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NSI-BL-2026-002

Single-Cell Protein: Can Microbes Become a Mainstream Source of Global Nutrition?

Microbial biomass can produce protein with limited land, but sustainability depends on feedstock, energy, safety, and consumer context.

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PUBLICATION	COLLECTION	REVIEW	LICENSE
22 July 2026	BioFrontiers Launch Collection 2026	Editorially reviewed	CC BY 4.0

ABSTRACT

Single-cell protein refers to protein-rich biomass or extracted protein produced from microorganisms such as yeast, bacteria, fungi, and microalgae. The idea is not new, but it has gained renewed attention because microbial production can be rapid, vertically scalable, and less dependent on fertile land than conventional livestock or crop protein. Microorganisms can also use diverse feedstocks, including sugars, agricultural side streams, methane, hydrogen, carbon dioxide-derived substrates, and industrial gases. These possibilities have led to claims that microbes could help feed a growing population while reducing pressure on land and climate. The evidence supports genuine potential, but not a universal environmental advantage. Energy source, substrate origin, reactor operation, downstream processing, nucleic-acid removal, digestibility, contamination control, regulation, and consumer acceptance can determine whether a product is sustainable and nutritious. This Article argues that single-cell protein should be understood as a family of production systems rather than one solution. Its strongest role may be where microbial physiology is matched carefully to local resources and a specific use, such as aquaculture feed, livestock feed, nutrition ingredients, or familiar fermented foods.

KEYWORDS single-cell protein; microbial protein; fermentation; alternative protein; food security; life-cycle assessment

ARTICLE AT A GLANCE

- Single-cell protein is a family of microbial production systems, not one uniform product.
- Land-use advantages can be substantial, but energy source and feedstock determine climate performance.
- Protein percentage is insufficient; digestibility, amino-acid quality, nucleic acids, allergens, and contaminants matter.

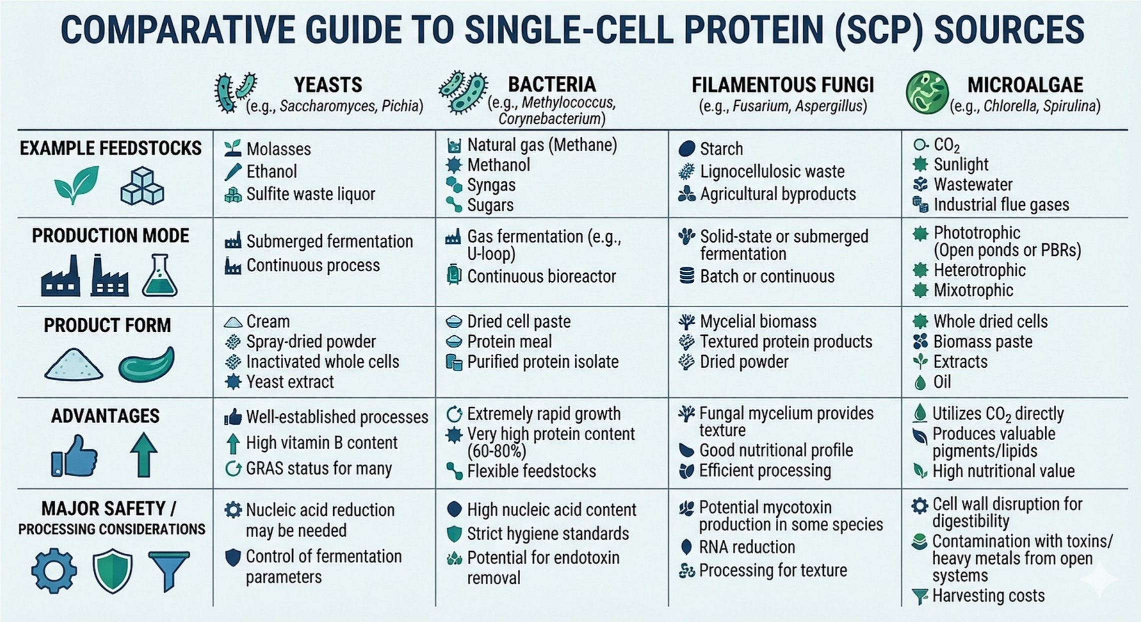

Figure 1. Comparative guide to major single-cell-protein source groups, production modes, product forms, advantages, and processing or safety considerations.

1. An old concept has returned in a new food system

Humans have consumed microbial biomass for centuries through foods such as yeast-containing ferments, edible fungi, and microalgae. The modern term single-cell protein (SCP) emerged when researchers began treating microbial cells as an industrial protein source. Despite the name, the organisms are not always single-celled: filamentous fungi used for mycoprotein are included because the central idea is the controlled cultivation of microbial biomass. SCP products can contain substantial protein together with lipids, fibre, vitamins, minerals, and other cellular components (Anupama & Ravindra, 2000; Ritala et al., 2017).

The renewed interest comes from a structural problem in food production. Protein demand is rising, while livestock and major protein crops compete for land, water, fertiliser, and feed. Microbes grow much faster than animals and many crops, can be cultivated in closed reactors, and may operate throughout the year. Their small physical footprint has encouraged visions of protein factories located near cities, industrial carbon sources, or renewable-energy hubs. Matassa et al. (2016) describe microbial protein as a route that could partially decouple protein production from agricultural land.

That possibility is scientifically important, but the category is too diverse for simple claims. Algae grown in sunlight, yeast grown on molasses, fungi grown on glucose, methanotrophs grown on methane, and hydrogen-oxidising bacteria grown using electricity have different inputs and environmental profiles. The correct unit of analysis is therefore not “SCP versus meat” in the abstract. It is a defined organism, process, feedstock, energy mix, product, and nutritional function compared with a realistic alternative.

2. How microorganisms turn carbon into protein

Microbial cells require carbon, nitrogen, minerals, water, and energy. Heterotrophic organisms such as yeast and many fungi obtain energy and carbon from organic substrates, including glucose, molasses, hydrolysates, or food-processing side streams. Methanotrophic bacteria use methane. Other bacteria can use hydrogen for energy and carbon dioxide as a carbon source. Microalgae use light and carbon dioxide, although large-scale cultivation must manage light penetration, temperature, contamination, and harvesting.

Production usually involves inoculum preparation, fermentation or cultivation, harvesting, washing, stabilisation, and drying. Food applications may require disruption of cell walls, flavour improvement, decolourisation, removal of unwanted metabolites, or reduction of nucleic acids. High nucleic-acid intake can increase uric-acid production in humans, so processing and serving size matter for some microbial biomasses. The product must also be tested for allergens, toxins, heavy metals, pathogens, and residues from the growth substrate (Ritala et al., 2017).

Nutritional quality varies by organism and processing. Many microbial proteins have favourable essential-amino-acid profiles, but digestibility can be limited by rigid cell walls. Heat treatment may improve digestibility while reducing some vitamins. Some microalgae provide pigments and micronutrients; yeasts may contribute B vitamins; fungal biomass can provide fibre-like cell-wall components. A credible nutrition assessment therefore considers amino-acid availability, digestibility, serving size, and the complete diet rather than crude protein percentage alone.

3. The sustainability promise is conditional

SCP can reduce land demand because production occurs in compact reactors and does not require pasture. This advantage is especially strong for processes driven by low-carbon electricity or waste-derived substrates. Modelling suggests that industrial microbial feed pathways could reduce agricultural land use when they replace conventional feed ingredients, although the outcome depends on system boundaries and displaced production (Pikaar et al., 2018). Land sparing can create climate and biodiversity benefits only if the freed land is actually protected or restored rather than converted to another intensive use.

Energy is often the decisive variable. Aeration, agitation, cooling, gas compression, harvesting, drying, and substrate preparation can require substantial electricity or heat. A microbial protein made with coal-intensive power may have a larger climate footprint than the same process supplied by renewable energy. Sillman et al. (2019) showed that protein produced through renewable electricity and carbon capture has long-term potential, but current economics and environmental performance depend strongly on electricity efficiency and infrastructure.

Feedstock choice creates additional trade-offs. Using refined sugar links fermentation to crop agriculture and may shift rather than eliminate land pressure. Using agricultural residues can improve circularity, but hydrolysis may be costly and inhibitors can reduce microbial growth. Methane offers high productivity but leakage can undermine climate benefits. Food waste streams are attractive yet variable and may carry contaminants. Life-cycle assessment must therefore include upstream substrate production, reactor energy, downstream processing, transport, and the fate of co-products.

4. Safety, regulation, and acceptance determine market reality

Microbial protein enters different regulatory pathways depending on whether the organism has a history of food use, whether the cells are alive, whether genetic engineering is involved, and whether the product is whole biomass or a purified ingredient. Regulators may require identity, composition, manufacturing controls, toxicology, allergenicity, stability, and intended-use data. Novel feed ingredients also need evidence for target-animal safety, human food-chain safety, and environmental impact. A technically efficient fermentation process has no market if the product cannot meet these evidentiary requirements.

Consumer acceptance is equally contextual. Products presented as familiar foods, such as fungal mycoprotein or spirulina supplements, may face lower barriers than powders described as bacterial biomass. Taste, colour, odour, texture, price, cultural meaning, and transparent labelling influence adoption. “Microbial” can signal natural fermentation to one consumer and contamination to another. Communication should explain the organism, production process, nutritional role, and safety controls without pretending that all microbial proteins are identical.

Feed markets may scale earlier than direct human food because aquaculture, poultry, and livestock industries already purchase formulated proteins and evaluate ingredients through performance trials. Microbial meals can provide consistent composition and reduce reliance on fishmeal or imported soy, but price and digestibility remain critical. Linder (2019) argues that microorganisms deserve a larger place in food systems, yet integration will occur through specific value chains rather than a single global transition.

5. Where single-cell protein can make the greatest contribution

The strongest applications are likely to combine resource advantage with nutritional need. In regions with abundant molasses or starch-processing side streams, yeast or fungal biomass may add value to existing industries. Near renewable-energy resources, hydrogen-oxidising bacteria could convert electricity and carbon dioxide into protein. In natural-gas or biogas systems with strict methane control, methanotrophs may produce feed. In sunny climates, microalgae can supply specialised nutrition and functional ingredients, although water and harvesting remain constraints.

SCP should also be evaluated as part of a portfolio. Pulses, oilseeds, improved livestock systems, reduction of food loss, and dietary diversification remain essential. Microbial protein does not need to replace all conventional protein to matter. It may reduce pressure in specific sectors, supply protein during climate shocks, strengthen local feed security, or produce high-value ingredients that improve the economics of biorefineries.

The global opportunity is therefore real but disciplined. Microbes offer unusual biological productivity and the ability to use carbon sources unavailable to ordinary agriculture. The scientific task is to identify where those advantages survive full accounting of energy, safety, nutrition, regulation, and consumer behaviour. The future of SCP will not be decided by protein percentage alone. It will be decided by whether a complete production system delivers affordable nutrition with lower total harm than the system it replaces.

6. A research agenda for honest comparisons

Future SCP studies should compare systems on a common nutritional basis. Kilograms of dry biomass are not equivalent when protein concentration, digestibility, essential amino acids, and usable serving size differ. Researchers can report impact per kilogram of digestible indispensable amino-acid score-adjusted protein or per defined animal-performance outcome. Comparisons should include realistic conventional alternatives produced in the same region, not a global worst case selected to make the microbial process appear favourable.

Process studies should publish mass and energy balances. Feedstock input, conversion yield, oxygen demand, heat removal, water recycling, harvesting loss, drying energy, and co-products determine cost and environmental performance. Pilot facilities often operate below industrial efficiency, while models assume future improvements. Both current and projected results are useful when clearly separated. Sensitivity analysis can show which variable must improve before a process becomes competitive.

Nutrition and safety research should move beyond compositional screening. Human-food products need digestibility, tolerance, allergenicity, and repeated-consumption evidence in intended populations. Feed products need long-duration trials, animal-health endpoints, product-quality assessment, and evaluation of residues in meat, milk, eggs, or fish where relevant. This research will narrow the field toward the microbial systems that offer genuine advantages and away from those sustained mainly by broad sustainability claims.

Key takeaways

- Single-cell protein is a family of microbial production systems, not one uniform product.
- Land-use advantages can be substantial, but energy source and feedstock determine climate performance.
- Protein percentage is insufficient; digestibility, amino-acid quality, nucleic acids, allergens, and contaminants matter.
- Feed applications may scale faster than human food because they fit established formulation and testing systems.
- The best opportunities match a microorganism and process to local resources, infrastructure, and dietary needs.

Declarations

Author contributions: All listed authors contributed to literature synthesis, manuscript development, revision, and approval of the publication version.

Funding: No specific funding was reported for this article.

Competing interests: The authors declare no competing interests.

Ethics: Not applicable. This article does not report new research involving human participants, animals, or identifiable personal data.

AI-assisted tools: AI-assisted tools were used for language refinement, structural review, and preparation of selected conceptual visuals. All scientific claims, citations, interpretations, and final text were reviewed and approved by the authors and the NiviScholar editorial team.

How to cite this article

Amruta Bramhadnyan Ashtekar; Gawate Poonam Laxman (2026). Single-Cell Protein: Can Microbes Become a Mainstream

Source of Global Nutrition?. NiviScholar Insights, NSI-BL-2026-002. https://insights.nivischolar.com/articles/single-cell-protein-global-nutrition

References

Anupama, & Ravindra, P. (2000). Value-added food: Single cell protein. Biotechnology Advances, 18(6), 459–479. https://doi.org/10.1016/S0734-9750(00)00045-8

Food and Agriculture Organization of the United Nations. (2022). Thinking about the future of food safety: A foresight report. https://www.fao.org/3/cb8667en/cb8667en.pdf

Good Food Institute. (2024). 2023 state of the industry report: Fermentation. https://gfi.org/resource/fermentation-state-of-the-industry-report/

Linder, T. (2019). Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system. Food Security, 11, 265–278. https://doi.org/10.1007/s12571-019-00912-3

Matassa, S., Boon, N., Pikaar, I., & Verstraete, W. (2016). Microbial protein: Future sustainable food supply route with low environmental footprint. Microbial Biotechnology, 9(5), 568–575. https://doi.org/10.1111/1751-7915.12369

Nasseri, A. T., Rasoul-Amini, S., Morowvat, M. H., & Ghasemi, Y. (2011). Single cell protein: Production and process. American Journal of Food Technology, 6(2), 103–116. https://doi.org/10.3923/ajft.2011.103.116

Pikaar, I., Matassa, S., Rabaey, K., Bodirsky, B. L., Popp, A., Herrero, M., & Verstraete, W. (2018). Decoupling livestock from land use through industrial feed production pathways. Environmental Science & Technology, 52(13), 7351–7359. https://doi.org/10.1021/acs.est.8b00216

Ritala, A., Häkkinen, S. T., Toivari, M., & Wiebe, M. G. (2017). Single cell protein—State-of-the-art, industrial landscape and patents 2001–2016. Frontiers in Microbiology, 8, 2009. https://doi.org/10.3389/fmicb.2017.02009

Sillman, J., Nygren, L., Kahiluoto, H., Ruuskanen, V., Tamminen, A., Bajamundi, C., Nappa, M., Wuokko, M., Lindh, T., Vainikka, P., Pitkänen, J.-P., & Ahola, J. (2019). Bacterial protein for food and feed generated via renewable energy and direct air capture of CO2: Can it reduce land and water use? Global Food Security, 22, 25–32. https://doi.org/10.1016/j.gfs.2019.09.007

Strong, P. J., Xie, S., & Clarke, W. P. (2015). Methane as a resource: Can the methanotrophs add value? Environmental Science & Technology, 49(7), 4001–4018. https://doi.org/10.1021/es504242n