Understanding the potential of microbial protein as a more sustainable food source

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Summary and Abstract

Summary

The rising global protein demand and the unsustainability of the food chain challenge conventional food systems. Adopting more sustainable alternatives like microbial protein holds promise. Despite its potential to address environmental concerns and meet human nutritional needs, aspects such as carbon footprint, conversion to appealing food, legal considerations, and public acceptance require further investigation.

Abstract

The increasing global demand for protein, driven by population growth and dietary shifts, poses a challenge to conventional, inefficient food production systems. In response, alternative protein sources like microbial protein have gained traction for their potential to supply nutritional food more sustainably. Microbial protein, the protein-rich biomass of microorganisms, offers a promising solution due to its high nutritional value, resource efficiency, and climate resilience. However, challenges persist in transitioning to the use of sustainable feedstocks and navigating complex legislative frameworks, hindering widespread adoption. Effective legislative reforms, streamlined regulatory processes, and technological innovations are essential to unlock the full potential of microbial protein as a more sustainable food source. Moreover, consumer acceptance and behavioral changes are crucial for driving adoption and harnessing the environmental benefits of microbial protein. Ultimately, collaborative efforts across stakeholders, informed consumer choices, and policy interventions are imperative for realizing a sustainable food future, with microbial protein playing a pivotal role in this transformative journey.

Keywords

alternative food production; circular economy; consumer acceptance; environmental sustainability; food law regulation; food product development; food safety; microbial food; single cell protein; sustainable protein sources; techno-functional food properties

Learning Outcomes

1. Explain the significance of microbial protein as a healthy and sustainable food source.
2. Compare primary resource-based and recovered resource-based approaches for microbial protein production.
3. Describe the processes involved in the production of microbial foods.
4. Explain the importance of converting microbial protein into appealing food products for societal acceptance.
5. Acquire knowledge on the legal and regulatory frameworks governing microbial protein production and distribution.
6. Identify challenges and opportunities in microbial protein production and its integration in the global food system.

Which Sustainable Development Goals (SDGs) Does the Case Support?

Goal 2: Zero hunger – Microbial protein production can be viewed as a more sustainable, climate independent and scalable solution to address food insecurity, offering nutritious alternatives to conventional protein sources and enhancing food accessibility worldwide.

Goal 3: Good health and well-being – Microbial protein can provide a multitude of essential macromolecules and nutrients and be part of a healthy diet.

Goal 9: Industry, innovation, and infrastructure – Exploring innovative production methods for microbial protein and discussing technological advancements in this field may contribute to fostering innovation and sustainable industrial practices.

Goal 12: Responsible consumption and production – Microbial protein has the potential to be a more sustainable food source, thus promoting more efficient resource utilization and environmentally friendly production practices.

Goal 13: Climate action – Highlighting microbial protein as a sustainable alternative to traditional animal agriculture can help mitigate greenhouse gas emissions and promote climate-resilient food production.

Background and Context

The world's need for protein is forecasted to increase by up to 78% by 2050 compared to 2017, driven by a growing population and the adoption of protein-rich diets (Henchion *et al.*, 2017). Meeting this demand presents a significant challenge, posing a threat to conventional food production, which not only struggles to keep up with this rising protein demand but also contributes to resource depletion and environmental degradation (Dury *et al.*, 2019).

Recognizing these issues, various sustainable protein sources, such as cultured meat, insects (Onwezen *et al.*, 2021) and microbial protein (Ravindra, 2000), have emerged as potential alternatives. Microbial protein, the protein-rich biomass of bacteria, yeasts, fungi, or microalgae, which is also referred to as single-cell protein (Goldberg, 1985), presents a compelling solution to address food scarcity (Goldberg, 1985), more sustainably than conventional agriculture (Leger *et al.*, 2021), while being highly nutritional for humans (Finnigan, Needham and Abbott, 2016).

Despite its historical association with alleviating food scarcity (Cooney and Levine, 1972), microbial protein is gaining renewed attention due to its potential as a putatively sustainable protein source. Due to its production in closed bioreactors, the shift towards microbial protein offers the possibility of bypassing traditional agricultural practices, thereby reducing the associated environmental impacts (Leger *et al.*, 2021). Indeed, microbial protein can be more sustainable than animal-derived proteins. Substituting animal-derived proteins with microbial protein can reduce land use by 40,000 times (Cumberlege, Blenkinsopp and Clark, 2016) and water requirements by 20 times (Pennings *et al.*, 2013; Karl Hsu, John Kazer, 2018) while having 10 times higher nitrogen efficiency (Pikaar *et al.*, 2017) and 10 times higher protein yield (Ravindra, 2000). Additionally, microbes double their weight 700 times faster compared to animals (Goldberg, 1985). Finally, the potential climate independence of microbial protein production in engineered systems offers resilience against climate variability.

Understanding the role of microbial protein as a more sustainable protein source is pivotal for addressing pressing global food security challenges and environmental concerns. Thus, this case study provides a comprehensive exploration of the potential of microbial protein, facilitating informed discussions and fostering a deeper understanding of the complexities surrounding protein production and consumption.

Finally, it should be noted that microbial food ingredients can be produced using synthetic biology approaches, such as utilizing the entire biomass of genetically modified microbes or solely their extracellular products produced via precision fermentation. However, this case study will exclusively focus on utilizing the entire biomass of microbes with natural metabolisms.

What resources do we need to produce microbial protein?

Microbial protein stands out from traditional sources due to its flexibility in utilizing diverse feedstocks for its production. These feedstocks should contain macronutrients (e.g. carbon, nitrogen, phosphorus), micronutrients (e.g. copper, iron) and vitamins, to support microbial growth. Carbon, nitrogen, and phosphorus, the elements that need to be supplied in larger amounts in comparison to the rest, can be organic or inorganic sources as well as gaseous, liquid, or solid. For example, carbon sources range from CO_2 and methane to complex organics like sugars or alcohols, while common nitrogen sources include ammonia or proteins. Phosphorus, is mostly supplied in its inorganic (PO_4^{2-}) form. Carefully selecting the source of the feedstock used is vital, as the substrate can substantially affect the environmental footprint of the process, contributing up to 50% of the greenhouse gas emissions in microbial protein production (Finnigan *et al.*, 2010).

The use of primary resources

Industrial microbial protein production currently relies on essential macronutrients (carbon, nitrogen, phosphorus) sourced from primary resources (Fig. 1). For instance, carbon-rich feedstocks such as food-grade sugars derived from wheat or natural gas are commonly utilized. However, sugar production contributes significantly to CO_2 emissions, responsible for about 50% of the emissions related to microbial protein production (Finnigan *et al.*, 2010), and also uses fertilizers containing nitrogen and phosphorus to produce them, thereby indirectly contributing to the well-known environmental impacts of conventional agriculture. Nitrogen in the form of ammonia is synthesized through the energy-intensive Haber-Bosch process, which relies on fossil methane and contributes about 2% of global greenhouse gas emissions (Humphreys, Lan and Tao, 2021). Regarding phosphorus, inorganic phosphorus from mined phosphate rock is predominantly used, emitting approximately 950 kg of CO_2 per ton of P_2O_5 produced (Belboom, Szöcs and Léonard, 2015). Apart from the carbon footprint, extracting primary resources from the environment leads to, among others, water pollution, biodiversity loss, and generates large quantities of waste. Even though microbial protein is more resource-efficient compared to traditional sources, their reliance on primary and finite resources remains an environmental concern.

Towards a circular economy using recovered resources for protein production

The inefficiency of the conventional linear approach to sourcing primary (macro)nutrients for microbial protein production highlights the urgency for transitioning to a more sustainable, circular model. Alternative substrates like sugars contained in side-streams (e.g. cheese whey permeate, fruit processing residues) present potential alternatives (Fig. 1). Additionally, CO_2 can serve as a gaseous substrate (Kerckhof *et al.*, 2021) or be converted into platform chemicals such as (m)ethanol, formic acid, and acetic acid through biological or physicochemical processes (Van Peteghem *et al.*, 2022).

Instead of relying solely on Haber-Bosch-derived ammonia, nitrogen recovery via air stripping from wastewater treatment plants offers a promising avenue for significant greenhouse gas emission reduction, potentially lowering emissions by up to six times per ton of NH_3 produced (Kar *et al.*, 2023). Recent studies have demonstrated the feasibility of this approach without adversely affecting protein content, biomass yield, and growth rates compared to primary resources (Van Peteghem *et al.*, 2023). As for phosphorus, recovering struvite from industrial side streams presents an alternative to phosphate rock mining (Muys *et al.*, 2023), with net negative greenhouse gas emissions of 1.40 kg CO_2 eq. per kg of P_2O_5 produced. Although the recovery of nutrients is a promising concept, these processes are driven by electricity. Globally, electricity generation is still partly relying on using fossil fuels resulting in a high carbon footprint (Sun *et al.*, 2018), which can compromise their goal. Given the anticipated decreases in the carbon footprint of electricity generation by 2030, CO_2 emissions associated with microbial protein production from recovered resources could be significantly lower compared to current levels (Van Peteghem *et al.*, 2022). Despite the technical feasibility, challenges persist within the European Union's (EU) legal framework concerning the reuse of by-products from the food production chain, hindering the widespread adoption of recovered resources for microbial protein production (Van Raamsdonk *et al.*, 2023).

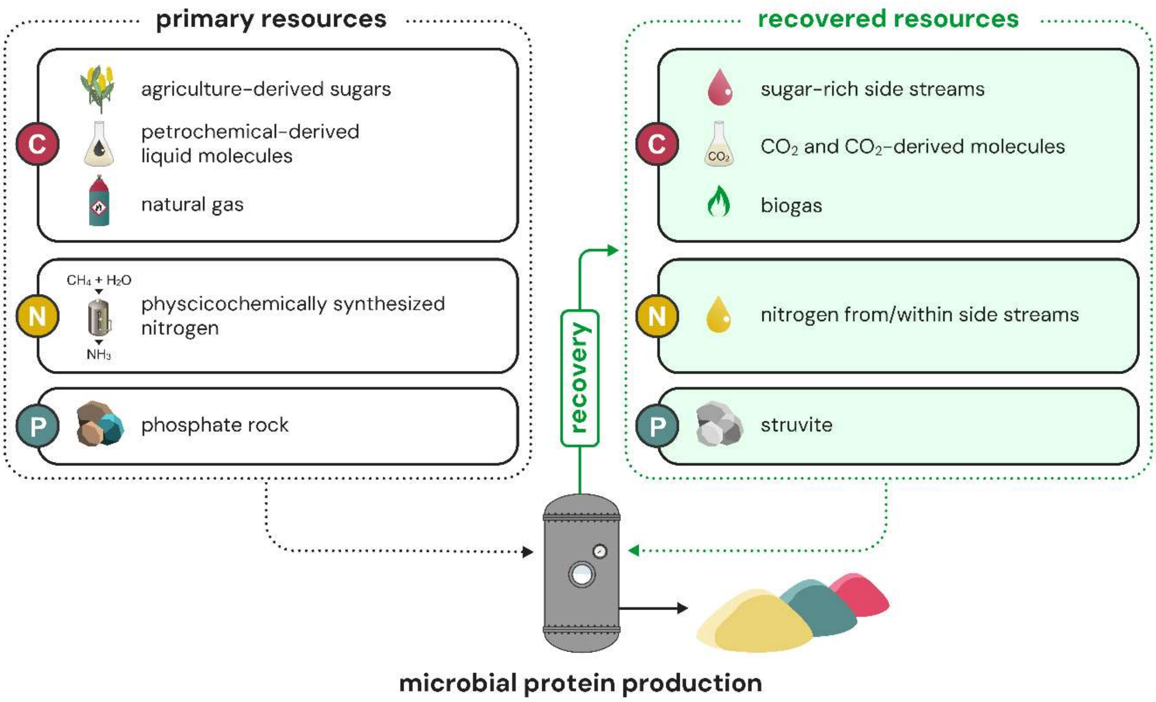

Fig. 1: Primary resources often used for microbial protein production, and suggested recovered resources as putatively more sustainable alternatives. Only the main macro-nutrients (carbon, nitrogen, phosphorus) needed for microbial growth are considered.

How will microbial protein be converted to microbial foods?

After bioproduction, microbial protein finds versatile application in the food industry, where it can be utilized as a whole-cell ingredient, protein concentrate, isolate, and hydrolysate (Soto-Sierra, Stoykova and Nikolov, 2018), depending on the downstream processing (Fig. 2). The process of obtaining whole-cell ingredients typically involves harvesting biomass, often through centrifugation or filtration, followed by stabilization, commonly achieved by spray drying for bacteria and yeasts (Leger *et al.*, 2021), and chilling for fungal biomass to preserve its filamentous morphology (Wiebe, 2002). Additionally, reducing the high nucleic acid content of microbial protein, which can have adverse health effects if not kept below the safe limit (Parajo, Santos, & Dominguez, 1995), is a common step in processing, often accomplished through treatments like the endogenous RNAase-heat-shock process resulting in biomass losses (Wiebe, 2002), and denaturation of proteins (Marson *et al.*, 2022).

While whole-cell ingredients offer benefits such as improving nutritional quality when included in small quantities (e.g. increasing the protein content in meat analogues), their use as the main ingredient faces challenges due to their inherent low functionality, such as low solubility (Kinsella and Shetty, 1978).

Evaluating techno-functionality throughout downstream processing is crucial to determine the suitability of the final product for various applications. Parameters of techno-functionality enable food scientists to assess properties like water and oil retention, foam stability, gel and emulsion formation, and pH-dependent solubility. Further enhancement of techno-functionality and protein content for specific food and/or health applications can be achieved by concentrating whole-cell ingredients into protein concentrates, isolates, hydrolysates (i.e. hydrolyzed isolates), and bioactive peptides (i.e. short peptides of around 3-40 amino acids) (Soto-Sierra, Stoykova and Nikolov, 2018) (Fig. 2) using process steps such as cell disruption and protein extraction.

Downstream processing methods vary depending on the starting material (e.g. type of microbial biomass) and desired end-product. For example, the rough cell wall of microalgae makes cell disruption challenging, while the high protein content of bacteria simplifies downstream processing. Sustainability should always be a key consideration in choosing downstream processing strategies to maximize the eco-friendliness of microbial protein production. Additionally, increased purification and extraction steps raise production costs, reducing cost-competitiveness and accessibility. A potential solution lies in co-extracting multiple ingredients from the production line of whole-cell products (Suarez Ruiz *et al.*, 2018; Lonchamp *et al.*, 2020).

These microbial ingredients find application as main or secondary components in alternatives to animal-derived products, such as meat and dairy analogues, as well as in microbial ingredient-enriched food and beverages like snacks, smoothies, and pasta (Fig. 2). Achieving the desired texture and flavor often requires additional plant-based or microbial-based ingredients. While the addition of these ingredients can offer nutritional and health benefits, the environmental sustainability perspective favors the use of microbial protein as the main ingredient. However, the optimization and understanding of the interplay between sustainability, techno-functionality, and nutritional value of microbial food ingredients, dependent on the microbial strains used and process steps employed, remain areas of significant under-exploration. Finally, production processes should reflect the end-goal: mimicking existing products or creating new ones with appealing qualities.

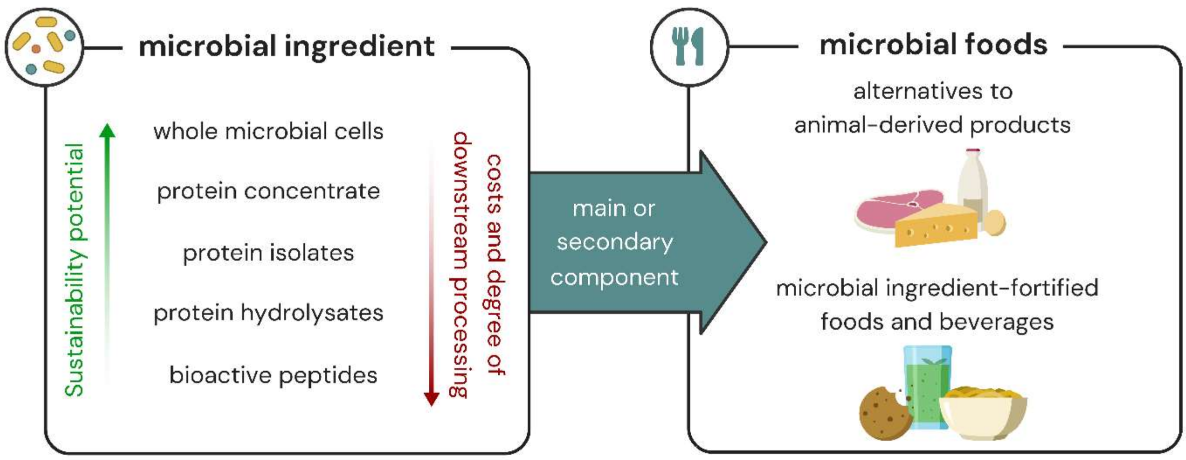

Fig. 2: Microbial ingredients derived from natural metabolisms for the production of microbial foods. These encompass alternatives to animal-derived products (i.e. meat, dairy, eggs) where microbial

ingredients serve as either main or secondary components, as well as microbial ingredient-fortified foods and beverages (i.e. cookies, pasta, smoothies) where microbial ingredients act as secondary components.

Are microbial foods a healthy food source?

As a whole-cell ingredient, microbial protein can reach a protein content up to 83% in cell dry weight, with an amino acid composition comparable to that of animal products and meeting the FAO/WHO standard for human nutrition (Matassa *et al.*, 2016). However, the composition of microbial protein can vary significantly based on various factors, including the type of organism(s) employed and downstream processing. Generally, whole-cell bacteria demonstrate the highest protein content (50-83%), followed by microalgae (42-75%), yeasts (45-55%), and fungi (10-70%) (Ravindra, 2000; Ritala *et al.*, 2017). Furthermore, a fungi-based (also known as mycoprotein) meat alternative, has a protein content of 11% in wet weight (Finnigan, Needham and Abbott, 2016), falls below that of chicken (26%) and red meat (20-24%) (Wyness, 2016), suggesting a higher consumption requirement to meet the nutritional needs with mycoprotein.

Moreover, protein quality is influenced by factors such as digestibility and bioavailability (Otero *et al.*, 2022). To assess protein quality for human consumption, parameters like the Protein Digestibility-Corrected Amino Score (PDCAAS) are crucial. While there is limited data on these parameters for microbial food products, downstream processing can improve them (Ben-Shitrit *et al.*, 2022). Mycoprotein-based meat analogues, for instance, exhibit a remarkable PDCAAS of 99.6% (Finnigan, Needham and Abbott, 2016), surpassing beef at 92% (Schaafsma, 2000), pea (67%), and soy (91%), and closely aligning with milk and eggs (100%) (van Vliet, Burd and van Loon, 2015).

In addition to protein, microbial biomass contains other macro- and micro-nutrients that enhance its nutritional value, food and health applications. For example, polyunsaturated fatty acids, essential in human diets, can accumulate in microbial biomass up to 80% in dry weight (Ochsenreither *et al.*, 2016). Microbial carbohydrates can serve as dietary fibers (Majumder *et al.*, 2023), while key minerals (e.g. iron and zinc) and vitamins (e.g. vitamin B12, which is often limiting in vegan diets) can also be provided through microbial foods (Pawlak, 2021). Health benefits have also been reported for microbial foods. For example, lower cholesterol levels, prevention of obesity and diabetes, muscle protein production in youngsters have also been described for the consumption of fungi-derived microbial protein (Khan *et al.*, 2023). Furthermore, microbial foods can have prebiotic (de Schryver *et al.*, 2010) and probiotic (Gil de los Santos *et al.*, 2012) properties.

A significant drawback of microbial protein production is the higher nucleic acid content of microorganisms (up to 25%) (Makino *et al.*, 2003) compared to other food sources such as plants and animal-derived foods (≤1%) (Lassek and Montag, 1990; Nissen, Jorgensen and Oksbjerg, 2004). This content is dependent on the type of microbial biomass (Table 1) and requires reduction through downstream processing to prevent adverse health effects. Unlike some animals, humans lack the ability to metabolize the uric acid resulting from the metabolism of nucleic acids, which can lead to its accumulation in the body and the development of gout and kidney stones (Ravindra, 2000).

The nutritional and health benefits of microbial protein depend largely on downstream processing. While some nutrients may be lost during this process as protein is concentrated, others may be converted to components offering health benefits (e.g. bioactive peptides) (Wang *et al.*, 2023). Additionally, downstream processing can improve techno-functionality, influencing the physical, chemical, and sensory attributes of food products derived from protein-rich microbial biomass and its social acceptance.

Table 1: Average macromolecular composition of different types of microbial protein (whole-cell ingredient and meat analogue) and comparison with conventional plant and animal-based food products (in % dry weight)

	Protein	Fats/Lipids	Nucleic acids	References
Microbial protein				
Bacteria	50-83	1-3	8-25	(Ravindra, 2000; Makino *et al.*, 2003; Ritala *et al.*, 2017)
Yeast	45-55	2-8	6-12	
Fungi	30-70	2-6	7-10	
Microalgae	42-75	7-20	3-8	
Mycoprotein meat analogue	45	13	<2	(Finnigan, Needham and Abbott, 2016; Aulia *et al.*, 2023)
Plants				
Soybeans	34-57	8-24	1	(Di Carlo, Schultz and Kent, 1955)
Plant-based meat analogue	42-44	28	ND*	(Yang *et al.*, 2023)
Animals				
Beef	46-76	17-68	1-3	(Cieślewicz *et al.*, 1988; Troy, Tiwari and Joo, 2016)
Chicken	64-82	9-18	1-3	(Cieślewicz *et al.*, 1988; Moustafa Edris *et al.*, 2012)

*ND = not disclosed

Exploring the factors that affect the appeal of microbial foods to consumers

While the quality of microbial protein is promising for food applications, its commercial success greatly depends on public and consumer acceptance, along with the economic feasibility of this unconventional protein source. Public approval of microbial protein as a food ingredient is influenced by various psychological, social, cultural, ethical, and religious factors, as well as the general perception of products originating from microbes (Nasseri *et al.*, 2011; Happer and Wellesley, 2019). Indeed, despite the growing consumer preference for sustainable food options in the EU, factors like taste, texture, and price remain primary considerations (Torán-Pereg *et al.*, 2023). Some individuals may desire more sustainable diets but face barriers such as accessibility and affordability. For example, meat analogues are currently 3 times more expensive than animal products (GFI, 2024), posing an accessibility barrier, particularly for economically disadvantaged populations. However, as microbial protein production technologies develop (e.g. using low-cost feedstocks, optimizing ingredient formulation), projections indicate that by 2025, microbial protein-based meat alternatives could potentially reach price parity with traditional animal products (Witte *et al.*, 2021).

The sensory experience of food, involving taste, smell, sight, touch, and hearing, significantly influences consumer acceptance (Hoppu, Puputti and Sandell, 2020). Flavor, the combination of taste and scent, is a primary criterion for food ingredient acceptability (Lawless, 1991). Sensory properties outweigh factors like nutrition and price in consumer preference (Muñoz and Civille, 1987). For instance, unpleasant odors affect the food choice and portion size, they can hinder the adoption of novel food sources, impacting their commercial viability (Ferriday and Brunstrom, 2008). While microbial protein exhibits aroma profiles influenced by substrate and microorganism selection (Sakarika *et al.*, 2020), it is unknown whether achieving a pleasant or neutral smell with all types of microbial protein is possible. Moreover, due to limited knowledge regarding the taste profiles of microbial protein, it remains uncertain whether and how the taste can be manipulated.

Texture, often more critical than flavor, significantly influences food acceptance, particularly among young age groups (Werthmann *et al.*, 2015; Nederkoorn, Houben and Havermans, 2019). Cultural, social, and economic factors shape the perception of “right” and a “wrong” textures, indicating the necessity for careful consideration in food ingredient development (Muñoz and Civille, 1987). Taking meat analogues as example, commercially-available products made from mycoprotein, that have been successfully incorporated to the market, mimic meat texture due to the filamentous nature of fungi (Trinci, 1992). For microbial protein products originating from other cell types (bacteria, yeast, microalgae), texturization has only recently started to be explored and much remains unknown.

In conclusion, there is a clear need for additional research to develop microbial foods that are appealing to consumers, as consumer appeal is a crucial factor for the integration of microbial foods into our diets.

Current legislation regarding microbial protein as a food source

Legislation regarding the production and development of microbial protein-based products varies across different regions, often posing a significant barrier to their development and commercialization (Piercy *et al.*, 2022). This is particularly the case in the EU, where the process of approval can take from 18 months to up to 3 years. Foods derived from microorganisms typically fall under the "novel food" regulation if they lack a significant history of consumption prior to the regulation's implementation (EU, 2015; GFI, 2023). For instance, baker’s yeast (*Saccharomyces cerevisiae*), certain microalgal strains (e.g., *Spirulina* sp.), and a mycoprotein-derived meat alternative (*Fusarium venenatum*) are exempt from this regulation (Lähteenmäki-Uutela *et al.*, 2021). In other cases, a comprehensive toxicological and safety assessment of the microorganism, as well as a characterization of its production, metabolism, and nutritional composition, is required (Miquel *et al.*, 2015). Specifically, the product must adhere to permissible toxin levels, particularly important for fungi- and bacteria-derived microbial protein where toxin production may occur (Ritala *et al.*, 2017), and must not provoke widespread medical conditions. Proving the safety of the microorganism is facilitated if it already holds Qualified Presumption of Safety (QPS) status (EFSA, 2024). Other regions, such as Singapore and USA, have a more brief and efficient process. For example, in Singapore, regulatory approvals take between 9-12 months, considerably less than the EU.

Regulations become more complex regarding the utilization of recovered substrates for novel food production (Vapnek J., Purnhagen K. and Hillel B., 2021). Recovered substrates may contain contaminants (e.g., heavy metals) that can accumulate in the microbial biomass during production (Van Peteghem *et al.*, 2023), potentially hindering its approval under regulatory frameworks. EU legislation, for example, provides maximum levels for certain contaminants in food and fertilizers produced from recovered nutrients for food or feed production (European Commission, 2019). It is expected that if recovered resources are used for microbial protein production, not only is the human health impacts expected to be thoroughly assessed, public acceptance of microbial products derived from these sources is imperative.

Lastly, the FAO/WHO/UNICEF has recommended a daily additional dietary nucleic acid intake of 2g from microbial protein (Parajo, Santos and Dominguez, 1995). Consequently, many industrial microbial protein processes include a step to reduce the nucleic acid content to mitigate potential health risks. For consumer transparency, there is currently no obligation to include nucleic acid content in food labelling in the listing of nutrients (FAO, 2013).

Can the adoption of microbial protein in our diets solve the issue of unsustainability in the food chain?

To address the question of whether microbial protein can contribute to a more sustainable food chain, it is essential to first identify the factors currently rendering the food chain unsustainable. Here we will focus on the greenhouse gas emissions, given that the lower environmental impacts of microbial protein compared to common food sources on other impact categories are (relatively) well established. Greenhouse gas emissions play a significant role in the unsustainability of the food chain, with the majority arising from primary production (39%), land use (32%) and end-of-life food disposal (9 % of total) (Crippa *et al.*, 2021).

Comparing the environmental footprint of microbial protein production to conventional protein sources reveals promising insights. Despite the energy-intensive steps involved, current calculations indicate that microbial protein can yield lower emissions than beef and lamb (Van Peteghem *et al.*, 2022). Furthermore, microalgal microbial protein has a significantly lower carbon footprint than egg protein concentrate, and mycoprotein-based meat analogues exhibit comparable CO_2 emissions to chicken (Smetana *et al.*, 2015). However, certain commercially available microbial protein-based products have a 1.6 times higher carbon footprint compared to traditional plant-based protein sources (Blonk, Kool and Luske, 2008; Smetana *et al.*, 2017). Approximately 50% of the total greenhouse gas emissions from microbial protein production are attributed to feedstock production, primarily due to CO_2 generation from electricity production (Finnigan *et al.*, 2010; Van Peteghem *et al.*, 2022). Transitioning to recovered or CO_2-derived feedstocks, coupled with using renewable electricity, could substantially reduce CO_2 emissions (Van Peteghem *et al.*, 2022).

Another notable drawback is the need for reduction of nucleic acid content. Current methods result additional capital and operational costs, resulting in a potential 40% increase in total carbon footprint (Van Peteghem *et al.*, 2022). However, calculations show that carbon-neutral microbial protein production can be achieved when linking carbon capture and utilization, and recovering and reusing the metabolically-produced CO_2 (Van Peteghem *et al.*, 2022). Unlike conventional agriculture, which faces challenges in reducing CO_2 emissions due to inherent inefficiencies (Delarue *et al.*, 2011), microbial protein production is done within a closed system, which can be better controlled, thereby offering the possibility to recover and reuse resources.

Technological advancements in the electricity, chemical and biotech sectors present avenues for further minimizing the environmental footprint of microbial protein. Notably microbial protein production does not substantially contribute to land-use emissions, as the required infrastructure occupies minimal space – in the order of magnitude of 0.05 m^2/kg product (Cumberlege, Blenkinsopp and Clark, 2016). In cases where agriculture-derived substrates like glucose are used (where the land required for substrate production should be considered), the CO_2 footprint of microbial protein is drastically reduced to only a fraction (3 – 36 %) of that of animal products (Kazer, Orfanos and Gallop, 2021). It was also recently shown that a full replacement of livestock production with cellular agriculture (cultured meat and microbial protein) can reduce annual emissions by 52%, reduce phosphorus demand by 53% and use 83% less land compared to traditional agriculture (El Wali *et al.*, 2024). These findings show the potential for microbial protein to emerge as a more sustainable protein source compared to animal protein.

However, for microbial protein or any alternative protein source to have a meaningful environmental impact, widespread adoption is necessary. Texture and flavor remain to be optimized to be appealing for the consumer. Balancing economic and environmental considerations may require trade-offs to achieve an appealing product, and understanding public perceptions is crucial in this regard (Eskelinen and Kajanus, 2020). Communication strategies aimed at increasing consumer awareness play a crucial role in driving the adoption of (more) sustainable diets (Poore and Nemecek, 2018). Higher consumer awareness can lead to dietary shifts and influence consumer choices towards low-impact products. Moreover, public opinion strongly influences decision-making, highlighting the importance of consumer demand in shaping production systems (Croney *et al.*, 2018). Incorporating the environmental footprint into food prices, thereby reflecting the "climate cost" of each product, could incentivize consumers to opt for more sustainable choices (Pieper, Michalke and Gaugler, 2020).

A global shift towards more plant-based diets, improved technologies and management, or reduced food losses or waste would not be sufficient to decrease the impact of food production on our environment. Rather, a combination of different new measures is required to counteract environmental pressure (Springmann *et al.*, 2018). In such context, a swift transition towards secure protein production strategies, with low environmental impacts in terms of greenhouse gas emissions and biodiversity loss, is necessary (Davis *et al.*, 2016; Linder, 2019). However, achieving widespread behavioral changes for adoption of microbial protein in diets within the necessary timeframe (*e.g.* to effectively minimize global warming, biodiversity loss) poses significant challenges.

Therefore, while microbial protein and alternative protein sources offer potential sustainability benefits, effective communication strategies, coupled with pricing mechanisms that reflect environmental impacts, are essential for driving widespread adoption of sustainable diets and promoting a more environmentally friendly food chain.

Conclusions

Addressing the increasing global demand for protein while ensuring the sustainability of food systems is a pressing challenge. Exploring alternative protein sources has become paramount, with microbial protein emerging as a promising solution. Microbial protein, the protein-rich biomass of microorganisms, offers a more sustainable means of meeting nutritional needs and plays a crucial role in shaping future food systems. Its potential climate independence provides resilience against climate variability, enhancing food security in the face of environmental challenges.

One of the key advantages of microbial protein lies in the versatility of feedstocks suitable for its production. This versatility offers opportunities to transition towards more sustainable practices in protein production. However, current processes often rely on primary and finite resources such as food-grade sugars, natural gas, fossil fuel-derived nitrogen and mined phosphorus. Transitioning to a circular economy model, where recovered resources are used for protein production, could mitigate these challenges. By repurposing side-streams such as agricultural residues, significant improvements in resource efficiency can be achieved. Nonetheless, challenges persist in reducing CO_2 emissions and ensuring the scalability and cost-effectiveness of these approaches.

Microbial protein can be utilized in various forms in the food industry, such as whole-cell ingredients, protein concentrates, isolates, and hydrolysates, to form alternatives to animal-derived products. The evaluation of techno-functionality and optimization of downstream processing techniques is crucial to determine the suitability of the final product for different applications. Sustainability considerations are essential in choosing downstream processing strategies, with co-extraction of multiple ingredients from whole-cell products as a potential solution to reduce costs and increase eco-friendliness.

Effective legislative frameworks are essential for the widespread adoption of microbial protein as a food source. Streamlining regulations and approval processes can accelerate market entry for novel foods, promoting consumer acceptance and encouraging further innovation in this field. However, existing legislation often creates obstacles to the development and commercialization of microbial protein-based products. Overcoming regulatory complexities and ensuring efficient safety assessments are crucial steps in promoting the widespread adoption of microbial protein.

While microbial protein holds promise as a sustainable protein source, its environmental benefits rely on widespread adoption. Effective communication strategies, coupled with pricing mechanisms that reflect environmental "costs", can incentivize consumer choices towards more sustainable diets. Overcoming barriers to accessibility and affordability will be critical in realizing the potential of microbial protein to contribute to a more sustainable food chain. In conclusion, collaboration across stakeholders, innovative technologies, regulatory bodies, and informed consumer choices are essential for realizing a sustainable food future, with microbial protein playing a central role in this transformation.

Exercises / Group Discussion Questions

Group Discussion Questions

- What would motivate you to consume or stop you from consuming microbial protein?
- Is the environmental impact of the food you consume important for you?
- How can we mitigate the environmental impacts of microbial protein production while ensuring scalability and economic viability?
- How can we address potential barriers to the widespread adoption of microbial protein as a food source?
- How can intensive downstream processing improve or reduce consumer acceptability of microbial protein?
- How can we ensure that microbial foods meet nutritional requirements and contribute to overall health and well-being?
- What policy interventions are needed to support sustainable and responsible production and consumption of microbial foods?
- How can research and innovation contribute to addressing remaining challenges and optimizing the sustainability and efficiency of microbial protein production?

Exercises

Case study:

- Divide participants into groups and provide them with case studies related to microbial protein production from different regions or industries.
- Ask each group to analyze the case study, considering factors such as environmental impact, societal acceptance, health implications, and economic viability.
- Have groups present their findings and discuss the potential implications for sustainable consumption and production.

Scenario planning:

- Present participants with hypothetical scenarios related to challenges or opportunities in microbial protein production (e.g., technological advancements, regulatory changes, market trends).
- Ask participants to brainstorm potential responses to each scenario, considering sustainability, innovation, and stakeholder engagement.

- Encourage participants to discuss the potential outcomes and trade-offs associated with different strategies.

Conflict of Interest

The authors have no conflict of interest to declare.

Further Reading

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