

Review

Not peer-reviewed version

---

# Innovative Use of Cereals and Starch-Rich By-Products in Single-Cell Protein Production: Opportunities and Challenges

---

[Olumide Joseph Olubiyo](#) and [Sungil Ferreira](#) \*

Posted Date: 9 March 2026

doi: 10.20944/preprints202603.0658.v1

Keywords: mycoprotein; starch by-products; valorization; sustainability; circular bioeconomy



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Review

# Innovative Use of Cereals and Starch-Rich By-Products in Single-Cell Protein Production: Opportunities and Challenges

Olumide Joseph Olubiyo and Sungil Ferreira \*

The University of Arkansas System, Division of Agriculture (UADA), Department of Food Science, Fayetteville, AR 72704, United States of America

\* Correspondence: sunfer@uark.edu

## Abstract

The growing worldwide need for sustainable, high-quality protein sources has intensified interest in single-cell protein (SCP) production, particularly mycoproteins derived from filamentous fungi. Concurrently, the agricultural sector generates vast quantities of starch-rich by-products, such as broken rice, cassava peels, potato waste and cereal processing residues, that remain largely underutilized despite their high carbohydrate content. This literature review examines the potential of starch-based agricultural by-products as low-cost, renewable feedstocks for mycoprotein production. Key topics include the chemical characteristics of starch residues, pretreatment and enzymatic hydrolysis strategies for efficient saccharification and the metabolic suitability of fungal strains such as *Neurospora* and *Fusarium* spp. for biomass and protein synthesis. In addition, the review evaluates optimization of fermentation processes, including maximizing biomass yield and improving overall feedstock valorization to enhance process efficiency. Furthermore, considerations related to process design, environmental benefits and techno-economic feasibility are evaluated in the context of converting starch residues into fungal protein. In summary, the evidence suggests that valorizing starch by-products for mycoprotein fermentation, used as a protein alternative and as an ingredient, represents a promising strategy to reduce waste, lower production costs and support global food sustainability.

**Keywords:** mycoprotein; starch by-products; valorization; sustainability; circular bioeconomy

## 1. Introduction

The global population growth crisis has become one of the most pressing issues of the 21st century, impacting economic, environmental, and social systems worldwide. Over the last decade, the world population has increased exponentially, reaching 8 billion in 2022 and it is expected to exceed 9.7 billion by 2050 (United Nations, 2022). This rapid expansion has buttressed the need for sustainable and efficient food production methods to meet the growing demand for protein and other essential nutrients. Traditionally, animal husbandry has been the fundamental source of protein for human consumption, with global meat production recorded at 371 million tons in 2023 and expected to increase to 500 million tons annually by 2050 (FAO, 2024). However, the environmental degradation of meat production is significant, contributing immensely to greenhouse gas emissions, land and water degradation, and toxicity from pesticides used in feed cultivation (Röös et al., 2013).

This demographic pressure, projected to increase protein requirements by 30–50% in developing regions, has catalyzed innovations in plant-based proteins like pea and soy isolates, which mimic meat textures in products from companies such as Beyond Meat and Impossible Foods, offering complete amino acid profiles with lower environmental footprints (GFI, 2024; Poore & Nemecek, 2018). Similarly, alternative protein platforms have emerged to address sustainability and nutritional challenges associated with conventional animal proteins. Mycoprotein derived from filamentous

fungi, such as *Fusarium venenatum* used in Quorn products, provides high protein content and dietary fiber while enabling scalable production from low-cost agricultural substrates (Finnigan et al., 2019). In parallel, cultivated meat technologies aim to replicate animal proteins at the cellular level with substantially lower greenhouse gas emissions while insect- and algae-based proteins offer protein-rich, nutrient-dense options that are increasingly adopted in global food and feed markets to meet rising future protein demands (Caporgno & Mathys, 2018; van Huis, 2020;Tuomisto & Teixeira De Mattos, 2011). These alternatives collectively mitigate the protein gap by diversifying sources, reducing reliance on land-intensive farming, and enhancing nutritional equity, though scalability and consumer acceptance remain key hurdles (Santo et al., 2020).

Agricultural and agro-industrial by-products, including crop residues, bran, spent grains, and fruit processing wastes, remain largely underutilized despite their abundance and nutritional potential, often being diverted to low-value uses or disposal (Ayoo et al., 2020). This inefficiency, driven by factors such as high moisture content, lignocellulosic recalcitrance, and contamination risks, results in significant environmental burdens and economic losses, while representing a missed opportunity for sustainable valorization within the bioeconomy (Lynch et al., 2016; Ravindran & Jaiswal, 2016). However, recent literature highlights their substantial potential as feedstocks for mycoprotein production, where filamentous fungi such as *Fusarium venenatum* or *Neurospora crassa* can ferment these residues into protein-rich biomass (45–60% protein dry weight) via solid-state or submerged fermentation, converting low-cost substrates like wheat bran or rice husks into edible mycoprotein with complete amino acid profiles and high digestibility (Souza Filho et al., 2018). Nevertheless, comprehensive studies focusing on the valorization of specific agricultural by-products, particularly starch-rich grains, for single-cell protein production remain limited, especially with respect to their potential contributions to sustainability goals (Betoret et al., 2024).

This review examines the potential use of cereal by-products (brewers’ spent grains and broken rice kernels) as well as starch-rich agro-industrial by-products (potato peel waste and cassava bagasse) substrates for single-cell protein production and considers the broader implications of this utilization for the development of sustainable food systems.

1.1. Method

This literature review examines the current state of knowledge on the conversion of agricultural by-products, specifically upcycled starch-based grains, into single-cell protein via microbial fermentation processes. The review synthesizes evidence from peer-reviewed journals, books, and other scholarly sources identified through systematic searches using the Google Academic search engine. The literature considered spans publications from 1866 to 2025.

1.2. Production and Consumption of Animal Proteins

Animal protein has long been a staple in human diets, offering a rich source of essential amino acids, vitamins and minerals. In the food industry, animal-derived proteins like meat, dairy and eggs play pivotal roles in both traditional and processed foods due to their nutritional value, taste and functional properties. Traditional meat proteins are obtained from livestock and poultry production systems, including cattle, poultry, pigs, and sheep, as well as from seafood sources (Adejumo & Adebisi, 2024). According to the Food and Agriculture Organization (2023) and data summarized by OurWorldinData (Table 1), livestock production and consumption have skyrocketed in recent decades.

Table 1. Global meat production between 1960 and 2022.

| Region | Production per year |                     |                 |
|--------|---------------------|---------------------|-----------------|
|        | 1961 (million tons) | 2022 (million tons) | Relative change |

|               |        |         |        |
|---------------|--------|---------|--------|
| Africa        | 3.681  | 22.742  | +518%  |
| Asia          | 9.034  | 155.082 | +1617% |
| Europe        | 29.454 | 59.082  | +101%  |
| North America | 19.582 | 63.992  | +227%  |
| Oceania       | 2.296  | 6.537   | +185%  |
| South America | 6.516  | 48.023  | +637%  |

Source: Data obtained from FAO-United Nations (2025).

The world yearly production of meat increased from 70.563 million tons in 1961 to 355 million tons in 2022 with the Asian region emerging as the leading region in meat production, accounting for a significant share of the total global output. In 2023, China produced about 96.41 million metric tons of meat, pork dominated with 57.94 million metric tons accounting for about 60% of national meat output, followed by poultry at 24.31 million metric tons accounting for about 20% and beef and veal at 8.62 million metric tons accounting for 8.9% (Statista, 2025). The United States, the second-largest meat producer and the largest poultry producer globally, produced 48 million metric tons of meat in 2023. Poultry meat (broiler chicken) accounted for 21 million metric tons, representing 44% of its total meat production that year. Pork, beef, and turkey comprised 26%, 25%, and 4% of the production, respectively, while other varieties such as lamb and mutton accounted for less than 1% (FAO, 2024; Statista, 2025). Consumption has accompanied this production growth, with the global consumption in 1961 and 2013 for beef and buffalo, pork, poultry and sheep and goat showing a 39.23, 87.5, 100.1 and 8.02 million tons increase respectively. This consumption growth is projected to continue with an expected 36% consumption increase in buffalo and beef, 21% for pork, 40% for poultry and 44% for sheep and goat by 2050 (FAO, 2025).

1.3. Nutritional, Functional, Sensorial and Religious Reasons of Meat Consumption

Humans consume meat for consumption for various reasons, including its high nutritional density, functionality, and cultural significance (Leroy et al., 2023). For instance, consumers accept and enjoy the flavor and roasted aroma of meat seasoned with sugars. This characteristic meat-like flavor arises from Maillard reactions between amino acids and reducing sugars, a process that is further enhanced by lipid degradation during cooking, leading to the formation of brown coloration and desirable flavor compounds (Mottram, 1998). Thermal degradation of lipids, present as triglycerides, phospholipids, and free fatty acids, via oxidation, pyrolysis, and Maillard-related pathways generates reactive carbonyls and heterocyclic volatiles responsible for roasted, meaty, and caramelized aromas, while saturated fatty acids such as palmitic and stearic acids decompose into aldehydes, ketones, and alcohols that contribute fatty and waxy flavor notes (Li et al., 2021; Mottram, 1998).

Conversely, unsaturated fatty acids, particularly polyunsaturated acids such as linoleic and arachidonic acids, are essential for meat flavor (Wang et al., 2021). They oxidize into a more complex array of aromatic volatile compounds like hexanal, nonanal, and other volatiles, contributing to green, grassy or fatty notes. However, the oxidation of omega-3 fatty acids, prevalent in fish or grass-fed beef, can introduce flavors described as fishy or metallic which are often not preferred (Shahidi & Pegg, 1994). Lipid profiles vary among meat species, influencing the flavor compounds produced. Beef, which is rich in oleic acid and saturated fats, generates compounds such as 2,3-octanedione and



2-methyl-3-furanthiol, contributing to its roasted, beefy aroma. Pork, with its higher linoleic acid content, produces more hexanal and pentanal, which creates its distinctive 'porky' flavor. Poultry, due to its unique fatty acid composition, develops milder grilled or savory flavors attributed to the presence of arachidonic and linoleic acids. Lamb's flavor is characterized by branched-chain fatty acids, such as 4-methyloctanoic acid, which impart its signature 'sheep-like' notes (Elmore et al., 2005; Jones & Woods, 1986).

The texture of meat is widely regarded as a critical determinant of product quality and a key factor influencing consumer acceptance and purchasing decisions. Tenderness, juiciness, and chewiness, the three principal textural attributes, depend significantly on muscle composition, the degree of connective tissue, and the meat's water-holding capacity (WHC). Myofibrillar proteins and collagen are two key protein components responsible for meat texture. Collagen transforms into gelatin upon heating, contributing to the gelling properties required for products like sausages, pâtés, and gelatin-based items. This gelling not only affects mouthfeel and firmness but also helps bind meat particles, creating a cohesive structure in processed meats. Proteins such as actomyosin form a matrix that holds other ingredients together, ensuring product integrity (Huff-Lonerger & Lonergan, 2005; Chang et al., 2011).

Myofibrillar proteins also play a vital role in water retention, with WHC being influenced by factors such as pH, ionic strength, and muscle structure integrity. High WHC reduces cooking loss, preserving meat's moisture and sensory qualities, while also impacting economic factors by minimizing weight loss during processing (Huff-Lonerger & Lonergan, 2005). The emulsification of meat products is facilitated by the amphiphilic nature of muscle proteins, which stabilize fat and water. Pork and poultry proteins are particularly effective at this, enabling even dispersion of fat in products such as emulsified sausages. This not only enhances sensory qualities but also extends shelf life by preventing fat separation. Maintaining stable emulsions is essential for ensuring consistent texture and flavor (Jime'nez-Colmenero et al., 2001).

Beyond these technical attributes, the consumption of meat has deep cultural roots. Throughout human history, meat has been more than sustenance; it has served as a symbol of status, celebration, and cultural identity. In many cultures, meat consumption is intertwined with religious rituals, social interactions, and economic prosperity. For instance, lamb is central to the celebration of Easter in many Christian cultures, while pork plays a significant role in the Chinese New Year celebrations. Additionally, the act of sharing meat can strengthen social bonds, symbolizing hospitality and prosperity. Meat's role in cultural traditions further emphasizes its importance beyond just its nutritional and functional properties (Fiddes, 2004).

#### *1.4. Meat Production Environmental Impact*

Despite the functional and nutritional benefits of meat, production and consumption have significant impacts on the environment, notably contributing to the greenhouse effect and other ecological challenges. The greenhouse gases (GHG) emitted through livestock farming include methane (CH<sub>4</sub>), primarily from enteric fermentation in ruminants like cattle; nitrous oxide from manure management and fertilizer use for feed crops; and carbon dioxide (CO<sub>2</sub>) from deforestation and land use changes (Gerber, 2013). Methane, although short-lived compared to CO<sub>2</sub>, has a high global warming potential, with estimates suggesting it is 28 to 36 times more effective at trapping heat than CO<sub>2</sub> over a 100-year period (Shindell et al., 2013).

Although comparing the environmental impact of traditional meat across studies is challenging due to difference in functional unit and country of evaluation, beef/cattle production has been identified as one of the largest contributors to the livestock sector's environmental footprint, with emissions ranging from 80 to 99.48 kg CO<sub>2</sub>-eq per kilogram of meat produced. This can be attributed to methane emissions from enteric fermentation, extensive land use, and the long maturation period of cattle. Additionally, cattle ranching has been established as a primary driver of deforestation, particularly in the Amazon region (Gerber et al., 2013; Strassburg et al., 2014). Pork production emits less GHG than beef but more than poultry, with emissions estimated between 10 and 12.31 kg CO<sub>2</sub>-

eq per kilogram of meat, mainly from feed production, manure management, and energy use in farming and processing (Poore & Nemecek, 2018). Although pigs do not produce methane at the same level as ruminants, their concentrated waste systems still pose environmental risks. Poultry has the lowest GHG emissions of the three, with about 6 kg CO<sub>2</sub>-eq per kilogram of chicken meat (Leip, 2010; de Vries & de Boer, 2010). The shorter life cycle to slaughter and efficient feed conversion reduces emissions, but the scale of production can lead to substantial environmental impacts, particularly in terms of water and air pollution from concentrated animal feeding operations (Walker et al., 2005).

In conclusion, these environmental and cultural implications of meat consumption, combined with the specific functional properties that dictate meat quality, highlight the complex position of this food source in the modern world. There is a need for sustainable meat and protein production strategies and the exploration of meat alternatives that can balance nutritional needs, cultural preferences, and environmental impacts. This review will explore mycoproteins as one potential solution, examining their fermentation from *Neurospora crassa* using rice as a carbon source.

2. Single-Cell Protein

Single-cell protein (SCP) refers to protein-rich biomass derived from microorganisms such as bacteria, yeasts, fungi, and algae, cultivated on various carbon sources for use as nutritional supplements in human food, animal feed, and aquaculture (Ugalde & Castrillo, 2002). First introduced in 1966 by Carroll Wilson to replace less appealing terms like “microbial protein,” SCP, also known as microbial biomass, typically contains more than 300 g/kg protein (dry weight) and is distinguished from single-cell oils (SCO), which can contain up to 800 g/kg lipids (Chamodi et al., 2025; Galán et al., 2019). Although the deliberate use of microorganisms in foods dates back thousands of years, modern SCP production gained prominence during the two World Wars, when yeasts such as *Saccharomyces cerevisiae* and *Candida utilis* were cultivated at scale to mitigate protein shortages. Commercial developments continued through the 1970s with products such as pruteen and, more successfully, with mycoprotein from Quorn, produced via submerged fermentation since 1985 (Trinci, 1994; Ye et al., 2024). SCPs offer several advantages over conventional protein sources, including balanced amino acid profiles, low fat content, high protein-to-carbohydrate ratios, rapid microbial growth, and independence from agricultural land, climate conditions, or seasonal variability (Sharif et al., 2021).

Table 2. Nutrient composition of SCP from different sources.

|            | Protein | Fat  | Ash  | Nucleic acid |
|------------|---------|------|------|--------------|
| Fungi      | 30-45   | 2-8  | 9-14 | 7-10         |
| Macroalgae | 40-60   | 7-20 | 8-10 | 3-8          |
| Yeast      | 45-55   | 2-6  | 5-10 | 6-12         |
| Bacteria   | 50-65   | 1-3  | 3-7  | 8-12         |

Source: Li et al. (2024).

SCP systems may be first generation or second generation. First-generation SCP systems rely on microorganisms converting food-grade substrates such as sugars and raw food crops into biomass, whereas second-generation approaches incorporate agricultural residues (co-products or by-products) and other nonfood feedstocks, along with genetically engineered strains and advanced

bioreactor designs, to improve yields and reduce production costs (Abdul Manan & Webb, 2017; Braho et al., 2024). These innovations also enable the exploration of specialty proteins such as bioactive peptides. SCP production differs from cultured meat in that it focuses on microbial protein rather than animal cell proliferation; inactivated microbial cells may be fed directly to animals, while SCP intended for human consumption typically undergoes additional purification (Post, 2012; Ugalde & Castrillo, 2002). By leveraging low-cost substrates, including agro-wastes such as fruit peels or sugarcane bagasse, SCP contributes to sustainable protein production and aligns with global efforts to reduce food loss and waste under Sustainable Development Goal 12 (United Nations, 2025).

Single-cell proteins contain essential vitamins, amino acids, minerals, nucleic acids, and lipids, enabling their use not only in food and feed applications but also in broader industrial sectors such as paper manufacturing (Khumchai et al., 2022). Their production draws from a wide variety of carbon sources, including sugars and starches, as well as side streams and waste substrates such as fruit residues, molasses, methane, methanol, ethanol, and other combustible by-products (Rodero et al., 2024). In particular, SCP generated through gas fermentation has gained significant interest, as syngas ( $\text{CO}/\text{H}_2$ ) and biogas ( $\text{CH}_4$ ) can be derived from numerous waste biomass streams, while  $\text{H}_2/\text{CO}_2$  systems enable the direct recycling of carbon dioxide from industrial emissions or atmospheric capture (Li et al., 2024; Rodero et al., 2024). The ability to convert low-cost or waste-derived inputs into high-value protein-rich biomass offers considerable environmental and economic advantages, reducing reliance on conventional agricultural resources while mitigating waste accumulation and greenhouse gas emissions.

### 2.1. Fungal Scp as Alternative Protein

Alternative proteins are proteins derived from non-traditional sources of proteins. They can be classified based on their source such as plants, microbial, cultured and algae. In recent times, several of these proteins have been studied and developed for commercial use, employing modern extraction methods that highlight their potential as sustainable replacements for animal-based proteins, with plant-based proteins currently leading the food industry as most utilized (Pojić et al., 2018). Non-traditional proteins sources such as soybean, almonds, and rice-based milk alternatives, extracted using novel extraction techniques like high-pressure processing, microwave-assisted extraction and ultrasound-assisted extraction, have gained popularity among consumers seeking healthier, environmentally friendly options. However, challenges related to sensory attributes, allergenicity and functional properties have limited their broader acceptance (Jeske et al., 2018). Boye et al., 2010 studied the functional properties of protein concentrates from yellow pea, chickpea and lentil extracted using ultrafiltration and isoelectric precipitation methods. Although these pulses showed high protein content yield and certain functional properties improvement (excluding water holding capacity), there were notable variations depending on the type of pulse. However, the functional properties and protein profile of these concentrates remained inferior to those of animal protein and soy proteins.

Consumers consider a good alternative protein as one that closely replicates the sensory and functional characteristics of traditional meat while aligning with their dietary restrictions. Soy protein, a common ingredient in plant-based meat analogues, is especially valued for its high protein content, evidenced by a Protein Digestibility Corrected Amino Acid Score (PDCAAS) of 1, and for its functional versatility in creating meat-like textures (Hertzler et al., 2020). Similarly, pea protein combined with wheat gluten has become prominent due to the wheat gluten's ability to enhance flavor and sensory qualities in meat analogues. However, concerns over allergies and sensitivities associated with these meat analogues have limited their broader adoption. Several studies have examined the protein digestibility of meat analogues compared to animal meat. Zhou et al. (2021) and a team of colleagues conducted an in-vitro comparison of the protein digestibility and gastrointestinal behavior of meat analogues with that of beef, finding that proteins in beef were more easily digested in the stomach than those in soy-based meat analogues. Similarly, Reynaud (2021) investigated the digestible indispensable amino acid score (DIAAS) and true ileal amino acid

digestibility (TID) of plant-based proteins, comparing gel and emulsion forms. The study concluded that protein digestibility is influenced by both the protein source and processing methods. These differences can be attributed to the structural properties of plant-based meat analogues. Mycoprotein, a protein-rich biomass derived from the fungal fermentation of the filamentous fungus *Neurospora crassa*, has gained notable attention in recent years as an attractive alternative protein source due to its nutritional profile and environmental sustainability. Although mycoprotein has a lower immediate protein digestibility compared to whey protein isolate, it has an amino acid profile comparable to meat and a higher essential amino acid content than plant-based proteins (You et al., 2024; Ahangi et al., 2008).

## 2.2. Evolution of Mycoprotein as Alternative Protein

The journey of *Neurospora crassa* as a mycoprotein source for meat alternatives can be traced back to its natural occurrence and historical use in food. *Neurospora crassa*, commonly known as red bread mold, has been part of human dietary practices, particularly in Southeast Asia, where it is used to produce “oncom”, a fermented food like tempeh. Oncom is made from by-products like peanuts press cake or okara (soybean residue), showcasing *N. crassa*’s ability to convert agricultural waste into nutritious food (Perkins & Davis, 2000).

*N. crassa* first gained scientific attention not for its food potential but for its utility in genetic research. Its life cycle, ease of cultivation and well-characterized genetics made it a model organism for genetic studies beginning in the mid-20th century. The work of George Beadle and Edward Tatum on *N. crassa* in the 1940s, which earned them a Nobel Prize in the 1940s, highlighted its role in understanding gene function, laying the groundwork for its later exploration in food science.

The shift toward considering *Neurospora crassa* as a mycoprotein for food applications came with increased interest in sustainable protein sources amid growing concerns about the environmental impact of traditional meat production. Unlike *Fusarium venenatum*, the fungus behind the well-known mycoprotein Quorn, *N. crassa* has a broader historical use in food and it is known not to produce mycotoxins even under stress, which might ease regulatory approval and consumer acceptance (FDA, 2025; Z. Wang et al., 2022). Early studies focused on the safety and nutritional profile of *N. crassa* mycoprotein. Research confirmed its long history of safe use in Asian cuisines, high protein content (up to 45% dry weight), essential amino acid composition comparable to animal proteins, and the presence of beneficial nutrients like dietary fiber, vitamins and minerals (Perkins, 1992). Furthermore, the application of biotechnological techniques such as submerged fermentation and solid-state fermentation has been pivotal in scaling up production from *N. crassa*. These methods allow for high yields of biomass with controlled nutritional content, effectively adapting traditional fermentation processes to modern industrial standards (Singh Nee Nigam & Pandey, 2009).

Mycoprotein, produced from the filamentous fungus *Fusarium venenatum*, was first developed in the 1960s when concerns over global food security led to efforts to identify alternative protein sources that could be produced efficiently (Wiebe, 2002). Initial research by British scientists, who focused on fungal fermentation to produce protein-rich biomass, eventually led to the commercial product known today as Quorn, which was introduced in the UK in the 1980s. Advancements in fermentation technology have driven the evolution of mycoprotein. Unlike traditional livestock protein, which requires extensive resources, mycoprotein is produced through continuous fermentation in controlled conditions, significantly reducing land, water, and energy use and offering a more environmentally efficient alternative (Finnigan et al., 2019). Consumer acceptance has been essential to the evolution of mycoprotein. Initially, its market was limited to the UK; however, as global demand for sustainable proteins has increased, Quorn and other mycoprotein-based products have expanded into markets across the United States, Europe, and Asia. Today, mycoprotein is among the leading single-cell protein sources, appealing to vegetarians, flexitarians, and individuals concerned with the environmental impact of conventional meat production, with its health and nutritional benefits being primary factors in consumer choice (Dean et al., 2022). Further research is needed focusing on optimizing mycoprotein production to improve texture, flavor, and nutritional



properties. Additionally, developments in genetic and metabolic engineering may allow enhanced strains with higher nutrient density and digestibility. However, challenges remain, including reducing production costs to make mycoprotein more accessible and addressing regulatory issues in new markets.

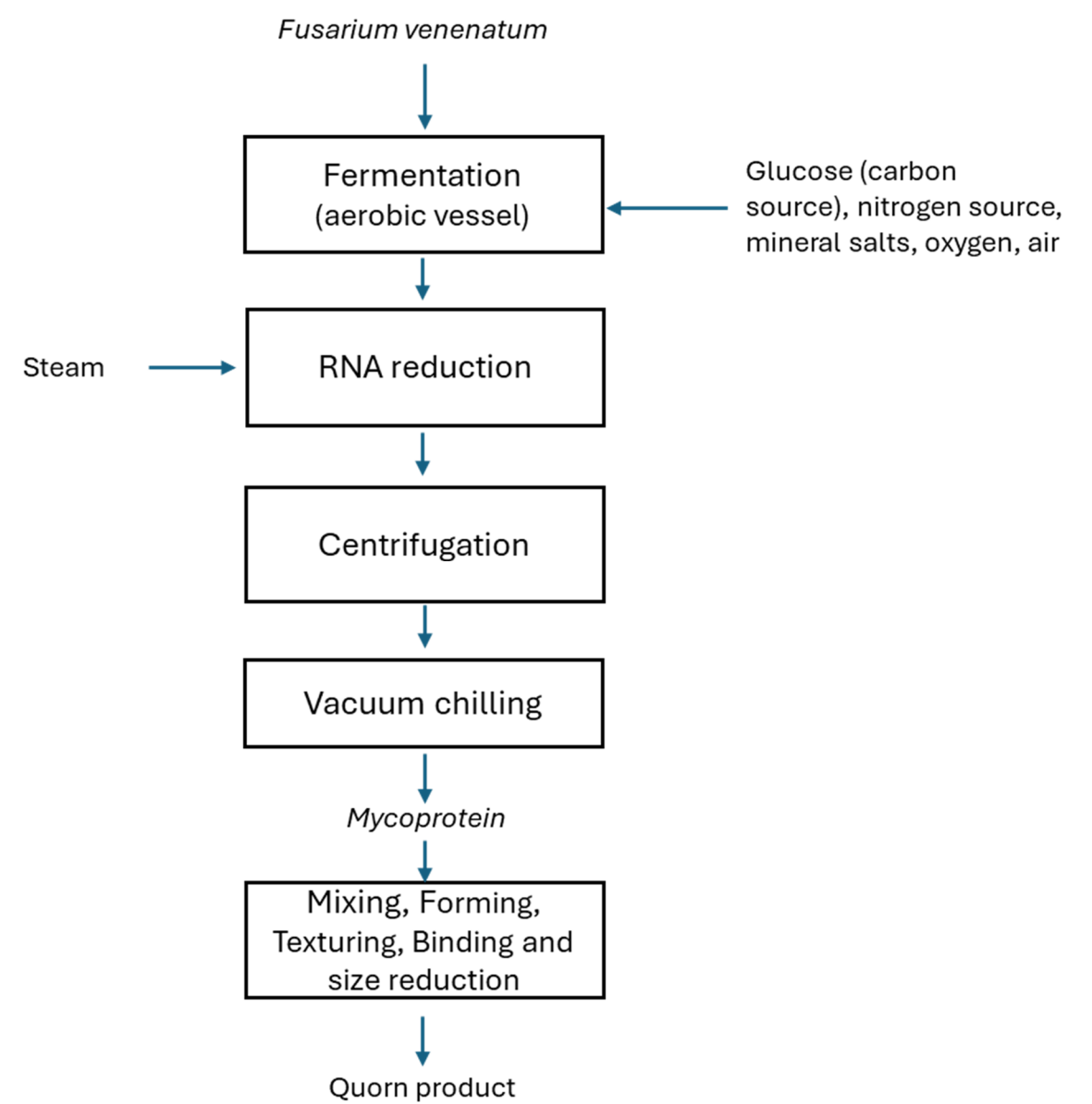
### 3. Fermentation

Fermentation has been a fundamental process in the food industry for thousands of years, transforming the culinary landscape and preserving food long before the advent of modern food processing and preservation techniques. The earliest evidence of fermentation dates to around 7000 BCE in the Fertile Crescent (crescent shaped region in the middle east), where archeological findings suggest that fermented beverages like beer and wine were produced (McGovern, 2009). These practices were not only used for creating alcohol but also for preserving grains and fruits that would otherwise spoil quickly. In Asia, fermentation was pivotal in producing foods like soy sauce, miso and various fermented foods vegetables such as kimchi and sauerkraut, which originated from preservation of cabbage by Germanic tribes around 1000 BCE (Steinkraus, 1996). These foods not only extended shelf life but also enhanced flavor, nutrition and digestibility. By the Middle Ages in Europe, fermentation had become central to bread making, with yeast fermentation enabling the production of leavened bread. The Industrial Revolution in the 19th century marked a significant shift toward understanding fermentation at a scientific level, as Louis Pasteur's work in the 1850s established the role of microorganisms in fermentation processes (Pasteur, 1866). This breakthrough laid the foundation for controlled fermentation in food production, leading to the development of modern fermented dairy products such as cheese and yogurt. In the 20th century, fermentation expanded into industrial applications, including the production of antibiotics like penicillin, demonstrating its role beyond food preservation to include health benefits (Chain et al., 1940). Today, fermentation is widely used in the production of various foods, from traditional items like beer, wine, cheese, and bread to emerging applications in alternative proteins, probiotics and meat substitutes.

Mycoprotein, commonly produced through the fermentation of *Fusarium venenatum*, has been extensively described in literature, with few modifications by Edwards (1986), followed by comprehensive process analyses by Trinci (1994). Industrial manufacture is based on submerged, continuous, aerobic fermentation conducted in large, aseptic stainless-steel airlift bioreactors, typically pressure-cycle vessels with volumes above 130,000 L. In this system, *F. venenatum* is cultivated under nutrient-excess conditions with a continuous supply of glucose as the primary carbon source and ammonium as the nitrogen source, supplemented with essential vitamins and minerals, while critical operational parameters, including temperature (28–30 °C), pH (~6.0), and carbon dioxide evolution, are tightly regulated to sustain rapid growth, ensure process stability, and maintain high productivity. Under these optimized conditions, the fungus attains specific growth rates of 0.17–0.20 h<sup>-1</sup>, generating approximately 300–350 kg of dry biomass per hour, while continuous withdrawal and replacement of the culture medium every 5–6 hours maintain a constant fermenter volume (Trinci, 1994; Wiebe, 2002). Figure 1 shows a flowchart of the production of Quorn mycoprotein.

After fermentation, the harvested culture is subjected to an RNA reduction step, which is essential due to the inherently high RNA content of fungal biomass (approximately 10% on a dry weight basis). This step aims to lower purine intake and reduce the risk of hyperuricemia-related diseases, by applying controlled thermal treatment to activate endogenous ribonucleases (Denny et al., 2008). Traditional protocols involve heating the biomass to 64–65 °C for 20–30 minutes; however, more recent approaches use rapid heating above 68 °C, optimally at 72–74 °C, which enhances protein retention and decreases biomass losses from roughly 35–38% to 30–33% (Wiebe, 2002). The process subsequently includes heating to 90 °C, centrifugation to remove liberated nucleotides, and concentration of the mycelium into a paste containing more than 20% solids. This concentrated biomass is then combined with binding agents, such as egg albumen, and mechanically aligned to

produce a fibrous texture analogous to meat, facilitating the manufacture of a wide range of food products, including mince, chunks, fillets and steaks (Denny et al., 2008; Wiebe, 2002).



**Figure 1.** Flowchart of *Fusarium venenatum* mycoprotein production.

3.1. Types of Fermentation and Technological Advances of Fermentation

Fermentation can be broadly classified into two main types: solid-state fermentation (SSF) and submerged fermentation (SMF) (Cedeno et al., 2025). Solid-state fermentation involves the growth of microorganisms on solid substrates with low moisture content. SSF is widely used in Asia for producing traditional foods such as koji, which is essential for soy sauce and sake production, as well as tempeh. This method offers several advantages, including lower water requirements, reduced energy costs, and the ability to utilize agricultural by-products (Pandey et al., 2009).

SSF closely mimics the natural growth conditions of many fungi and bacteria involved in food fermentation. For this reason, it is commonly employed in propionic fermentation, which is essential for Swiss cheese production. In this process, propionibacteria convert lactic acid into propionic acid and carbon dioxide, creating the characteristic holes and distinctive flavor of Swiss cheese (Fox et al., 2000). Conversely, submerged fermentation (SMF) involves the growth of microorganisms in a liquid medium and is commonly used in the production of antibiotics and metabolites. This method allows

for better control of key conditions such as oxygenation, temperature, and pH, making it more efficient for large-scale biomass or metabolite production (Stanbury et al., 2008). However, SSF has been observed to yield higher levels of enzymes and  $\beta$ -glucans from hulled barley compared with submerged fermentation SMF (Lee & Ra, 2021)

In the food industry, SMF is utilized in various fermentation processes, including lactic acid, alcoholic, and acetic acid fermentation. Lactic acid fermentation involves lactic acid bacteria converting sugars into lactic acid, as seen in foods like sauerkraut, kimchi, and yogurt. This process improves the nutritional value and shelf life of the product by inhibiting microbial spoilage (Hutkins, 2007). Alcoholic fermentation, driven by yeasts, converts sugars into alcohol and carbon dioxide, playing a crucial role in brewing beer, making wine, and leavening bread, thereby enhancing both preservation and flavor (Boulton et al., 1999). Acetic fermentation, carried out by bacteria such as *Acetobacter*, converts ethanol into acetic acid, a vital process in vinegar production that contributes to both preservation and taste (Soibam et al., 2014).

Despite its many benefits, fermentation faces several challenges. One significant challenge is the risk of contamination by unwanted organisms, which can spoil the fermented product, alter its taste or even pose health risks. This is common in various types of fermentation, as noted by Hutkins (2007), who discussed the importance of hygiene in preventing contamination in lactic acid fermentation. Additionally, Stanbury et al. (2008) highlighted that fermentation can be time-consuming, requires high energy inputs and lack precise control over factors such as temperature, pH and oxygen, particularly in large-scale production. Variabilities in solid-state and submerged fermentation can also lead to inconsistencies in product quality (Pandey et al., 2009). Lastly, consumer acceptance remains a challenge, as novel fermented products may face resistance due to unfamiliar flavors or misconceptions about fermentation and genetically modified organisms (GMOs), similar to perception issues in synthetic biology applications (Paddon et al., 2013).

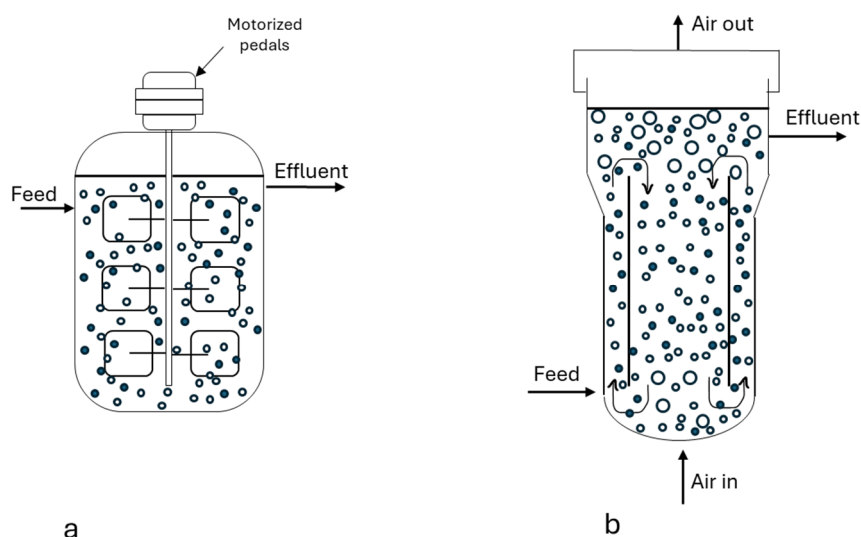
Recent technological advances have significantly improved the efficiency of fermentation processes despite their drawbacks. The advent of precision fermentation, also known as cell factory engineering, has revolutionized microbial production by leveraging molecular biology and metabolic engineering techniques to construct microorganisms optimized for high-yield production of specific target compounds. This approach allows for more controlled, predictable and scalable fermentation, while expanding the ability to produce a wider range of products beyond the natural capabilities of microbes. One key advantage of precision fermentation is its ability to produce high-value, specific proteins without relying on animal sources, thereby reducing environmental impact. However, high production costs, consumer skepticism and regulatory complexities associated with this emerging technology remain significant hurdles for large-scale commercial adoption (Chai et al., 2022). Numerous studies have explored the potential of precision fermentation techniques to enhance traditional food fermentation processes. Augustin et al. (2024) reviewed several of these advancements, highlighting the patent prospects as well as the business and market potential for major fermentation-derived food ingredients.

Similarly, high-throughput screening (HTS) has enabled the rapid identification and optimization of microbial strains. Like precision fermentation, HTS aims to optimize biological processes, though this optimization may come at a high equipment cost. Despite this, HTS accelerates product development and enables the screening of a vast number of strains. However, its cost and complexity make it less feasible as a routine production tool for smaller-scale operations. Several studies have explored the potential of HTS in identifying beneficial microbial strains. For example, Wang et al. (2022) used HTS for identifying mutant strain of *Saccharomyces cerevisiae* with enhanced ethanol production. Their research reported a 20.5% increase in ethanol yield and an 81.6% increase in sucrose utilization using the optimized strain (Wang et al., 2022).

Furthermore, metabolic engineering represents a significant advancement in fermentation technology. This technique involves modifying microbial pathways, gene editing, or enzyme enhancement to improve efficiency and increase the yield of desired compounds. Substantial efforts have been made to engineer *Saccharomyces cerevisiae* to co-ferment D-xylose and L-arabinose, two

prevalent sugars in lignocellulosic hydrolysate, thereby boosting ethanol yields by 20–40%. Similarly, considerable efforts have been made to minimize glycerol formation during bioethanol production using *S. cerevisiae*. Glycerol accumulation can be reduced by deleting the genes encoding cytosolic NADH-dependent glycerol-3-phosphate dehydrogenases, GPD1 and GPD2. However, this modification has been observed to impact both growth and ethanol productivity (Nielsen et al., 2013).

Lastly, advanced bioreactors (fermenters) provide better mixing and aeration, improving performance and consistency of both SSF and SMF. Automated monitoring systems and advanced control algorithms also enable tighter regulation of crucial fermentation parameters like pH, temperature and dissolved oxygen levels of bioreactors. These enhanced control and monitoring capabilities improve scalability, efficiency and versatility in various fermentation processes over time. However, like precision fermentation and HTS, the high costs associated with complex bioreactor setups remain a significant barrier to adoption, particularly for smaller producers. Several studies have demonstrated the benefits of advanced bioreactor designs in food fermentation. For instance, Fink et al. (2021) investigated the use of Biolector micro-bioreactors as a high-throughput screening platform for *E. coli* clones producing recombinant proteins for biopharmaceutical applications. Their findings show strong transferability between micro-bioreactor screening data and performance observed in fully controlled fed-batch bioreactors, with consistent clone growth, expression profiles, and ranking. Figure 2 shows airlift and stirred tank bioreactors used in fungal biomass production.



**Figure 2.** Examples of bioreactor designs: a. Stirred tank and b. Airlift bioreactors.

#### 4.0. Agricultural and Agro-Industrial Byproducts

Agro-industrial waste, also referred to as agro-waste, is broadly defined as the unwanted or unsalable materials generated from agro-industrial processing activities, encompassing residues from food manufacturing, beverage production, and related operations (Zhang et al., 2021). These waste streams are commonly underutilized and are often disposed of through landfilling, incineration, or low-value applications, contributing to environmental pollution and resource inefficiency (Solanki et al., 2024). However, for the purpose of this review, we would be limiting our analysis to some agricultural/agro-industrial co-products and by products.

Many of these materials, whether co-products or by-products, contain valuable carbohydrates, lipids, proteins, vitamins, and minerals that can be repurposed to mitigate the environmental and economic impacts associated with their disposal (Megavitry & Silamat, 2024).

Cereal by-products are generated during the industrial processing of grains such as wheat, corn, and barley, including milling, brewing, and starch or ethanol production. During these processes, valuable components such as the nutrient-rich germ, fiber-dense bran, hulls, and gluten are separated



from the starchy endosperm, which serves as the primary source of flour and starch (Bamigbade et al., 2025). Upcycling byproducts are dependent on the nature of these byproducts and yield of useful compounds to be obtained responsibly. This approach provides an opportunity to convert underutilized biomass into high-value microbial proteins, thereby addressing food waste and supporting a circular bioeconomy (Koukoumaki et al., 2024; Rasool et al., 2023).

5. Starch

Starch, a polymeric carbohydrate composed of numerous glucose units linked by glycosidic bonds, serves as the primary energy storage molecule in plants and a crucial dietary component for humans, supplying significant nutritional sustenance (Rashwan et al., 2024). Similarly, animals store glucose as glycogen, a structurally analogous but more highly branched polysaccharide that fulfills the same role as starch in plants. This highly branched glucose homopolymer is densely packed and serves as a temporary or long-term energy reserve, produced by plants because of photosynthesis (Junejo et al., 2022).

Starch, a major dietary carbohydrate widely present in cereal grains (e.g., maize, wheat, rice, sorghum, and barley) and tuber crops (e.g., potato, cassava, yam, and sweet potato), consists primarily of two polysaccharides: amylose, a predominantly linear  $\alpha$ -1,4-linked glucan, and amylopectin, a highly branched polymer containing  $\alpha$ -1,6 linkages. Variations in the proportion and molecular architecture of these components influence key physicochemical properties, such as gelatinization, retrogradation, and rheological behavior, which in turn determine starch functionality in food systems, including its roles as a thickener, stabilizer, gelling agent, emulsifier, and fat replacer (Rashwan et al., 2024; Wang et al., 2024). Table 3 presents the percentages of total starch, amylose, amylopectin, and relative crystallinity across various cereals, roots, and tubers, thereby illustrating the functional diversity of starch and its varied applications within the food industry.

**Table 3.** Total starch, amylose, amylopectin and relative crystallinity of some cereal, roots and tubers.

| Starch       | Amylose (%) | Amylopectin (%) | Ratio |    | Relative crystallinity | References                |
|--------------|-------------|-----------------|-------|----|------------------------|---------------------------|
| Wheat        | 20-30       | 70-80           | 20:80 | to | 27-30                  | Prückler et al. (2014)    |
|              |             |                 | 30:70 |    |                        |                           |
| Rice         | 15-35       | 65-85           | 15:85 | to | 34                     | C. Zhang et al. (2023)    |
|              |             |                 | 35:65 |    |                        |                           |
| Rice (waxy)  | <1          | >99             | <1:99 |    | 30-35                  | Waterschoot et al. (2015) |
| Maize (corn) | 25-30       | 70-75           | 25:75 | to | 32-33                  | Ranum et al. (2014)       |
|              |             |                 | 30:70 |    |                        |                           |

|              |       |       |                |       |                           |
|--------------|-------|-------|----------------|-------|---------------------------|
| Maize (high) | >50   | <50   | >50:<50        | 20-25 | Li et al. (2008)          |
| Potato       | 20-30 | 70-80 | 20:80 to 30:70 | 37-38 | Waterschoot et al., 2015  |
| Sweet potato | 15-25 | 75-85 | 15:85 to 25:75 | 33    | Singh et al. (2003)       |
| Cassava      | 15-25 | 75-85 | 15:85 to 25:75 | 38-40 | Pulido Diaz et al. (2016) |
| Yam          | 20-30 | 70-80 | 20:80 to 30:70 | 25-35 | Riley et al. (2006)       |
| Maize (waxy) | <1    | >99   | <1:99          | 35-40 | (Buléon et al., 1998)     |

Starch-derived materials are widely used in numerous sectors, such as food, textiles, plastic, cosmetics, adhesives, and pharmaceutical industries. However, native starch performs poorly in processing, often requiring modification to enhance its functional properties for specific applications (Bashir & Aggarwal, 2019; Dar et al., 2018). Several methods are employed to modify native starch, aiming to enhance or suppress its intrinsic attributes or confer specific properties to align with industrial needs. These modifications are broadly divided into four main categories: physical, chemical, enzymatic, and genetic alterations, each imparting distinct changes to the starch granule structure and functional characteristics (El Farkhani et al., 2024)

5.1. Starch Modifications for Use as A Feedstock for Fermentation

Starch to be used as feedstock for fermentation usually undergoes enzymatic or acid modification. These chemical and enzymatic hydrolysis serve as central pretreatment strategies for converting starch-rich agricultural residues into fermentable substrates suitable for fermentation. Chemical hydrolysis typically employs dilute mineral acids such as hydrochloric or sulfuric acid, operating at elevated temperatures to disrupt the granular structure of starch and rapidly cleave  $\alpha$ -1,4 and  $\alpha$ -1,6 glycosidic linkages (Wang & Copeland, 2015). This process, which involves a series of liquefaction and saccharification reactions, yields glucose, maltose, and short-chain dextrans, with maximum glucose conversion yield of about 60%; however, it requires careful optimization to prevent excessive degradation that can result in the formation of fermentation inhibitory compounds such as hydroxymethylfurfural (HMF) and furfural, by-products known to impair fungal growth, enzyme secretion, and biomass accumulation (Feldman et al., 2019). Despite these challenges, acid hydrolysis remains attractive for industrial applications due to its rapid reaction kinetics and compatibility with high-solids processing. However, challenges with environmental concerns and downstream processing remain significant drawbacks (Cabeza et al., 2025).

In contrast, enzymatic hydrolysis utilizes highly specific amylolytic enzymes to catalyze the controlled depolymerization of starch under mild conditions.  $\alpha$ -Amylase facilitates endo-hydrolysis of  $\alpha$ -1,4 linkages, decreasing starch viscosity and producing linear and branched dextrans; glucoamylase subsequently cleaves both  $\alpha$ -1,4 and  $\alpha$ -1,6 bonds to generate high-purity glucose suitable for microbial fermentation (Liu et al., 2023). Debranching enzymes such as pullulanase and isoamylase enhance saccharification efficiency by removing  $\alpha$ -1,6 linkages that restrict enzyme accessibility, improving overall conversion yields (Hii et al., 2012). Enzymatic pretreatment offers several advantages over chemical methods, including reduced inhibitor formation, improved selectivity, lower energy input, and enhanced compatibility with fungal species that prefer consistent and gradual glucose release. Recent studies demonstrate that optimized enzymatic hydrolysis can significantly increase substrate digestibility and support higher fungal biomass productivity, particularly for strains of *Neurospora intermedia*, *Fusarium venenatum*, and *Rhizopus oryzae*, which exhibit strong amylolytic and carbohydrate-utilization capacities (Braho et al., 2024; Liu et al., 2023).

## 5.2. Brewers' Spent Grain

Brewers' spent grain (BSG) is the principal by-product of the brewing industry, generated as the insoluble residue remaining after malted barley undergoes mashing and lautering, during which enzymes convert starches into fermentable sugars and the resulting wort is separated from the solid grain fraction (Mussatto, 2014). Representing approximately 85% of total brewing by-products, BSG is produced at an estimated rate of 20 kg per hectoliter of beer, contributing to a global annual output of 36–40 million metric tons, with the European Union alone generating about 10 million metric tons (Wilkinson et al., 2016). Its composition, derived largely from the husk, pericarp, and seed coat layers of barley along with residual endosperm, consists of lignocellulosic material rich in cellulose (20–25%), hemicellulose (20–40%), lignin (12–28%), protein (15–30%), lipids (5–10%), and minor levels of  $\beta$ -glucan (approximately 1%) (Mussatto et al., 2007; Waters et al., 2012). Although its precise chemical profile varies with barley variety, malting conditions, mashing efficiency, and brewery practices, BSG consistently exhibits a high dietary fiber content (25–50%) (Prentice et al., 1978; Waters et al., 2012), significantly exceeding that of many cereals and legumes. Hemicellulose, particularly arabinoxylan, is its predominant fiber component and has been associated with potential health benefits such as prebiotic effects, improved glycemic regulation, and antioxidant activity (Mitri et al., 2022; Nyhan et al., 2023). Despite its abundance, BSG's high moisture content and susceptibility to microbial spoilage limit its shelf life and contribute to its predominant use as low-value animal feed or, in some regions, disposal via landfill, practices that are environmentally burdensome, with each metric ton of landfilled BSG emitting approximately 513 kg CO<sub>2</sub>-equivalent greenhouse gases (Lynch et al., 2016; Kavalopoulos et al., 2021). Although drying can extend its usability and facilitate incorporation into food systems, the inclusion of BSG may negatively affect product techno-functional and sensory properties, highlighting the need for value-added applications that can capitalize on its rich nutritional and lignocellulosic profile (Waters et al., 2012).

BSG contains approximately 30% protein and 30% residual starch on a dry weight basis (Mussatto et al., 2006), exceeding the protein content of most cereals, including wheat, barley, and oat, and aligning with levels observed in several legume sources such as lentils, chickpeas, peas, and faba beans. Although its protein concentration is lower than that of high-protein legumes like soybeans, BSG exhibits an essential amino acid profile typical of cereal proteins, with essential amino acids comprising up to 38% of total protein and lysine contributing as much as 87% of the recommended requirement per gram of protein (Nyhan et al., 2023). In addition to its protein composition, BSG offers functional advantages, such as enhanced foaming and gelation, and a notably high dietary fiber content (up to 50%), characteristics that frequently surpass those observed in conventional cereals and legumes and expand its applicability in food systems. This makes BSG a material of interest for both food and non-food applications, as it contains bioactive constituents such as arabinoxylans and ferulic acid, which have been associated with improved gut health and antioxidant activity (Celus et al., 2007; Jaeger et al., 2023; Vogelsang-O'Dwyer et al., 2020). However,

its lignocellulosic structure often necessitates pretreatment to enhance digestibility, as protein bioavailability is generally lower than that of legume proteins.

Protein quality indicates that a BSG-derived barley–rice protein isolate exhibits a DIAAS of approximately 51%, comparable to that of other cereal proteins but lower than the values reported for pea and faba bean proteins (64–76%) and soy protein (98–103%) (Herreman et al., 2020; Mathai et al., 2017). Nevertheless, the complementary amino acid profiles of BSG and legumes, particularly the combination of BSG's sulfur-containing amino acids with the lysine-rich nature of legume proteins, present a strategic opportunity to improve overall DIAAS and enhance protein quality in blended formulations. Although the protein and fiber composition of brewers' spent grain has been extensively documented, systematic investigations into its residual starch and overall carbohydrate profile relevant to fermentation processes remain limited, underscoring the need for further research to clarify effective valorization of these fractions in microbial bioprocesses for sustainable protein production

As a fermentation feedstock, BSG's favorable nutrient profile, rich in fermentable carbohydrates, proteins, and minerals, supports microbial bioconversion into value-added products and aligns with circular economy strategies in the food sector. However, its carbohydrates and proteins are largely embedded within complex biopolymeric matrices, necessitating chemical or enzymatic depolymerization to release fermentable sugars and bioavailable nutrients to achieve sustainability goal (Su et al., 2015; Mitri et al., 2022).

The chemical cleavage of brewers' spent grain (BSG) biopolymer units typically involves hydrolytic processes aimed at depolymerizing cellulose and hemicellulose into fermentable sugars suitable for downstream bioprocessing, such as ethanol and other fermentation-derived products. Acid pretreatments, including the use of dilute phosphoric acid, have been shown to enhance carbohydrate solubilization (Rojas-Chamorro et al., 2020). Sequential alkaline–acid treatments, for example sodium hydroxide followed by sulfuric acid, further improve delignification efficiency, achieving up to 80% lignin removal and increasing cellulose accessibility, with reported glucose concentrations of up to 75 g/L in resulting hydrolysates for ethanol fermentation (Liguori et al., 2015). In addition, physical approaches such as subcritical water hydrolysis (200–250 °C, 12–25 MPa) offer a comparatively green alternative, enabling the cleavage of hemicellulose into xylooligosaccharides and glucose without the use of chemical reagents, and yielding approximately 40–60% total sugars (Nunes et al., 2024). Despite these advantages, such pretreatment strategies are associated with notable limitations, including the formation of inhibitory compounds (e.g., furfural), high energy requirements, and variability in BSG composition, all of which can adversely affect process efficiency and yield consistency (Mitri et al., 2022).

Enzymatic hydrolysis, employing cellulases and hemicellulases, offers a milder approach, often yielding higher sugar concentrations and fewer inhibitory compounds, though enzyme costs can be substantial (Paz et al., 2019). Several studies have documented BSG's use in fermentation. In lactic acid fermentation, BSG functions as a self-sufficient substrate for producing optically pure L-lactic acid by *Lactobacillus* strains, achieving yields of 5.4 g/L following enzymatic pretreatment to hydrolyze its polysaccharides (Mussatto et al., 2007). For bioethanol production, its hemicellulose and residual starch fractions can be efficiently fermented by *Fusarium oxysporum*, generating ethanol concentrations of approximately 109g per kg of dry BG after enzymatic hydrolysis and offering a sustainable alternative to first-generation biofuel substrates (Xiros & Christakopoulos, 2009).

Brewers' spent grain (BSG) serves as an effective substrate for the cultivation of edible filamentous fungi, such as *Rhizopus oligosporus*, and shows potential as a growth substrate for *Fusarium venenatum*, enhancing amino acid profiles, citric acid production and nutritional values, thereby supporting its application in meat analog formulations (Cooray & Chen, 2018). Similarly, fermentation with *Rhizopus oryzae* has yielded a protein content of 23.3%, demonstrating improved protein solubility and the formation of protein structures that enhance surface bonding within the fermented matrix compared to untreated BSG (Rusbjerg-Weberskov et al., 2025). Furthermore, in the energy sector, BSG is also utilized in anaerobic digestion, where its organic matter is converted into

biogas with methane yields ranging from 10.53 L CH<sub>4</sub>/kg, thereby integrating food waste valorization with renewable energy production (Sganzerla et al., 2023)

Despite these advantages, several limitations constrain the utilization of BSG. Its high moisture content (70–80%) promotes rapid microbial spoilage and increases transportation and storage costs, while its lignocellulosic structure necessitates energy-intensive pretreatment processes to release fermentable sugars. Potential contaminants, including mycotoxins and heavy metals originating from barley cultivation, pose additional safety concerns and require stringent quality control measures (Drakopoulos et al., 2021; Kavalopoulos et al., 2021).

### 5.3. Rice Byproducts

Rice by-products refer to the secondary materials generated during rice processing, primarily including husks (also known as hulls), bran, straw, and broken kernels, which are lignocellulosic residues rich in cellulose, hemicellulose, lignin, and minor nutrients (Sharif et al., 2014). These by-products arise from the rice milling process in the food industry, where paddy rice undergoes hulling to remove the outer husks (20–22% of paddy weight), followed by polishing to separate the bran layer (5–8% of paddy weight), resulting in white rice as the primary product and by-products as waste streams (Muthayya et al., 2014). Annually, global rice production for 2025/26 is projected at approximately 313.4 million cwt (hundredweight), generating substantial by-products: rice husks/hulls at 130–170 MMT and bran at 40–50 MMT, with total residues (including straw) exceeding 750 MMT when accounting for field wastes (Research Nester, 2025; USDA, 2025). This derivation occurs in rice mills worldwide, particularly in Asia (e.g., China and India, producing over 50% of global rice), where mechanical dehulling and abrasive polishing minimize losses but produce nutrient-dense wastes often underutilized or discarded (FAO, 2025).

Rice straw and husk are the most frequently upcycled rice by-products. These by-products are primarily composed of cellulose, hemicellulose, and lignin, providing substantial carbon sources with fixed carbon contents of approximately 15.9% and 16.2%, respectively, that can be transformed into value-added products through microbial processes (Jenkins et al., 1998). Bioconversion strategies, commonly demonstrated with *Saccharomyces cerevisiae*, typically require physicochemical pretreatment to disrupt the recalcitrant lignocellulosic matrix, followed by enzymatic hydrolysis and fermentation. For instance, microwave–acid–alkali pretreatment of rice straw has been reported to yield a theoretical ethanol production of 0.42 L/kg dry solids (Binod et al., 2010; Zhu et al., 2006). Nevertheless, strong cross-linking among lignin, cellulose, and hemicellulose necessitates energy-intensive and costly pretreatment steps, constraining process efficiency. In contrast, rice bran exhibits a comparatively nutrient-dense profile, containing 12–17.5% protein, 13.1% lipids, 50–52.3% carbohydrates, substantial dietary fiber, and antioxidant compounds (Faria et al., 2012; Manzoor et al., 2023), and has been applied in alcoholic fermentation for bioethanol production and in solid-state fermentation to enhance bioactive properties (Oliveira et al., 2012; Siepmann et al., 2020). Despite these demonstrated applications and the low cost and global availability of rice by-products, their use as substrates for single-cell protein production remains underexplored, highlighting a significant opportunity for future research into sustainable microbial protein bioprocesses (Ghosh et al., 2017; Morya et al., 2023; W. Zhang et al., 2023).

Broken and immature rice kernels, which account for 10–25% of milled rice, with even higher proportions in small mills due to moisture-related breakage or grain chalkiness, present strong potential as fermentation feedstocks because of their high starch content (70–80%) and minimal pretreatment requirements (USDA, 2025; Muthayya et al., 2014). In industrial applications, these milling by-products have been used for bioethanol production, yielding 449–483 L/MT through simultaneous saccharification and fermentation using granular starch–hydrolyzing enzymes and yeast, as demonstrated in no-cook ethanol processes employing Indian broken rice (Gohel & Duan, 2012). Low-quality rice fractions, including immature kernels often classified under broken kernels, can also be effectively valorized through microbial fermentation, capitalizing on their readily accessible carbohydrates and proteins for biomass and metabolite synthesis (Babini et al., 2020).



Despite this demonstrated utility, further research is necessary to assess their suitability as substrates for fermented foods, including single-cell protein production, where rice kernels may generate protein-enriched biomass and provide cost-effective alternatives to whole grains while mitigating food waste.

#### 5.4. Cassava Bagasse

Cassava bagasse, the fibrous residue remaining after starch extraction from cassava roots (*Manihot esculenta*), is a major agro-industrial by-product in tropical regions where cassava is a staple crop. Derived in the food industry during wet milling processes, where roots are peeled, grated, pressed, and sieved to separate starch, bagasse comprises 15–20% of the root weight and consists of cellulose (30–50%), hemicellulose (20–30%), residual starch (10–20%), and minor proteins and lipids (Pandey et al., 2000). Globally, cassava production exceeds 300 million metric tons annually, yielding approximately 45–60 million metric tons of bagasse, primarily in Africa, Asia, and Latin America, where it is often discarded or used as low-value fuel (FAOSTAT, 2025). This derivation generates a starch-rich waste stream suitable for bioconversion, though its high moisture (60–80%) lignocellulosic structure and cyanide content pose processing challenges (Mukhtar et al., 2023).

As a substrate for fermentation and single-cell protein (SCP) production, cassava bagasse generally requires physicochemical pretreatment, such as acid hydrolysis or steam explosion, to disrupt its lignocellulosic matrix and liberate fermentable monosaccharides, principally glucose and mannose, that are readily assimilated by microorganisms. Empirical studies have demonstrated the feasibility of utilizing pretreated cassava bagasse in submerged fermentation systems with *Candida utilis*, resulting in SCP biomass yields with protein contents of approximately 40–50% and volumetric concentrations ranging from 8 to 12 g/L (Ezekiel et al., 2012). In parallel, solid-state fermentation approaches employing *Trichoderma pseudokoningii* have been reported to substantially enrich the protein content of cassava bagasse to levels of 36.9–48.1%, thereby improving its nutritional quality and suitability for animal feed applications (Bayitse et al., 2015). In general, the integration of cassava bagasse into biorefinery-based processing frameworks represents a promising strategy for the concurrent production of single-cell protein and bioethanol, enabling the efficient valorization of up to 70–80% of its lignocellulosic fraction while contributing to sustainable protein production and improved nutritional security in resource-limited regions (Pandey et al., 2000).

#### 5.5. Potato Peel Waste

Potato peel, a starchy waste from potato processing, is generated during peeling and cutting in the food industry for products like chips and fries, comprising 15–40% of the tuber weight with cellulose (20–30%), starch (10–20%), and minor proteins (5–10%) (Arapoglou et al., 2010). Annual global potato production of ~383 million metric tons yields 50–150 million metric tons of peels, primarily in Europe, Asia, and North America, often landfilled or composted (FAO, 2023). This derivation produces a nutrient-dense residue suitable for valorization, though its high phenolic content can inhibit microbial activity (Gebrechistos et al., 2020).

Potato peel, similarly to its use in bioethanol processes, typically undergoes chemical or enzymatic pretreatment to liberate fermentable sugars; however, enzymatic hydrolysis is generally preferred due to its operation under mild conditions, biodegradability, improved sugar yields, and reduced energy, water consumption, and by-product formation compared with acidic treatments (Arapoglou et al., 2010). Following pretreatment, submerged fermentation with *Saccharomyces cerevisiae* has been reported to yield SCP biomass containing approximately 12.5–21.9% protein (Maxwell et al., 2019), while solid-state fermentation with *Aspergillus parasiticus* can enrich potato peel substrates to protein levels of up to 51.1%, enhancing digestibility for feed applications (Khan et al., 2021). More recently, integrated multi-waste fermentation strategies, including co-fermentation with fruit peels, have been proposed to further enhance SCP yields to up to 50% protein, thereby reducing waste streams in potato-processing industries and supporting circular economy objectives (Troepe et al., 2022).

## 6. Life Cycle Assessment

The objectives of a circular bioeconomy cannot be fully realized without the application of Life Cycle Assessment (LCA). LCA is a critical methodological framework for evaluating the environmental sustainability of products and processes within a circular bioeconomy, providing a comprehensive analysis of impacts across the entire life cycle—from raw material extraction to end-of-life (ISO, 2006). Originating in the late 1960s through early resource and energy analyses conducted by industry and research institutions, LCA evolved into a formalized scientific approach during the 1990s through the efforts of the Society of Environmental Toxicology and Chemistry (SETAC) and the development of standardized guidelines (Klöpper, 2006). Subsequent international standardization by ISO through the ISO 14040 and 14044 series established LCA as a globally recognized and consistent assessment methodology (ISO 2006a; ISO, 2006b). Over time, LCA expanded beyond energy and waste metrics to encompass broader environmental indicators such as greenhouse gas emissions, water and land use, and resource depletion, supported by advancements in software tools, databases, and impact assessment methods (Finnveden et al., 2009; (Goedkoop & Huijbregts, 2008). Today, LCA is widely applied across sectors, including agriculture, manufacturing, and alternative protein production, to inform sustainability decisions and policy development, although ongoing research continues to address challenges related to data quality, regional specificity, and the integration of socio-economic dimensions into environmental assessments (Bare et al., 2003; Hauschild et al., 2017).

Several Life Cycle Impact Assessment (LCIA) methodologies have been developed to evaluate environmental impact within LCA, with several frameworks gaining widespread adoption due to their scientific rigor, comprehensive coverage, and regulatory relevance. ReCiPe is a widely used method that integrates midpoint indicators, representing specific environmental mechanisms such as climate change and eutrophication, and endpoint indicators that assess damage to human health, ecosystems, and resource availability, enabling both detailed and holistic analyses (Goedkoop & Huijbregts, 2008). CML method, developed at Leiden University, emphasizes midpoint impact categories and is recognized for its structured, mechanism-based evaluation of environmental effects (Guinee, 2004). TRACI, created by the U.S. Environmental Protection Agency, focuses on midpoint indicators tailored to the U.S. regulatory and geographical context, covering impacts such as global warming, acidification, and smog formation (Bare et al., 2003). IMPACT 2002+ combines midpoint and damage-oriented approaches, linking multiple midpoint categories to broader damage areas including human health, ecosystem quality, climate change, and resource depletion, thereby offering an integrated framework for comprehensive environmental assessment (Joliet et al., 2003).

### 6.1. Lca on Mycoprotein

Numerous LCA studies have evaluated the environmental burdens associated with conventional livestock-based food systems, including beef, pork, and poultry, and have compared these impacts with those of meat alternatives (Smetana et al., 2015). Traditional livestock production exerts substantial environmental pressure, contributing approximately 27–34% of anthropogenic greenhouse gas emissions, accounting for nearly 45% of global land use, and consuming around 70% of freshwater resources (GFI, 2024). However, relatively few studies have comprehensively evaluated the environmental footprint of emerging alternative protein sources, particularly mycoprotein-based single-cell proteins derived from agricultural by-products, including detailed comparisons of land-use requirements and water scarcity impacts (Fernández-López et al., 2024).

Upcraft et al. 2021 evaluated *F. venenatum* cultivated from lignocellulosic agricultural residues, including rice straw. The findings demonstrated a promising strategy for reducing the carbon footprint associated with conventional animal- and plant-based protein production. Techno-economic and life cycle assessments indicated that lignocellulosic-derived mycoprotein can be produced at competitive costs. Additionally, greenhouse gas emissions were substantially lower, accounting for less than 14% of those associated with beef protein. These results underscore the

potential of lignocellulosic-derived mycoprotein as a sustainable alternative protein source. (Upcraft et al., 2021). Similarly, economic modeling analysis of continuous mycoprotein production using airlift bioreactors, incorporating extensive process and cost inputs, indicated that mycoprotein has the potential to be cost-competitive with beef when evaluated on a price-per-protein basis. Sensitivity analyses further identified key process parameters influencing economic feasibility and supported the development of customizable production scenario tools for industry stakeholders. However, despite these advantages, mycoprotein may remain less economically competitive relative to lower-cost animal protein sources, such as chicken or meat by-product streams commonly used in pet food, highlighting both its commercial promise and current market limitations (Risner et al., 2023). Further optimization in saccharification yields and feedstock utilization, particularly using high-cellulose feedstocks, could significantly reduce production costs, making mycoprotein a more viable and sustainable protein alternative.

## Conclusions

This review highlights the substantial potential of starch-rich agricultural by-products as sustainable substrates for the production of fungal single-cell protein, particularly mycoprotein derived from filamentous fungi. The collective evidence demonstrates that residues possess significant carbohydrate content that can be efficiently converted into fermentable sugars through appropriate pretreatment and enzymatic saccharification strategies. When coupled with optimized submerged or solid-state fermentation systems, these substrates support robust fungal growth, high biomass productivity, and the generation of nutritionally valuable protein-rich products.

Advances in fermentation process engineering, strain selection, and biorefinery integration further strengthen the feasibility of converting low-value starch residues into functional protein ingredients suitable for food and feed applications. Moreover, techno-economic assessments and life cycle analyses consistently indicate that valorization of agricultural by-products can reduce raw material costs, minimize waste streams, and lower environmental burdens associated with conventional meat production systems. Despite these advantages, challenges remain, including feedstock variability, pretreatment energy requirements, scalability constraints, and the need for standardized downstream processing approaches that ensure product safety and consistent quality.

Overall, the integration of starch-based agro-industrial residues into mycoprotein production frameworks represents a viable pathway toward circular bioeconomy objectives by transforming underutilized agricultural residues into high-value protein resources. Continued research focused on process optimization, strain improvement, and comprehensive sustainability assessment will be critical to advancing industrial adoption and ensuring that fungal SCP contributes meaningfully to future resilient, resource-efficient, and environmentally responsible protein supply systems.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

- Abdul Manan, M., & Webb, C. (2017). *Design aspects of solid state fermentation as applied to microbial bioprocessing*. <https://doi.org/10.15406/jabb.2017.04.00094>
- Adejumo, I. O., & Adebisi, O. a. (2024). *Risky Benefits and Beneficial Risks of Animal Protein*. <https://doi.org/10.32388/V4WM4Q>
- Arapoglou, D., Varzakas, T., Vlyssides, A., & Israilides, C. (2010). Ethanol production from potato peel waste (PPW). *Waste Management*, 30(10), 1898–1902. <https://doi.org/10.1016/j.wasman.2010.04.017>
- Augustin, M. A., Hartley, C. J., Maloney, G., & Tyndall, S. (2024). Innovation in precision fermentation for food ingredients. In *Critical Reviews in Food Science and Nutrition* (Vol. 64, Number 18, pp. 6218–6238). Taylor and Francis Ltd. <https://doi.org/10.1080/10408398.2023.2166014>

- Ayoo, C., Bonti-Ankomah, S., & Aryee, A. N. A. (2020). *Byproducts from Agriculture and Fisheries: Adding Value for Food, Feed, Pharma, and Fuels*.
- Bamigbade, G. B., Oyelami, O. I., Babalola, O. O., Adewolu, A., Omemu, A. M., Ogunsanya, T. F., Sanusi, J. O. F., & Daniel, O. M. (2025). An updated comprehensive review on waste valorization: Informetric analysis, current insights and future perspectives on cereal waste and byproduct utilization for sustainable industrial applications. *Bioresource Technology*, 418, 131868. <https://doi.org/10.1016/J.BIORTECH.2024.131868>
- Bare, J. C., Norris, G. A., Pennington, D. W., & McKone, T. (2003). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. In *Journal of Industrial Ecology* (Vol. 6, Numbers 3–4, pp. 49–78). MIT Press Journals. <https://doi.org/10.1162/108819802766269539>
- Bashir, K., & Aggarwal, M. (2019). Physicochemical, structural and functional properties of native and irradiated starch: a review. *Journal of Food Science and Technology* 2019 56:2, 56(2), 513–523. <https://doi.org/10.1007/S13197-018-3530-2>
- Betoret, N., Betoret, E., & Glicerina, V. T. (2024). Valorization and Utilization of Food Wastes and By-Products: Recent Trends, Innovative Technologies and Sustainability Challenges. In *Foods* (Vol. 13, Number 1). Multidisciplinary Digital Publishing Institute (MDPI). <https://doi.org/10.3390/foods13010009>
- Binod, P., Sindhu, R., Singhanian, R. R., Vikram, S., Devi, L., Nagalakshmi, S., Kurien, N., Sukumaran, R. K., & Pandey, A. (2010). Bioethanol production from rice straw: An overview. *Bioresource Technology*, 101(13), 4767–4774. <https://doi.org/10.1016/J.BIORTECH.2009.10.079>
- Boulton, R. B., Singleton, V. L., Bisson, L. F., & Kunkee, R. E. (1999). Principles and Practices of Winemaking. *Principles and Practices of Winemaking*. <https://doi.org/10.1007/978-1-4757-6255-6>
- Boye, J. I., Aksay, S., Roufik, S., Ribéreau, S., Mondor, M., Farnworth, E., & Rajamohamed, S. H. (2010). Comparison of the functional properties of pea, chickpea and lentil protein concentrates processed using ultrafiltration and isoelectric precipitation techniques. *Food Research International*, 43(2), 537–546. <https://doi.org/10.1016/j.foodres.2009.07.021>
- Braho, V., Sar, T., & Taherzadeh, M. J. (2024). Cultivation of edible filamentous fungi on pomegranate by-products as feedstocks to produce mycoprotein. *Systems Microbiology and Biomanufacturing*, 4(2), 675–686. <https://doi.org/10.1007/S43393-023-00212-0>
- Buléon, A., Colonna, P., Planchot, V., & Ball, S. (1998). Starch granules: structure and biosynthesis. *International Journal of Biological Macromolecules*, 23(2), 85–112. [https://doi.org/10.1016/S0141-8130\(98\)00040-3](https://doi.org/10.1016/S0141-8130(98)00040-3)
- Cabeza, C., Ahmed, A. E. G., Minauf, M., Wieland, K., & Harasek, M. (2025). Starch hydrolysates, their impurities and the role of membrane-based technologies as a promising sustainable purification method at industrial scale. *Food Research International*, 209, 116300. <https://doi.org/10.1016/J.FOODRES.2025.116300>
- Caporgno, M. P., & Mathys, A. (2018). Trends in Microalgae Incorporation Into Innovative Food Products With Potential Health Benefits. In *Frontiers in Nutrition* (Vol. 5). Frontiers Media S.A. <https://doi.org/10.3389/fnut.2018.00058>
- Cedeno, F. R. P., Olubiyo, O. J., & Ferreira, S. (2025). From microbial proteins to cultivated meat for alternative meat-like products: a review on sustainable fermentation approaches. *Journal of Biological Engineering* 2025 19:1, 19(1), 44-. <https://doi.org/10.1186/S13036-025-00509-9>
- Celus, I., Brijs, K., & Delcour, J. A. (2007). Enzymatic Hydrolysis of Brewers' Spent Grain Proteins and Technofunctional Properties of the Resulting Hydrolysates. *Journal of Agricultural and Food Chemistry*, 55(21), 8703–8710. <https://doi.org/10.1021/JF071793C>
- Chai, K. F., Ng, K. R., Samarasiri, M., & Chen, W. N. (2022). Precision fermentation to advance fungal food fermentations. In *Current Opinion in Food Science* (Vol. 47). Elsevier Ltd. <https://doi.org/10.1016/j.cofs.2022.100881>
- Chain, E., Florey, H. W., Gardener, A. D., Heatley, N., & Jennings, M. A. (1940). THE CLASSIC: Penicillin as a Chemotherapeutic Agent. *Clin Orthop Relat Res.*, 439, 23–26.
- Chamodi, K. K. D., Vu, N. T., Domingos, J. A., & Loh, J. Y. (2025). Cellular Solutions: Evaluating Single-Cell Proteins as Sustainable Feed Alternatives in Aquaculture. *Biology*, 14(7), 764. <https://doi.org/10.3390/BIOLOGY14070764>



- Chang, H., Wang, Q., Xu, X., Li, C., Huang, M., Zhou, G., & Dai, Y. (2011). Effect of heat-induced changes of connective tissue and collagen on meat texture properties of beef Semitendinosus muscle. *International Journal of Food Properties*, 14(2), 381–396. <https://doi.org/10.1080/10942910903207728>
- Cooray, S. T., & Chen, W. N. (2018). Valorization of brewer's spent grain using fungi solid-state fermentation to enhance nutritional value. *Journal of Functional Foods*, 42, 85–94. <https://doi.org/10.1016/J.JFF.2017.12.027>
- Dar, M. Z., Deepika, K., Jan, K., Swer, T. L., Kumar, P., Verma, R., Verma, K., Prakash, K. S., Jan, S., & Bashir, K. (2018). Modification of structure and physicochemical properties of buckwheat and oat starch by  $\gamma$ -irradiation. *Int J Biol Macromol*, 108, 1348–1356. <https://doi.org/10.1016/j.ijbiomac.2017.11.067>
- de Vries, M., & de Boer, I. J. M. (2010). Comparing environmental impacts for livestock products: A review of life cycle assessments. *Livestock Science*, 128(1–3), 1–11. <https://doi.org/10.1016/J.LIVSCI.2009.11.007>
- Dean, D., Rombach, M., Koning, W. de, Vriesekoop, F., Satyajaya, W., Yuliandari, P., Anderson, M., Mongondry, P., Urbano, B., Luciano, C. A. G., Hao, W., Eastwick, E., Achirimbi, E., Jiang, Z., Boereboom, A., Rashid, F., Khan, I., Alvarez, B., & Aguiar, L. K. (2022). Understanding Key Factors Influencing Consumers' Willingness to Try, Buy, and Pay a Price Premium for Mycoproteins. *Nutrients*, 14(16). <https://doi.org/10.3390/nu14163292>
- Denny, A., Aisbitt, B., & Lunn, J. (2008). Mycoprotein and health. In *Nutrition Bulletin* (Vol. 33, Number 4, pp. 298–310). <https://doi.org/10.1111/j.1467-3010.2008.00730.x>
- Drakopoulos, D., Sulyok, M., Krska, R., Logrieco, A. F., & Vogelgsang, S. (2021). Raised concerns about the safety of barley grains and straw: A Swiss survey reveals a high diversity of mycotoxins and other fungal metabolites. *Food Control*, 125, 107919. <https://doi.org/10.1016/J.FOODCONT.2021.107919>
- Edwards, G. (1986). Myco-protein—the development of a new food [*Fusarium graminearum*]. *Food Laboratory Newsletter*, (6), 21–24.
- El Farkhani, M., Dadou, S., El Miz, Y., Elyoussfi, A., El Miz, M., Salhi, A., Koudad, M., & Benchat, N. (2024). A review of the chemical modification and applications of starch. *BIO Web of Conferences*, 109. <https://doi.org/10.1051/bioconf/202410901020>
- Elmore, J. S., Cooper, S. L., Enser, M., Mottram, D. S., Sinclair, L. A., Wilkinson, R. G., & Wood, J. D. (2005). Dietary manipulation of fatty acid composition in lamb meat and its effect on the volatile aroma compounds of grilled lamb. *Meat Science*, 69(2), 233–242. <https://doi.org/10.1016/j.meatsci.2004.07.002>
- Ezekiel, O. O., Aworh, O. C., Du Preez, J. C., & Steyn, L. (2012). Cultivation of *Candida utilis* on Cassava Peel Hydrolysates for Single-cell Protein Production. *Journal of Food Science and Engineering*, 2, 452–461.
- FAO. (2024). *Meat Market Review: Overview of global market developments in 2023*. <https://Openknowledge.Fao.Org/Server/Api/Core/Bitstreams/Ae4eb1ec-613d-478c-8361-C9bdba1df559/Content#:~:Text=production%20increases%20across%20all%20meat,In%20Africa%20and%20Northern%20America>
- FAO. (2025). *FAO Rice Price Update*. <https://www.fao.org/markets-and-trade/commodities/rice/fao-rice-price-update/en>
- FAOSTAT. (2025). *Data on yield of crops and area harvested*. <https://www.fao.org/faostat/en/#data/QCL/visualize>
- FAO-United Nations. (2025). *Meat and Dairy Production*. Our World in Data. <https://ourworldindata.org/meat-production>
- Faria, S. A. dos S. C., Bassinello, P. Z., & Pentead, M. de V. C. (2012). Nutritional composition of rice bran submitted to different stabilization procedures. *Brazilian Journal of Pharmaceutical Sciences*, 48(4), 651–657. <https://doi.org/10.1590/S1984-82502012000400008>
- FDA. (2025). GRAS Notice 1117, *Mycelial biomass from Neurospora crassa*.
- Feldman, D., Kowbel, D. J., Cohen, A., Glass, N. L., Hadar, Y., & Yarden, O. (2019). Identification and manipulation of *Neurospora crassa* genes involved in sensitivity to furfural. *Biotechnology for Biofuels*, 12(1). <https://doi.org/10.1186/s13068-019-1550-4>
- Fernández-López, L., González-García, P., Fernández-Ríos, A., Aldaco, R., Laso, J., Martínez-Ibáñez, E., Gutiérrez-Fernández, D., Pérez-Martínez, M. M., Marchisio, V., Figueroa, M., de Sousa, D. B., Méndez, D., & Margallo, M. (2024). Life cycle assessment of single cell protein production—A review of current technologies and emerging challenges. *Cleaner and Circular Bioeconomy*, 8, 100079. <https://doi.org/10.1016/J.CLCB.2024.100079>



- Fiddes, N. (2004). *Meat: A Natural Symbol* (1st Edition). Routledge. [https://doi.org/https://doi.org/10.4324/9780203168141?urlappend=%3Futm\\_source%3Dresearchgate.net%26utm\\_medium%3Darticle](https://doi.org/https://doi.org/10.4324/9780203168141?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle)
- Fink, M., Cserjan-Puschmann, M., Reinisch, D., & Striedner, G. (2021). High-throughput microbioreactor provides a capable tool for early stage bioprocess development. *Scientific Reports* 2021 11:1, 11(1), 2056-. <https://doi.org/10.1038/s41598-021-81633-6>
- Finnigan, T. J. A., Wall, B. T., Wilde, P. J., Stephens, F. B., Taylor, S. L., & Freedman, M. R. (2019). Mycoprotein: The Future of Nutritious Nonmeat Protein, a Symposium Review. *Current Developments in Nutrition*, 3(6). <https://doi.org/10.1093/cdn/nzz021>
- Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in Life Cycle Assessment. In *Journal of Environmental Management* (Vol. 91, Number 1, pp. 1–21). Academic Press. <https://doi.org/10.1016/j.jenvman.2009.06.018>
- Foxx, P. F., Guinee, T. P., Cogann, T. M., & Mcsweeney, P. L. H. (n.d.). *Fundamentals of Cheese Science Second Edition*.
- Galán, B., Santos-Merino, M., Nogales, J., de la Cruz, F., & García, J. (2019). *Microbial Oils as Nutraceuticals and Animal Feeds*. [https://scholar.google.com/scholar?hl=en&as\\_sdt=0%2C4&q=Gal%C3%A1n%2C+Beatriz%2C+et+al.+%22Microbial+oils+as+nutraceuticals+and+animal+feeds.%22+Health+consequences+of+microbial+interaction+s+with+hydrocarbons%2C+oils%2C+and+lipids.+Cham%3A+Springer+International+Publishing%2C+2020.+401-445.&btnG=](https://scholar.google.com/scholar?hl=en&as_sdt=0%2C4&q=Gal%C3%A1n%2C+Beatriz%2C+et+al.+%22Microbial+oils+as+nutraceuticals+and+animal+feeds.%22+Health+consequences+of+microbial+interaction+s+with+hydrocarbons%2C+oils%2C+and+lipids.+Cham%3A+Springer+International+Publishing%2C+2020.+401-445.&btnG=)
- Gebrechistos, H. Y., Ma, X., Xiao, F., He, Y., Zheng, S., Oyungerel, G., & Chen, W. (2020). Potato peel extracts as an antimicrobial and potential antioxidant in active edible film. *Food Science & Nutrition*, 8(12), 6338. <https://doi.org/10.1002/FSN3.1119>
- Gerber, P. J. . (2013). *Tackling climate change through livestock : a global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization of the United Nations.
- GFI. (2024). *State of Alternative protein: A global glimpse at the state of the industry*.
- Ghosh, S., Chowdhury, R., & Bhattacharya, P. (2017). Sustainability of cereal straws for the fermentative production of second generation biofuels: A review of the efficiency and economics of biochemical pretreatment processes. *Applied Energy*, 198, 284–298. <https://doi.org/10.1016/j.APENERGY.2016.12.091>
- Goedkoop, M. J., & Huijbregts, M. A. J. (2008). *ReCiPE 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. <https://www.researchgate.net/publication/302559709>
- Gohel, V., & Duan, G. (2012). No-Cook Process for Ethanol Production Using Indian Broken Rice and Pearl Millet. *International Journal of Microbiology*, 2012(1), 680232. <https://doi.org/10.1155/2012/680232>
- Guinee, J. B. . (2004). *Handbook on life cycle assessment operational guide to the ISO standards*. Kluwer Academic Publishers.
- Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2017). Life Cycle Assessment: Theory and Practice. *Life Cycle Assessment: Theory and Practice*, 1–1216. <https://doi.org/10.1007/978-3-319-56475-3>
- Herreman, L., Nommensen, P., Pennings, B., & Laus, M. C. (2020). Comprehensive overview of the quality of plant- And animal-sourced proteins based on the digestible indispensable amino acid score. *Food Science and Nutrition*, 8(10), 5379–5391. <https://doi.org/10.1002/FSN3.1809>
- Hertzler, S. R., Lieblein-Boff, J. C., Weiler, M., & Allgeier, C. (2020). Plant proteins: Assessing their nutritional quality and effects on health and physical function. In *Nutrients* (Vol. 12, Number 12, pp. 1–27). MDPI AG. <https://doi.org/10.3390/nu12123704>
- Hii, S. L., Tan, J. S., Ling, T. C., & Ariff, A. Bin. (2012). Pullulanase: Role in Starch Hydrolysis and Potential Industrial Applications. *Enzyme Research*, 2012, 921362. <https://doi.org/10.1155/2012/921362>
- Huff-Lonergan, E., & Lonergan, S. M. (2005). Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Science*, 71(1), 194–204. <https://doi.org/10.1016/j.meatsci.2005.04.022>
- Hutkins, R. W. (2007). Microbiology and Technology of Fermented Foods. *Microbiology and Technology of Fermented Foods*, 1–473. <https://doi.org/10.1002/9780470277515>

- ISO. (2006). *ISO 14040:2006—Environmental management — Life cycle assessment — Principles and framework*. <https://www.iso.org/standard/37456.html>
- Jaeger, A. ; Sahin, A. W. ;, Nyhan, L. ;, Zannini, E. ;, Arendt, E K, Casanova, F., Jaeger, Alice, Sahin, A. W., Nyhan, Laura, Zannini, Emanuele, & Arendt, Elke K. (2023). Functional Properties of Brewer's Spent Grain Protein Isolate: The Missing Piece in the Plant Protein Portfolio. *Foods* 2023, Vol. 12, Page 798, 12(4), 798. <https://doi.org/10.3390/FOODS12040798>
- Jenkins, B. M., Baxter, L. L., Miles, T. R., & Miles, T. R. (1998). Combustion properties of biomass. *Fuel Processing Technology*, 54(1–3), 17–46. [https://doi.org/10.1016/S0378-3820\(97\)00059-3](https://doi.org/10.1016/S0378-3820(97)00059-3)
- Jeske, S., Zannini, E., & Arendt, E. K. (2018). Past, present and future: The strength of plant-based dairy substitutes based on gluten-free raw materials. *Food Research International*, 110, 42–51. <https://doi.org/10.1016/J.FOODRES.2017.03.045>
- Jimenez-Colmenero, F., Carballo, J., & Cofrades, S. (n.d.). *Healthier meat and meat products: their role as functional foods*. Retrieved [www.elsevier.com/locate/meatsci](http://www.elsevier.com/locate/meatsci)
- Joliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (n.d.). *Presemmg a New Meth6d IMPACT 2002+: A New Life Cycle Impact Assessment Methodology*. Retrieved <http://www.epfl.ch/impact>
- Jones, D. T., & Woods, D. R. (1986). Acetone-Butanol Fermentation Revisited. In *MICROBIOLOGICAL REVIEWS* (Vol. 50, Number 4).
- Junejo, S. A., Flanagan, B. M., Zhang, B., & Dhital, S. (2022). Starch structure and nutritional functionality—Past revelations and future prospects. *Carbohydrate Polymers*, 277. <https://doi.org/10.1016/j.carbpol.2021.118837>
- Kavalopoulos, M., Stoumpou, V., Christofi, A., Mai, S., Barampouti, E. M., Moustakas, K., Malamis, D., & Loizidou, M. (2021). Sustainable valorisation pathways mitigating environmental pollution from brewers' spent grains. *Environmental Pollution*, 270, 116069. <https://doi.org/10.1016/J.ENVPOL.2020.116069>
- Khumchai, J., Wongchai, A., On-uma, R., Sabour, A., Alshiekheid, M., Narayanan, M., Karuppusamy, I., Pugazhendhi, A., Brindhadevi, K., & Lan Chi, N. T. (2022). A viable bioremediation strategy for treating paper and pulp industry effluents and assessing the prospect of resulted bacterial biomass as single cell protein (SCP) using indigenous bacterial species. *Chemosphere*, 304. <https://doi.org/10.1016/J.CHEMOSPHERE.2022.135246>
- Klöpffer, W. (2006). The role of SETAC in the development of LCA. In *International Journal of Life Cycle Assessment* (Vol. 11, Number SPEC. ISS. 1, pp. 116–122). <https://doi.org/10.1065/lca2006.04.019>
- Koukoumaki, D. I., Tsouko, E., Papanikolaou, S., Ioannou, Z., Diamantopoulou, P., & Sarris, D. (2024). Recent advances in the production of single cell protein from renewable resources and applications. *Carbon Resources Conversion*, 7(2), 100195. <https://doi.org/10.1016/J.CRCON.2023.07.004>
- Lee, S. Y., & Ra, C. H. (2021). Comparison of Liquid and Solid-State Fermentation Processes for the Production of Enzymes and Beta-Glucan from Hulled Barley. *Journal of Microbiology and Biotechnology*, 32(3), 317. <https://doi.org/10.4014/jmb.2111.11002>
- Leip, A. (2010). *Evaluation of the Livestock Sector's Contribution to the EU Greenhouse Gas Emissions (GGELS)-Final Report*. [http://commons.wikimedia.org/wiki/File:Franz\\_Mark-The\\_Yellow\\_Cow-1911.jpg](http://commons.wikimedia.org/wiki/File:Franz_Mark-The_Yellow_Cow-1911.jpg)
- Leroy, F., Smith, N. W., Adesogan, A. T., Beal, T., Iannotti, L., Moughan, P. J., & Mann, N. (2023). The role of meat in the human diet: evolutionary aspects and nutritional value. *Animal Frontiers: The Review Magazine of Animal Agriculture*, 13(2), 11. <https://doi.org/10.1093/AF/VFAC093>
- Li, L., Belloch, C., & Flores, M. (2021). The Maillard Reaction as Source of Meat Flavor Compounds in Dry Cured Meat Model Systems under Mild Temperature Conditions. *Molecules*, 26(1), 223. <https://doi.org/10.3390/MOLECULES26010223>
- Li, L., Jiang, H., Campbell, M., Blanco, M., & Jane, J. lin. (2008). Characterization of maize amylose-extender (ae) mutant starches. Part I: Relationship between resistant starch contents and molecular structures. *Carbohydrate Polymers*, 74(3), 396–404. <https://doi.org/10.1016/J.CARBPOL.2008.03.012>
- Li, Y. P., Ahmadi, F., Kariman, K., & Lackner, M. (2024). Recent advances and challenges in single cell protein (SCP) technologies for food and feed production. In *npj Science of Food* (Vol. 8, Number 1). Nature Research. <https://doi.org/10.1038/s41538-024-00299-2>

- Liguori, R., Soccol, C. R., de Souza Vandenberghe, L. P., Woiciechowski, A. L., & Faraco, V. (2015). Second Generation Ethanol Production from Brewers' Spent Grain. *Energies* 2015, Vol. 8, Pages 2575-2586, 8(4), 2575–2586. <https://doi.org/10.3390/EN8042575>
- Liu, P., Ma, L., Duan, W., Gao, W., Fang, Y., Guo, L., Yuan, C., Wu, Z., & Cui, B. (2023). Maltogenic amylase: Its structure, molecular modification, and effects on starch and starch-based products. *Carbohydrate Polymers*, 319, 121183. <https://doi.org/10.1016/J.CARBPOL.2023.121183>
- Lynch, K. M., Steffen, E. J., & Arendt, E. K. (2016). Brewers' spent grain: a review with an emphasis on food and health. *Journal of the Institute of Brewing*, 122(4), 553–568. <https://doi.org/10.1002/JIB.363;WGROU:STRING:PUBLICATION>
- Manzoor, A., Pandey, V. K., Dar, A. H., Fayaz, U., Dash, K. K., Shams, R., Ahmad, S., Bashir, I., Fayaz, J., Singh, P., Khan, S. A., & Ganaie, T. A. (2023). Rice bran: Nutritional, phytochemical, and pharmacological profile and its contribution to human health promotion. *Food Chemistry Advances*, 2, 100296. <https://doi.org/10.1016/J.FOCHA.2023.100296>
- Mathai, J. K., Liu, Y., & Stein, H. H. (2017). Values for digestible indispensable amino acid scores (DIAAS) for some dairy and plant proteins may better describe protein quality than values calculated using the concept for protein digestibility-corrected amino acid scores (PDCAAS). *British Journal of Nutrition*, 117(4), 490–499. <https://doi.org/10.1017/S0007114517000125>
- Maxwell, O. I., Chinwuba, U. B., Onyebuchukwu, M. G., Maxwell, O. I., Chinwuba, U. B., & Onyebuchukwu, M. G. (2019). Protein Enrichment of Potato Peels Using *Saccharomyces cerevisiae* via Solid-State Fermentation Process. *Advances in Chemical Engineering and Science*, 9(1), 99–108. <https://doi.org/10.4236/ACES.2019.91008>
- Megavitry, R., & Silamat, E. (2024). Utilisation of Agricultural Wastes as Alternative Raw Materials in Fermented Food Production. *West Science Agro*, 2(03), 109–122. <https://doi.org/10.58812/WSA.V2I03.1202>
- Mitri, S., Salameh, S.-J., Khelfa, A., Léonard, E., Maroun, R., Louka, N., Koubaa, M., Veeravalli, S., Leonard, E., & Maroun, R. G. (2022). Valorization of Brewers' Spent Grains: Pretreatments and Fermentation, a Review. *Valorization of Brewers' Spent Grains: Pretreatments and Fermentation, a Review*. <https://doi.org/10.3390/fermentation8020050>
- Morya, R., Andrianantenaina, F. H., Singh, S., Pandey, A. K., Kim, G. B., Verma, J. P., Kumar, G., Raj, T., & Kim, S. H. (2023). Exploring rice straw as substrate for hydrogen production: Critical challenges and opportunities. *Environmental Technology & Innovation*, 31, 103153. <https://doi.org/10.1016/J.ETI.2023.103153>
- Mottram, D. S. (1998). Flavour formation in meat and meat a review products. In *Food Chemistry* (Vol. 62, Number 4).
- Mukhtar, A., Latif, S., Barati, Z., & Müller, J. (2023). Valorization of Cassava By-Products: Cyanide Content and Quality Characteristics of Leaves and Peel. *Applied Sciences* 2023, Vol. 13, 13(10). <https://doi.org/10.3390/APP13106340>
- Mussatto, S. I. (2014). Brewer's spent grain: A valuable feedstock for industrial applications. *Journal of the Science of Food and Agriculture*, 94(7), 1264–1275. <https://doi.org/10.1002/jsfa.6486>
- Mussatto, S. I., Fernandes, M., Dragone, G., Mancilha, I. M., & Roberto, I. C. (2007). Brewer's spent grain as raw material for lactic acid production by *Lactobacillus delbrueckii*. *Biotechnology Letters* 29:12, 29(12), 1973–1976. <https://doi.org/10.1007/S10529-007-9494-3>
- Muthayya, S., Sugimoto, J. D., Montgomery, S., & Maberly, G. F. (2014). An overview of global rice production, supply, trade, and consumption. *Annals of the New York Academy of Sciences*, 1324(1), 7–14. <https://doi.org/10.1111/NYAS.12540>
- Nielsen, J., Larsson, C., van Maris, A., & Pronk, J. (2013). Metabolic engineering of yeast for production of fuels and chemicals. *Current Opinion in Biotechnology*, 24(3), 398–404. <https://doi.org/10.1016/J.COPBIO.2013.03.023>
- Nunes, L. F., Ugalde, G. A., Anschau, K. F., Müller, E. I., Tres, M. V., Zabot, G. L., & Kuhn, R. C. (2024). Clean Production of Sugars from Brewer's Spent Grains Using Subcritical Water Hydrolysis and Steam Explosion. *Sustainable Chemistry*, 5(4), 308–323. <https://doi.org/10.3390/suschem5040021>
- Nyhan, L., Sahin, A. W., Schmitz, H. H., Siegel, J. B., & Arendt, E. K. (2023). Brewers' Spent Grain: An Unprecedented Opportunity to Develop Sustainable Plant-Based Nutrition Ingredients Addressing Global

- Malnutrition Challenges. *Journal of Agricultural and Food Chemistry*, 71(28), 10543–10564. <https://doi.org/10.1021/ACS.JAFC.3C02489>
- Oliveira, M. dos S., Cipolatti, E. P., Furlong, E. B., & Soares, L. de S. (2012). Compostos fenólicos e atividade antioxidante em farelo de arroz (*Oryza sativa*) fermentado. *Ciencia e Tecnologia de Alimentos*, 32(3), 531–537. <https://doi.org/10.1590/S0101-20612012005000071>
- Paddon, C. J., Westfall, P. J., Pitera, D. J., Benjamin, K., Fisher, K., McPhee, D., Leavell, M. D., Tai, A., Main, A., Eng, D., Polichuk, D. R., Teoh, K. H., Reed, D. W., Treynor, T., Lenihan, J., Jiang, H., Fleck, M., Bajad, S., Dang, G., ... Newman, J. D. (2013). High-level semi-synthetic production of the potent antimalarial artemisinin. *Nature*, 496(7446), 528–532. <https://doi.org/10.1038/nature12051>
- Pandey, A., Soccol, C. R., Nigam, P., Soccol, V. T., Vandenberghe, L. P. S., & Mohan, R. (2000). Biotechnological potential of agro-industrial residues. II: cassava bagasse. *Bioresource Technology*, 74(1), 81–87. [https://doi.org/10.1016/S0960-8524\(99\)00143-1](https://doi.org/10.1016/S0960-8524(99)00143-1)
- Pasteur (1866) *études Sur le Vi.* (n.d.).
- PATRICK E. McGOVERN. (2009). THE NEAR EASTERN CHALLENGE. *Uncorking the Past*, 60.
- Paz, A., Outeiriño, D., Pérez Guerra, N., & Domínguez, J. M. (2019). Enzymatic hydrolysis of brewer's spent grain to obtain fermentable sugars. *Bioresource Technology*, 275, 402–409. <https://doi.org/10.1016/J.BIORTECH.2018.12.082>
- Perkins, D. D. (1992). Neurospora: the organism behind the molecular revolution. *Genetics*, 130(4), 687–701. <https://doi.org/10.1093/genetics/130.4.687>
- Perkins, D. D., & Davis, R. H. (2000). GUEST COMMENTARY Evidence for Safety of Neurospora Species for Academic and Commercial Uses. In *APPLIED AND ENVIRONMENTAL MICROBIOLOGY* (Vol. 66, Number 12). <http://vm.cfsan.fda>
- Pojić, M., Mišan, A., & Tiwari, B. (2018). Eco-innovative technologies for extraction of proteins for human consumption from renewable protein sources of plant origin. In *Trends in Food Science and Technology* (Vol. 75, pp. 93–104). Elsevier Ltd. <https://doi.org/10.1016/j.tifs.2018.03.010>
- Poore, J., & Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360(6392), 987–992. <https://doi.org/10.1126/science.aag0216>
- Post, M. J. (2012). Cultured meat from stem cells: Challenges and prospects. In *Meat Science* (Vol. 92, Number 3, pp. 297–301). <https://doi.org/10.1016/j.meatsci.2012.04.008>
- Prentice, N., Kissel, L. T., Lindsay, R. C., & Yamazaki, T. (1978). High Fiber cookies containing Brewers' Spent Grain. *The American Association of Cereal Chemistry*, 55(5), 712–721.
- Prückler, M., Siebenhandl-Ehn, S., Apprich, S., Höltinger, S., Haas, C., Schmid, E., & Kneifel, W. (2014). Wheat bran-based biorefinery 1: Composition of wheat bran and strategies of functionalization. *LWT—Food Science and Technology*, 56(2), 211–221. <https://doi.org/10.1016/J.LWT.2013.12.004>
- Pulido Diaz, A., Lourdin, D., Della Valle, G., Fernandez Quintero, A., Ceballos, H., Tran, T., & Dufour, D. (2016). *Thermomechanical characterization of an amylose-free starch extracted from cassava (Manihot esculenta, Crantz)*. <https://doi.org/10.1016/j.carbpol.2016.11.058i>
- Ranum, P., Peña-Rosas, J. P., & Garcia-Casal, M. N. (2014). Global maize production, utilization, and consumption. *Annals of the New York Academy of Sciences*, 1312(1), 105–112. <https://doi.org/10.1111/NYAS.12396>
- Rashwan, A. K., Younis, H. A., Abdelshafy, A. M., Osman, A. I., Eletmany, M. R., Hafouda, M. A., & Chen, W. (2024). Plant starch extraction, modification, and green applications: a review. *Environmental Chemistry Letters* 22:5, 22(5), 2483–2530. <https://doi.org/10.1007/S10311-024-01753-Z>
- Rasool, Kashif, Hussain, Sabir, Shahzad, Asif, Miran, Waheed, Mahmoud, Khaled A, Ali, Nisar, Almomani, Fares, Rasool, K, Mahmoud, K A, Hussain, S, Shahzad, A, Miran, W, Ali, N, & Almomani, F. (2023). Comprehensive insights into sustainable conversion of agricultural and food waste into microbial protein for animal feed production. *Reviews in Environmental Science and Bio/Technology* 2023 22:2, 22(2), 527–562. <https://doi.org/10.1007/S11157-023-09651-6>
- Ravindran, R., & Jaiswal, A. K. (2016). Exploitation of Food Industry Waste for High-Value Products. In *Trends in Biotechnology* (Vol. 34, Number 1, pp. 58–69). Elsevier Ltd. <https://doi.org/10.1016/j.tibtech.2015.10.008>



- Research Nester, 2025. (2025). *Rice Husk Ash Market Outlook*. <https://www.researchnester.com/reports/rice-husk-ash-market/3376>
- Reynaud, Y., Buffière, C., Cohade, B., Vauris, M., Liebermann, K., Hafnaoui, N., Lopez, M., Souchon, I., Dupont, D., & Rémond, D. (2021). True ileal amino acid digestibility and digestible indispensable amino acid scores (DIAAs) of plant-based protein foods. *Food Chemistry*, 338. <https://doi.org/10.1016/j.foodchem.2020.128020>
- Riley, C. K., Wheatley, A. O., & Asemota, H. N. (2006). Isolation and Characterization of Starches from eight *Dioscorea alata* cultivars grown in Jamaica . *African Journal of Biotechnology*, 5(17), 1528–1536.
- Risner, D., McDonald, K. A., Jones, C., & Spang, E. S. (2023). A techno-economic model of mycoprotein production: achieving price parity with beef protein. *Frontiers in Sustainable Food Systems*, 7. <https://doi.org/10.3389/fsufs.2023.1204307>
- Rodero, M. del R., Magdalena, J. A., Steyer, J. P., Escudié, R., & Capson-Tojo, G. (2024). Potential of enriched phototrophic purple bacteria for H<sub>2</sub> bioconversion into single cell protein. *Science of The Total Environment*, 908, 168471. <https://doi.org/10.1016/J.SCITOTENV.2023.168471>
- Rojas-Chamorro, J. A., Romero, I., López-Linares, J. C., & Castro, E. (2020). Brewer's spent grain as a source of renewable fuel through optimized dilute acid pretreatment. *Renewable Energy*, 148, 81–90. <https://doi.org/10.1016/J.RENENE.2019.12.030>
- Röös, E., Sundberg, C., Tidåker, P., Strid, L., & Hansson, P. A. (2013). Can carbon footprint serve as an indicator of the environmental impact of meat production? *Ecological Indicators*, 24, 573–581. <https://doi.org/10.1016/j.ecolind.2012.08.004>
- Rusbjerg-Weberskov, C. E., Foley, J. D., Yang, L., Terp, M., Gregersen Echers, S., Orlén, V., & Lübeck, M. (2025). Combined *Rhizopus oryzae* Fermentation and Protein Extraction of Brewer's Spent Grain Improves Protein Functionality. *Food and Bioprocess Technology* 2025 18:11, 18(11), 9574–9593. <https://doi.org/10.1007/S11947-025-03989-1>
- Santo, R. E., Kim, B. F., Goldman, S. E., Dutkiewicz, J., Biehl, E. M. B., Bloem, M. W., Neff, R. A., & Nachman, K. E. (2020). Considering Plant-Based Meat Substitutes and Cell-Based Meats: A Public Health and Food Systems Perspective. In *Frontiers in Sustainable Food Systems* (Vol. 4). Frontiers Media S.A. <https://doi.org/10.3389/fsufs.2020.00134>
- Sganzerla, W. G., Costa, J. M., Tena-Villares, M., Buller, L. S., Mussatto, S. I., & Forster-Carneiro, T. (2023). Dry Anaerobic Digestion of Brewer's Spent Grains toward a More Sustainable Brewery: Operational Performance, Kinetic Analysis, and Bioenergy Potential. *Fermentation*, 9(1). <https://doi.org/10.3390/FERMENTATION9010002>
- Shahidi, F., & Pegg, R. B. (1994). *Hexanal as an Indicator of the Flavor Deterioration of Meat and Meat Products*. <https://pubs.acs.org/sharingguidelines>
- Sharif, M. K., Butt, M. S., Anjum, F. M., & Khan, S. H. (2014). Rice Bran: A Novel Functional Ingredient. *Critical Reviews in Food Science and Nutrition*, 54(6), 807–816. <https://doi.org/10.1080/10408398.2011.608586>; JOURNAL:JOURNAL:BFSN18;WGROU:STRING:PUBLIC ATION
- Sharif, M., Zafar, M. H., Aqib, A. I., Saeed, M., Farag, M. R., & Alagawany, M. (2021). Single cell protein: Sources, mechanism of production, nutritional value and its uses in aquaculture nutrition. *Aquaculture*, 531, 735885. <https://doi.org/10.1016/J.AQUACULTURE.2020.735885>
- Shindell, D., Bréon, F., Collins, W., Fuglestedt, J., Huang, J., Koch, D., Lamarque, J., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., ... Midgley, P. (2013). *Anthropogenic and Natural Radiative Forcing*. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I*.
- Siepmann, F. B., Kalschne, D. L., Zabotti, C., de Moraes Flores, E. L., Canan, C., & Colla, E. (2020). Feasibility of bioethanol production from rice bran. *Semina:Ciencias Agrarias*, 41(6), 2951–2966. <https://doi.org/10.5433/1679-0359.2020V41N6SUPL2P2951>
- Singh, N., Singh, J., Kaur, L., Sodhi, N. S., & Gill, B. S. (2003). Morphological, thermal and rheological properties of starches from different botanical sources. *Food Chemistry*, 81(2), 219–231. [https://doi.org/10.1016/S0308-8146\(02\)00416-8](https://doi.org/10.1016/S0308-8146(02)00416-8)



- Singh Nee Nigam, P., & Pandey, A. (2009). Biotechnology for agro-industrial residues utilisation: Utilisation of agro-residues. In *Biotechnology for Agro-Industrial Residues Utilisation: Utilisation of Agro-Residues*. Springer Netherlands. <https://doi.org/10.1007/978-1-4020-9942-7>
- Smetana, S., Mathys, A., Knoch, A., & Heinz, V. (2015). Meat alternatives: life cycle assessment of most known meat substitutes. *International Journal of Life Cycle Assessment*, 20(9), 1254–1267. <https://doi.org/10.1007/s11367-015-0931-6>
- Soibam, H., Ayam, V. S., Chakraborty, I., Chandra, B., & Viswavidyalaya, K. (2014). Natural Resource Utilization by Acetic Acid Fermentation: A Method for Post Harvest Management. *Article in Advances in BioResearch*. <https://doi.org/10.15515/abr.0976-4585.5.3.5256>
- Solanki, A., Kumar, D., & Sharma, P. (2024). A mini-review on agro waste mediated technologies used for landfill leachate treatment. *Journal of Water Process Engineering*, 57(1), 104685. <https://doi.org/10.1016/j.jwpe.2023.104685>
- Souza Filho, P. F., Nair, R. B., Andersson, D., Lennartsson, P. R., & Taherzadeh, M. J. (2018). Vegan-mycoprotein concentrate from pea-processing industry byproduct using edible filamentous fungi. *Fungal Biol Biotechnol*, 5, 5. <https://doi.org/10.1186/s40694-018-0050-9>
- Stanbury, P. F. ., Whitaker, Allan., & Hall, S. J. . (2008). *Principles of fermentation technology*. Pergamon. <http://www.sciencedirect.com/5070/book/9780080361314/principles-of-fermentation-technology>
- Statista. (2025). *Global Meat Production Forecast*. Statista. <https://www.statista.com/statistics/237632/production-of-meat-worldwide-since-1990/?srsltid=AfmBOoopwekf182lxfHttTaZFvxxv0EB04KBXbr1IkUlvR1E1BRyVO2L>
- Steinkraus, K.H. (1996) *Handbook of Indigenous Fermented Foods*. Marcel Dekker, New York, 52-72.—References—Scientific Research Publishing. (n.d.). Retrieved January 31, 2025, from <https://www.scirp.org/reference/referencespapers?referenceid=1316333>
- Strassburg, B. B. N., Latawiec, A. E., Barioni, L. G., Nobre, C. A., da Silva, V. P., Valentim, J. F., Vianna, M., & Assad, E. D. (2014). When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil. *Global Environmental Change*, 28(1), 84–97. <https://doi.org/10.1016/j.gloenvcha.2014.06.001>
- Su, Y., Du, R., Guo, H., Cao, M., Wu, Q., Su, R., Qi, W., & He, Z. (2015). Fractional pretreatment of lignocellulose by alkaline hydrogen peroxide: Characterization of its major components. *Food and Bioprocess Processing*, 94, 322–330. <https://doi.org/10.1016/J.FBP.2014.04.001>
- Trinci, A. P. J. (1994). Evolution of the Quorn® myco-protein fungus, *Fusarium graminearum* A3/5. *Microbiology*, 140(9), 2181–2188. <https://doi.org/10.1099/13500872-140-9-2181>
- Tuomisto, H. L., & Teixeira De Mattos, M. J. (2011). Environmental impacts of cultured meat production. *Environmental Science and Technology*, 45(14), 6117–6123. <https://doi.org/10.1021/es200130u>
- Ugalde, U. O., & Castrillo, J. I. (2002). Single cell proteins from fungi and yeasts. *Applied Mycology and Biotechnology*, 2(C), 123–149. [https://doi.org/10.1016/S1874-5334\(02\)80008-9](https://doi.org/10.1016/S1874-5334(02)80008-9)
- Upcraft, T., Tu, W. C., Johnson, R., Finnigan, T., Van Hung, N., Hallett, J., & Guo, M. (2021). Protein from renewable resources: Mycoprotein production from agricultural residues. *Green Chemistry*, 23(14), 5150–5165. <https://doi.org/10.1039/d1gc01021b>
- USDA. (2025). *Rice—Rice Sector at a Glance*. <https://www.ers.usda.gov/topics/crops/rice/rice-sector-at-a-glance>
- van Huis, A. (2020). Nutrition and health of edible insects. *Current Opinion in Clinical Nutrition and Metabolic Car*, 22(3), 228–231. [https://journals.lww.com/clinicalnutrition/abstract/2020/05000/nutrition\\_and\\_health\\_of\\_edible\\_insects.13.aspx](https://journals.lww.com/clinicalnutrition/abstract/2020/05000/nutrition_and_health_of_edible_insects.13.aspx)
- Vogelsang-O'Dwyer, M., Bez, J., Petersen, I. L., Joehnke, M. S., Detzel, A., Busch, M., Krueger, M., Ispiryan, L., O'Mahony, J. A., Arendt, E. K., & Zannini, E. (2020). Techno-Functional, Nutritional and Environmental Performance of Protein Isolates from Blue Lupin and White Lupin. *Foods 2020, Vol. 9, Page 230*, 9(2), 230. <https://doi.org/10.3390/FOODS9020230>
- Walker, P., Rhubart-Berg, P., McKenzie, S., Kelling, K., & Lawrence, R. S. (2005). Public health implications of meat production and consumption. *Public Health Nutrition*, 8(4), 348–356. <https://doi.org/10.1079/phn2005727>

- Wang, L., Huang, Y., Wang, Y., & Shan, T. (2021). Effects of Polyunsaturated Fatty Acids Supplementation on the Meat Quality of Pigs: A Meta-Analysis. *Frontiers in Nutrition*, 8, 746765. <https://doi.org/10.3389/FNUT.2021.746765/FULL>
- Wang, S., & Copeland, L. (2015). Effect of Acid Hydrolysis on Starch Structure and Functionality: A Review. *Critical Reviews in Food Science and Nutrition*, 55(8), 1081–1097. <https://doi.org/10.1080/10408398.2012.684551;REQUESTEDJOURNAL:JOURNAL:BFSN20>
- Wang, W. Y., Wu, S. H., Xie, Y. H., Zhong, M., Wei, M. L., Li, Z. Y., Long, X. F., & Niu, F. X. (2022). A High-Throughput Screening Procedure (Py-Fe<sup>3+</sup>) for Enhancing Ethanol Production by *Saccharomyces cerevisiae* Using ARTP Random Mutagenesis. *Processes*, 10(11). <https://doi.org/10.3390/pr10112186>
- Wang, Z., Lopez-Giraldez, F., Slot, J., Yarden, O., Trail, F., Townsend, J. P., & Hug, L. A. (2022). Secondary Metabolism Gene Clusters Exhibit Increasingly Dynamic and Differential Expression during Asexual Growth, Conidiation, and Sexual Development in *Neurospora crassa*. *MSystems*, 7(3). <https://doi.org/10.1128/msystems.00232-22>
- Waters, D. M., Jacob, F., Titze, J., Arendt, E. K., & Zannini, E. (2012). Fibre, protein and mineral fortification of wheat bread through milled and fermented brewer's spent grain enrichment. *European Food Research and Technology* 2012 235:5, 235(5), 767–778. <https://doi.org/10.1007/S00217-012-1805-9>
- Waterschoot, J., Gomand, S. V., Fierens, E., & Delcour, J. A. (2015). Production, structure, physicochemical and functional properties of maize, cassava, wheat, potato and rice starches. *Starch—Stärke*, 67(1–2), 14–29. <https://doi.org/10.1002/STAR.201300238>
- Wiebe, M. (2002). Myco-protein from *fusarium venenatum*: A well-established product for human consumption. In *Applied Microbiology and Biotechnology* (Vol. 58, Number 4, pp. 421–427). <https://doi.org/10.1007/s00253-002-0931-x>
- Wilkinson, S., Smart, K. A., James, S., & Cook, D. J. (2016). Bioethanol Production from Brewers Spent Grains Using a Fungal Consolidated Bioprocessing (CBP) Approach. *BioEnergy Research* 2016 10:1, 10(1), 146–157. <https://doi.org/10.1007/S12155-016-9782-7>
- World population to reach 8 billion on 15 November 2022 | United Nations. (n.d.). Retrieved November 1, 2024, from <https://www.un.org/en/desa/world-population-reach-8-billion-15-november-2022>
- Xiros, C., & Christakopoulos, P. (2009). Enhanced ethanol production from brewer's spent grain by a *Fusarium oxysporum* consolidated system. *Biotechnology for Biofuels*, 2. <https://doi.org/10.1186/1754-6834-2-4>
- Ye, L., Bogicevic, B., Bolten, C. J., & Wittmann, C. (2024). Single-cell protein: overcoming technological and biological challenges towards improved industrialization. *Current Opinion in Biotechnology*, 88, 103171. <https://doi.org/10.1016/J.COPBIO.2024.103171>
- You, X. Y., Ding, Y., Bu, Q. Y., Wang, Q. H., & Zhao, G. P. (2024). Nutritional, Textural, and Sensory Attributes of Protein Bars Formulated with Mycoproteins. *Foods*, 13(5). <https://doi.org/10.3390/foods13050671>
- Zahra Ahangi, Seyed Shojaosadati, & Houshang Nikoopour. (2008). Study of Mycoprotein Production Using *Fusarium oxysporum* and Reduction of RNA Content. *Pakistan Journal of Nutrition*, 7(2), 240–243.
- Zhang, B., Zhan, B., & Bao, J. (2021). Reframing biorefinery processing chain of corn fiber for cellulosic ethanol production. *Industrial Crops and Products*, 170, 113791. <https://doi.org/10.1016/J.INDCROP.2021.113791>
- Zhang, C., Xue, W., Li, T., & Wang, L. (2023). Understanding the Relationship between the Molecular Structure and Physicochemical Properties of Soft Rice Starch. *Foods*, 12(19), 3611. <https://doi.org/10.3390/FOODS12193611>
- Zhang, W., Xu, X., Yuan, Y., & Wang, Z. (2023). Sustainable application of rice-waste for fuels and valuable chemicals-a mini review. *Frontiers in Chemistry*, 11, 1225073. <https://doi.org/10.3389/FCHEM.2023.1225073/BIBTEX>
- Zhou, H., Hu, Y., Tan, Y., Zhang, Z., & McClements, D. J. (2021). Digestibility and gastrointestinal fate of meat versus plant-based meat analogs: An in vitro comparison. *Food Chemistry*, 364. <https://doi.org/10.1016/j.foodchem.2021.130439>
- Zhu, S., Wu, Y., Yu, Z., Wang, C., Yu, F., Jin, S., Ding, Y., Chi, R., Liao, J., & Zhang, Y. (2006). Comparison of Three Microwave/Chemical Pretreatment Processes for Enzymatic Hydrolysis of Rice Straw. *Biosystems Engineering*, 93(3), 279–283. <https://doi.org/10.1016/J.BIOSYSTEMSENG.2005.11.013>

**Disclaimer/Publisher’s Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.