautam, A.; Singha, T.K.; Tiwari, A.; Tiwari, P.; Sahai, V.; Sharma, S. Mass production of *Pleurotus eryngii* mycelia under submerged culture conditions with improved minerals and vitamin D2. *LWT* **2020**, *131*, 109665. [[CrossRef](#)]
56. Abdel-Mageed, H.M.; Nada, D.; Radwan, R.A.; Mohamed, S.A.; Gohary, N.A.E.L. Optimization of catalytic properties of *Mucor racemosus* lipase through immobilization in a biocompatible alginate gelatin hydrogel matrix for free fatty acid production: A sustainable robust biocatalyst for ultrasound-assisted olive oil hydrolysis. *3 Biotech* **2022**, *12*, 285. [[CrossRef](#)] [[PubMed](#)]
57. Chen, Z.; Chen, C.; Yang, R.; Jin, H.; Liu, B.; Wang, Z.; Tan, Y.; Xue, Q.; Hu, Y. The formation mechanism of sufu gels fermented by *Mucor racemosus* during pre-fermentation. *LWT* **2024**, *203*, 116309. [[CrossRef](#)]

58. Salgado, J.C.S.; Heinen, P.R.; Messias, J.M.; Oliveira-Monteiro, L.M.; Cereia, M.; Rechia, C.G.V.; Maller, A.; Kadowaki, M.K.; Ward, R.J.; Polizeli, M.d.L.T.d.M. Enhancing Xylanase Production from *Aspergillus tamarii* Kita and Its Application in the Bioconversion of Agro-Industrial Residues into Fermentable Sugars Using Factorial Design. *Fermentation* **2024**, *10*, 241. [[CrossRef](#)]
59. Mano, J. Fast and easy edible protein production by nitrogen-supplemented koji fermentation. *NPJ Sci. Food* **2025**, *9*, 150. [[CrossRef](#)]
60. Wang, C.; Hu, C.; Li, X.; Shen, R.; Yin, L.; Wu, Q.; Hu, T. Effects of *Rhizopus oligosporus*-Mediated Solid-State Fermentation on the Protein Profile and  $\alpha$ -Glucosidase Inhibitory Activity of Selenium-Biofortified Soybean Tempeh. *Foods* **2025**, *14*, 2899. [[CrossRef](#)]
61. Gandia, A.; Nussbaum, N.; Zermatten, C.; Rühls, P.A. Fungal-Based Foods Beyond Mushrooms: Traditional Practices and Modern Innovations. In *Fungi*; Navarro Simarro, P., Ed.; Springer: New York, NY, USA, 2026; pp. 233–258. ISBN 978-1-0716-4989-3.
62. Wijaya, C.H.; Nuraida, L.; Nuramalia, D.R.; Hardanti, S.; Świader, K. Oncom: A Nutritive Functional Fermented Food Made from Food Process Solid Residue. *Appl. Sci.* **2024**, *14*, 10702. [[CrossRef](#)]
63. Maini Rekdal, V.; Villalobos-Escobedo, J.M.; Rodriguez-Valeron, N.; Olaizola Garcia, M.; Prado Vásquez, D.; Rosales, A.; Sørensen, P.M.; Baidoo, E.E.K.; Calheiros de Carvalho, A.; Riley, R.; et al. *Neurospora intermedia* from a traditional fermented food enables waste-to-food conversion. *Nat. Microbiol.* **2024**, *9*, 2666–2683. [[CrossRef](#)] [[PubMed](#)]
64. Akinsemolu, A.A.; Onyeaka, H.N. Mycoproteins as sustainable food sources: Current applications and future prospects. *Discov. Appl. Sci.* **2025**, *7*, 191. [[CrossRef](#)]
65. Risner, D.; McDonald, K.A.; Jones, C.; Spang, E.S. A techno-economic model of mycoprotein production: Achieving price parity with beef protein. *Front. Sustain. Food Syst.* **2023**, *7*, 1204307. [[CrossRef](#)]
66. Majumder, R.; Miatur, S.; Saha, A.; Hossain, S. Mycoprotein: Production and nutritional aspects: A review. *Sustain. Food Technol.* **2024**, *2*, 81–91. [[CrossRef](#)]
67. Amobonye, A.; Lalung, J.; Awasthi, M.K.; Pillai, S. Fungal mycelium as leather alternative: A sustainable biogenic material for the fashion industry. *Sustain. Mater. Technol.* **2023**, *38*, e00724. [[CrossRef](#)]
68. Reardon, K.F. Practical monitoring technologies for cells and substrates in biomanufacturing. *Curr. Opin. Biotechnol.* **2021**, *71*, 225–230. [[CrossRef](#)] [[PubMed](#)]
69. Niyigaba, T.; Küçükğöz, K.; Kołożyn-Krajewska, D.; Królikowski, T.; Trzaskowska, M. Advances in Fermentation Technology: A Focus on Health and Safety. *Appl. Sci.* **2025**, *15*, 3001. [[CrossRef](#)]
70. Borkertas, S.; Viskelis, J.; Viskelis, P.; Streimikyte, P.; Gasiunaite, U.; Urbonaviciene, D. Fungal Biomass Fermentation: Valorizing the Food Industry's Waste. *Fermentation* **2025**, *11*, 351. [[CrossRef](#)]
71. Hoxha, L.; Taherzadeh, M.J.; Marangon, M. Sustainable repurposing of grape marc: Potential for bio-based innovations. *Waste Manag.* **2025**, *203*, 114871. [[CrossRef](#)] [[PubMed](#)]
72. Parchami, M.; Sar, T.; Bulkan, G.; Ferreira, J.A.; Taherzadeh, M.J. 18—Versatility of filamentous fungi in novel processes. In *Current Developments in Biotechnology and Bioengineering*; Taherzadeh, M.J., Ferreira, J.A., Pandey, A., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 533–574. ISBN 978-0-323-91872-5.
73. Malos, I.G.; Ghizdareanu, A.-I.; Vidu, L.; Matei, C.B.; Pasarin, D. The Role of Whey in Functional Microorganism Growth and Metabolite Generation: A Biotechnological Perspective. *Foods* **2025**, *14*, 1488. [[CrossRef](#)]
74. Sousa, D.; Simões, L.; Oliveira, R.; Salgado, J.M.; Cambra-López, M.; Belo, I.; Dias, A. Evaluation of biotechnological processing through solid-state fermentation of oilseed cakes on extracts bioactive potential. *Biotechnol. Lett.* **2023**, *45*, 1293–1307. [[CrossRef](#)]
75. Organo, N.D.; Granada, S.M.J.M.; Pineda, H.G.S.; Sandro, J.M.; Nguyen, V.H.; Gummert, M. Assessing the potential of a *Trichoderma*-based compost activator to hasten the decomposition of incorporated rice straw. *Sci. Rep.* **2022**, *12*, 448. [[CrossRef](#)] [[PubMed](#)]
76. Wang, Y.; Cai, C.; Lu, J.; Li, X.; Wang, Z.; Chu, J. Efficient crop straws biotreatment using the fungus *Cerrena Unicolor* GC.u01. *AMB Express* **2024**, *14*, 28. [[CrossRef](#)] [[PubMed](#)]
77. Ng, Z.Y.; Kee, P.E.; Abdullah, R.; Lan, J.C.-W.; Ling, T.C.; Jiang, J.-J.; Lim, J.W.; Khoo, K.S. Conversion of lignocellulosic biomass waste into mycoprotein: Current status and future directions for sustainable protein production. *Biomass Convers. Biorefinery* **2024**, *15*, 31337–31363. [[CrossRef](#)]
78. Mili, C.; Kalita, S.; Tayung, K. Hydrolysis efficiency of sugarcane bagasse treated with fungal consortia isolated from leaf litter. *Biomass Convers. Biorefinery* **2025**, *15*, 2881–2892. [[CrossRef](#)]
79. Parchami, M.; Mahboubi, A.; Agnihotri, S.; Taherzadeh, M.J. Biovalorization of brewer's spent grain as single-cell protein through coupling organosolv pretreatment and fungal cultivation. *Waste Manag.* **2023**, *169*, 382–391. [[CrossRef](#)]
80. França, E.d.S.; de Souza, A.F.; Rodríguez, D.M.; de Paula, N.Z.; Neves, A.G.D.; Cardoso, K.B.B.; Campos-Takaki, G.M.d.; de Lima, M.A.B.; Porto, A.L.F. Valorization of Spent Coffee Grounds as a Substrate for Fungal Laccase Production and Biosorbents for Textile Dye Decolorization. *Fermentation* **2025**, *11*, 396. [[CrossRef](#)]
81. Svensson, S.; Bucuricova, L.; Ferreira, J.A.; Filho, P.F.S.; Taherzadeh, M.J.; Zamani, A. Valorization of Bread Waste to a Fiber- and Protein-Rich Fungal Biomass. *Fermentation* **2021**, *7*, 91. [[CrossRef](#)]

82. Ferreira, J.A.; Varjani, S.; Taherzadeh, M.J. A Critical Review on the Ubiquitous Role of Filamentous Fungi in Pollution Mitigation. *Curr. Pollut. Rep.* **2020**, *6*, 295–309. [[CrossRef](#)]
83. Rodríguez, L.A.; Groff, M.C.; Garay, S.A.; Díaz, M.E.; Sardella, M.F.; Scaglia, G. Bioconversion of Olive Pomace: A Solid-State Fermentation Strategy with *Aspergillus* sp. for Detoxification and Enzyme Production. *Fermentation* **2025**, *11*, 456. [[CrossRef](#)]
84. Saleem, M.; Saeed, M.T. Potential application of waste fruit peels (orange, yellow lemon and banana) as wide range natural antimicrobial agent. *J. King Saud Univ.—Sci.* **2020**, *32*, 805–810. [[CrossRef](#)]
85. Jadhav, R.; Mach, R.L.; Mach-Aigner, A.R. Protein secretion and associated stress in industrially employed filamentous fungi. *Appl. Microbiol. Biotechnol.* **2024**, *108*, 92. [[CrossRef](#)] [[PubMed](#)]
86. Whittaker, J.A.; Johnson, R.I.; Finnigan, T.J.A.; Avery, S.V.; Dyer, P.S. The Biotechnology of Quorn Mycoprotein: Past, Present and Future Challenges. In *Grand Challenges in Fungal Biotechnology*; Nevalainen, H., Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 59–79. ISBN 978-3-030-29541-7.
87. Zeng, B.; Nilsson, K.; Teixeira, P.G.; Bergenstahl, B. Study of mycoprotein extraction methods and its functional properties. *Colloids Surf. Physicochem. Eng. Asp.* **2023**, *659*, 130800. [[CrossRef](#)]
88. González, A.; Cruz, M.; Losoya, C.; Nobre, C.; Loreda, A.; Rodríguez, R.; Contreras, J.; Belmares, R. Edible mushrooms as a novel protein source for functional foods. *Food Funct.* **2020**, *11*, 7400–7414. [[CrossRef](#)]
89. Grossmann, L.; Weiss, J. Alternative Protein Sources as Technofunctional Food Ingredients. *Annu. Rev. Food Sci. Technol.* **2021**, *12*, 93–117. [[CrossRef](#)]
90. Kamal, H.; Le, C.F.; Salter, A.M.; Ali, A. Extraction of protein from food waste: An overview of current status and opportunities. *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 2455–2475. [[CrossRef](#)]
91. Machado, M.; Bautista-Hernández, I.; Gómez-García, R.; Silva, S.; Costa, E.M. Bioactive Food Proteins: Bridging Nutritional and Functional Benefits with Sustainable Protein Sources. *Foods* **2025**, *14*, 3035. [[CrossRef](#)]
92. Jafarzadeh, S.; Qazanfarzadeh, Z.; Majzoobi, M.; Sheiband, S.; Oladzadabbasabad, N.; Esmaeili, Y.; Barrow, C.J.; Timms, W. Alternative proteins; A path to sustainable diets and environment. *Curr. Res. Food Sci.* **2024**, *9*, 100882. [[CrossRef](#)]
93. Siddiqui, S.A.; Bahmid, N.A.; Karim, I.; Mehany, T.; Gvozdenko, A.A.; Blinov, A.V.; Nagdalian, A.A.; Arsyad, M.; Lorenzo, J.M. Cultured meat: Processing, packaging, shelf life, and consumer acceptance. *LWT* **2022**, *172*, 114192. [[CrossRef](#)]
94. Future Market Insights Fungal Protein Market Size, Demand & Forecast 2024–2034. Available online: <https://www.futuremarketinsights.com/reports/fungal-protein-market> (accessed on 30 November 2025).
95. Yang, M.; Qian, Z.; Zhan, Q.; Zhong, L.; Hu, Q.; Zhao, L. Application of definitive screening design to optimization of the protein extraction and functional properties of proteins in *Auricularia auricula*. *J. Sci. Food Agric.* **2023**, *103*, 1226–1236. [[CrossRef](#)]
96. Torres-Martínez, B.D.M.; Vargas-Sánchez, R.D.; Torrescano-Urrutia, G.R.; Esqueda, M.; Rodríguez-Carpena, J.G.; Fernández-López, J.; Perez-Alvarez, J.A.; Sánchez-Escalante, A. Pleurotus Genus as a Potential Ingredient for Meat Products. *Foods* **2022**, *11*, 779. [[CrossRef](#)]
97. Tzachor, A. Novel foods for human and planetary health. *Nat. Food* **2022**, *3*, 247–248. [[CrossRef](#)]
98. Mazac, R.; Meinilä, J.; Korkalo, L.; Järviö, N.; Jalava, M.; Tuomisto, H.L. Incorporation of novel foods in European diets can reduce global warming potential, water use and land use by over 80. *Nat. Food* **2022**, *3*, 286–293. [[CrossRef](#)] [[PubMed](#)]
99. Cheng, K.-E.; Lin, L.-Y.; Chen, C.-C.; Guo, J.-H. Mycoprotein as a functional ingredient in chiffon cake: Impacts on batter rheology, nutritional value, texture, and sensory quality. *Int. J. Food Sci. Technol.* **2025**, *60*, vvaf209. [[CrossRef](#)]
100. You, X.-Y.; Ding, Y.; Bu, Q.-Y.; Wang, Q.-H.; Zhao, G.-P. Nutritional, Textural, and Sensory Attributes of Protein Bars Formulated with Mycoproteins. *Foods* **2024**, *13*, 671. [[CrossRef](#)]
101. Kim, H.-S.; Oh, C.-J.; Jeong, K.-J.; Choi, M.-H.; Shin, H.-J.; Oh, D.-S. Culture and mycelium-mat formation characteristics of mutant strains by gamma-ray treatment. *J. Mushroom* **2020**, *18*, 393–397. [[CrossRef](#)]
102. Graham, A.E.; Ledesma-Amaro, R. The microbial food revolution. *Nat. Commun.* **2023**, *14*, 2231. [[CrossRef](#)] [[PubMed](#)]
103. Maini Rekdal, V.; van der Luijt, C.R.B.; Chen, Y.; Kakumanu, R.; Baidoo, E.E.K.; Petzold, C.J.; Cruz-Morales, P.; Keasling, J.D. Edible mycelium bioengineered for enhanced nutritional value and sensory appeal using a modular synthetic biology toolkit. *Nat. Commun.* **2024**, *15*, 2099. [[CrossRef](#)]
104. Stöppelmann, F.; Chan, L.F.; Hildebrand, G.; Hermann-Ene, V.; Vetter, W.; Rigling, M.; Zhang, Y. Molecular decoding a meat-like aroma generated from *Laetiporus sulphureus*-mediated fermentation of onion (*Allium cepa* L.). *Food Res. Int. Ott. Ont* **2024**, *192*, 114757. [[CrossRef](#)]
105. Zhang, X.-Y.; Li, B.; Huang, B.-C.; Wang, F.-B.; Zhang, Y.-Q.; Zhao, S.-G.; Li, M.; Wang, H.-Y.; Yu, X.-J.; Liu, X.-Y.; et al. Production, Biosynthesis, and Commercial Applications of Fatty Acids from Oleaginous Fungi. *Front. Nutr.* **2022**, *9*, 873657. [[CrossRef](#)]
106. Takahashi, J.A.; Barbosa, B.V.R.; Martins, B.d.A.; P Guirlanda, C.; A F Moura, M. Use of the Versatility of Fungal Metabolism to Meet Modern Demands for Healthy Aging, Functional Foods, and Sustainability. *J. Fungi* **2020**, *6*, 223. [[CrossRef](#)]
107. Chai, K.F.; Ng, K.R.; Samarasiri, M.; Chen, W.N. Precision fermentation to advance fungal food fermentations. *Curr. Opin. Food Sci.* **2022**, *47*, 100881. [[CrossRef](#)]

108. Liu, X.; Dong, J.; Liao, J.; Tian, L.; Qiu, H.; Wu, T.; Ge, F.; Zhu, J.; Shi, L.; Jiang, A.; et al. Establishment of CRISPR/Cas9 Genome-Editing System Based on Dual sgRNAs in *Flammulina filiformis*. *J. Fungi* **2022**, *8*, 693. [[CrossRef](#)]
109. Yamasaki, F.; Nakazawa, T.; Oh, M.; Bao, D.; Kawauchi, M.; Sakamoto, M.; Honda, Y. Gene targeting of dikaryotic *Pleurotus ostreatus* nuclei using the CRISPR/Cas9 system. *FEMS Microbiol. Lett.* **2022**, *369*, fnac083. [[CrossRef](#)] [[PubMed](#)]
110. Lian, L.; Zhang, G.; Zhu, J.; Wang, Y.; Wang, L.; Liu, R.; Shi, L.; Ren, A.; Zhao, M. Swi6B, an alternative splicing isoform of Swi6, mediates the cell wall integrity of *Ganoderma lucidum*. *Environ. Microbiol.* **2021**, *23*, 4405–4417. [[CrossRef](#)]
111. Hernández, G.; Ponce de la Cal, A.; Louis, Y.; Baró Robaina, Y.; Coll, Y.; Spengler, I.; Mirabal-Gallardo, Y. Identification of Secondary Metabolites by UHPLC-ESI-HRMS/MS in Antifungal Strain *Trichoderma harzianum* (LBAT-53). *J. Fungi* **2024**, *10*, 547. [[CrossRef](#)] [[PubMed](#)]
112. Leal, K.; Rojas, E.; Madariaga, D.; Contreras, M.J.; Nuñez-Montero, K.; Barrientos, L.; Gómez-Espinoza, O.; Iturrieta-González, I. Unlocking Fungal Potential: The CRISPR-Cas System as a Strategy for Secondary Metabolite Discovery. *J. Fungi* **2024**, *10*, 748. [[CrossRef](#)]
113. Gong, P.; Shi, R.; Liu, Y.; Luo, Q.; Wang, C.; Chen, W. Recent advances in *monascus* pigments produced by *Monascus purpureus*: Biosynthesis, fermentation, function, and application. *LWT-Food Sci. Technol.* **2023**, *185*, 115162. [[CrossRef](#)]
114. Cheng, Y.; Bi, X.; Xu, Y.; Liu, Y.; Li, J.; Du, G.; Lv, X.; Liu, L. Artificial intelligence technologies in bioprocess: Opportunities and challenges. *Bioresour. Technol.* **2023**, *369*, 128451. [[CrossRef](#)]
115. Todhunter, M.E.; Jubair, S.; Verma, R.; Saqe, R.; Shen, K.; Duffy, B. Artificial intelligence and machine learning applications for cultured meat. *Front. Artif. Intell.* **2024**, *7*, 1424012. [[CrossRef](#)] [[PubMed](#)]
116. Wainaina, S.; Taherzadeh, M.J. Automation and artificial intelligence in filamentous fungi-based bioprocesses: A review. *Bioresour. Technol.* **2023**, *369*, 128421. [[CrossRef](#)]
117. Yee, C.S.; Zahia-Azizan, N.A.; Abd Rahim, M.H.; Mohd Zaini, N.A.; Raja-Razali, R.B.; Ushidee-Radzi, M.A.; Ilham, Z.; Wan-Mohtar, W.A.A.Q.I. Smart Fermentation Technologies: Microbial Process Control in Traditional Fermented Foods. *Fermentation* **2025**, *11*, 323. [[CrossRef](#)]
118. Sharma, V.; Mottafegh, A.; Joo, J.-U.; Kang, J.-H.; Wang, L.; Kim, D.-P. Toward microfluidic continuous-flow and intelligent downstream processing of biopharmaceuticals. *Lab. Chip* **2024**, *24*, 2861–2882. [[CrossRef](#)]
119. Podražka, M.; Bącznyńska, E.; Kundys, M.; Jeleń, P.S.; Witkowska Nery, E. Electronic Tongue—A Tool for All Tastes? *Biosensors* **2018**, *8*, 3. [[CrossRef](#)]
120. Seesaard, T.; Wongchoosuk, C. Recent Progress in Electronic Noses for Fermented Foods and Beverages Applications. *Fermentation* **2022**, *8*, 302. [[CrossRef](#)]
121. Ajayeoba, T.A.; Ijbadeniya, O.A. Transforming Food for the Future: Precision Fermentation as a Key to Sustainability, Nutrition, and Health. *Nutr. Health* **2025**. [[CrossRef](#)]
122. Wang, Y.; Wang, Y.; Xu, F. Artificial intelligence-driven fermentation optimization for  $\alpha$ -amylase hyperproduction enabled by Raman monitoring and metabolic network analysis. *Bioresour. Technol.* **2026**, *439*, 133287. [[CrossRef](#)] [[PubMed](#)]
123. Kim, G.B.; Kim, W.J.; Kim, H.U.; Lee, S.Y. Machine learning applications in systems metabolic engineering. *Curr. Opin. Biotechnol.* **2020**, *64*, 1–9. [[CrossRef](#)]
124. Fischer, A.R.H.; Hilboesen, O. Consumer acceptance of mycelium as protein source. *Food Qual. Prefer.* **2025**, *122*, 105304. [[CrossRef](#)]
125. Focker, M.; Liu, C.; Wang, X.; van der Fels-Klerx, H.J. The use of artificial intelligence to improve mycotoxin management: A review. *Mycotoxin Res.* **2025**, *41*, 529–540. [[CrossRef](#)]
126. Holt, R.R.; Munafo, J.P.; Salmen, J.; Keen, C.L.; Mistry, B.S.; Whiteley, J.M.; Schmitz, H.H. Mycelium: A Nutrient-Dense Food To Help Address World Hunger, Promote Health, and Support a Regenerative Food System. *J. Agric. Food Chem.* **2024**, *72*, 2697–2707. [[CrossRef](#)]
127. Scott, N.; Ting, K.C. Controlled Biology-Based Indoor Circular Food Systems. *Am. Soc. Agric. Biol. Eng.* **2021**, *28*, 19–24.
128. Bhardwaj, A.; Vasselli, J.; Lucht, M.; Pei, Z.; Shaw, B.; Grasley, Z.; Wei, X.; Zou, N. 3D Printing of Biomass-Fungi Composite Material: A Preliminary Study. *Manuf. Lett.* **2020**, *24*, 96–99. [[CrossRef](#)]
129. Demircan, E.; Aydar, E.F.; Mertdinc (Mertdinç), Z.; Kasapoglu (Kasapoğlu), K.N.; Ozcelik (Özçelik), B. 3D printable vegan plant-based meat analogue: Fortification with three different mushrooms, investigation of printability, and characterization. *Food Res. Int.* **2023**, *173*, 113259. [[CrossRef](#)]
130. Tiupova, A.; Harasym, J. Structure-Forming Properties of *Pleurotus ostreatus*: A Promising Resource for Edible 3D Printing Applications. *Molecules* **2025**, *30*, 3350. [[CrossRef](#)]
131. Mandliya, S.; Pratap-Singh, A.; Vishwakarma, S.; Dalbhagat, C.G.; Mishra, H.N. Incorporation of Mycelium (*Pleurotus eryngii*) in Pea Protein Based Low Moisture Meat Analogue: Effect on Its Physicochemical, Rehydration and Structural Properties. *Foods* **2022**, *11*, 2476. [[CrossRef](#)]
132. Santhapur, R.; Jayakumar, D.; McClements, D.J. Formation and Characterization of Mycelium–Potato Protein Hybrid Materials for Application in Meat Analogs or Substitutes. *Foods* **2024**, *13*, 4109. [[CrossRef](#)]

133. Smith, K.; Watson, A.W.; Lonnie, M.; Peeters, W.M.; Oonincx, D.; Tsoutsoura, N.; Simon-Miquel, G.; Szepe, K.; Cochetel, N.; Pearson, A.G.; et al. Meeting the global protein supply requirements of a growing and ageing population. *Eur. J. Nutr.* **2024**, *63*, 1425–1433. [[CrossRef](#)]
134. Finnigan, T.J.A.; Theobald, H.E.; Bajka, B. Mycoprotein: A Healthy and Sustainable Source of Alternative Protein-Based Foods. *Annu. Rev. Food Sci. Technol.* **2025**, *16*, 105–125. [[CrossRef](#)]
135. Finnigan, T.J.A.; Wall, B.T.; Wilde, P.J.; Stephens, F.B.; Taylor, S.L.; Freedman, M.R. Mycoprotein: The Future of Nutritious Nonmeat Protein, a Symposium Review. *Curr. Dev. Nutr.* **2019**, *3*, nzz021. [[CrossRef](#)] [[PubMed](#)]
136. Derbyshire, E.J.; Delange, J. Fungal Protein—What Is It and What Is the Health Evidence? A Systematic Review Focusing on Mycoprotein. *Front. Sustain. Food Syst.* **2021**, *5*, 581682. [[CrossRef](#)]
137. Xiong, R.-G.; Zhou, D.-D.; Wu, S.-X.; Huang, S.-Y.; Saimaiti, A.; Yang, Z.-J.; Shang, A.; Zhao, C.-N.; Gan, R.-Y.; Li, H.-B. Health Benefits and Side Effects of Short-Chain Fatty Acids. *Foods* **2022**, *11*, 2863. [[CrossRef](#)] [[PubMed](#)]
138. Nussbaum, N.; von Wyl, T.; Gandia, A.; Romanens, E.; Rühs, P.A.; Fischer, P. Impact of malt concentration in solid substrate on mycelial growth and network connectivity in *Ganoderma* species. *Sci. Rep.* **2023**, *13*, 21051. [[CrossRef](#)]
139. Bezirhan Arikan, E.; Canli, O.; Caro, Y.; Dufossé, L.; Dizge, N. Production of Bio-Based Pigments from Food Processing Industry By-Products (Apple, Pomegranate, Black Carrot, Red Beet Pulps) Using *Aspergillus carbonarius*. *J. Fungi* **2020**, *6*, 240. [[CrossRef](#)]
140. Lin, L.; Xu, J. Production of Fungal Pigments: Molecular Processes and Their Applications. *J. Fungi* **2023**, *9*, 44. [[CrossRef](#)]
141. Mwaheb, M.A.; Hasanien, Y.A.; Zaki, A.G.; Abdel-Razek, A.S.; Al Halim, L.R.A. Fusarium verticillioides pigment: Production, response surface optimization, gamma irradiation and encapsulation studies. *BMC Biotechnol.* **2024**, *24*, 84. [[CrossRef](#)] [[PubMed](#)]
142. Jacobson, M.F.; DePorter, J. Self-reported adverse reactions associated with mycoprotein (Quorn-brand) containing foods. *Ann. Allergy. Asthma. Immunol.* **2018**, *120*, 626–630. [[CrossRef](#)]
143. Dzeladini, L.; Chan, D.; Kummerow, M. P41: A Case Report of Mycoprotein Allergy. *Intern. Med. J.* **2017**, *47*, 17. [[CrossRef](#)]
144. Cardoso Alves, S.; Díaz-Ruiz, E.; Lisboa, B.; Sharma, M.; Mussatto, S.I.; Thakur, V.K.; Kalaskar, D.M.; Gupta, V.K.; Chandel, A.K. Microbial meat: A sustainable vegan protein source produced from agri-waste to feed the world. *Food Res. Int.* **2023**, *166*, 112596. [[CrossRef](#)]
145. Patil, P.J.; Usman, M.; Zhang, C.; Mehmood, A.; Zhou, M.; Teng, C.; Li, X. An updated review on food-derived bioactive peptides: Focus on the regulatory requirements, safety, and bioavailability. *Compr Rev Food Sci Food Saf.* **2022**, *21*, 1732–1776. [[CrossRef](#)]
146. Dean, D.; Rombach, M.; de Koning, W.; Vriesekoop, F.; Satyajaya, W.; Yuliandari, P.; Anderson, M.; Mongondry, P.; Urbano, B.; Luciano, C.A.G.; et al. Understanding Key Factors Influencing Consumers' Willingness to Try, Buy, and Pay a Price Premium for Mycoproteins. *Nutrients* **2022**, *14*, 3292. [[CrossRef](#)]
147. Chezan, D.; Flannery, O.; Patel, A. Factors affecting consumer attitudes to fungi-based protein: A pilot study. *Appetite* **2022**, *175*, 106043. [[CrossRef](#)]
148. Cedeno, F.R.P.; Olubiyo, O.J.; Ferreira, S. From microbial proteins to cultivated meat for alternative meat-like products: A review on sustainable fermentation approaches. *J. Biol. Eng.* **2025**, *19*, 44. [[CrossRef](#)] [[PubMed](#)]
149. Brooker, P.G.; Hendrie, G.A.; Anastasiou, K.; Woodhouse, R.; Pham, T.; Colgrave, M.L. Marketing strategies used for alternative protein products sold in Australian supermarkets in 2014, 2017, and 2021. *Front. Nutr.* **2022**, *9*, 1087194. [[CrossRef](#)] [[PubMed](#)]

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