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Research Article

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Biowaste-based microbial protein for sustainable circular food systems and climate mitigation

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Abstract

Agriculture production and waste management is a major source of global greenhouse gas emissions. These emissions, however, can be mitigated by a circular bioeconomy approach that upcycles biowaste into high-value microbial protein capable of displacing animal feed like soybean protein. Here, we assess the global climate mitigation potential of scaling up methanotrophic microbial protein production using biogas derived from animal manure and food waste. We find that biowaste-based microbial protein has a carbon footprint of < 6 kg CO_2e kg^{-1} protein, similar to that of chicken and farmed fish. Its global production potential amounts to 97 Mt of protein by 2050, enough to replace 55% of global soybean protein demand and spare 79 Mha of soybean cropland in 2050. Combining avoided emissions from conventional waste management and soybean production with carbon removal on spared cropland could deliver 30 to 56 Gt CO_2e of cumulative climate mitigation by 2050. The magnitude of these benefits depends strongly on how quickly the microbial protein is scaled up and how the spared soybean cropland is managed. Our study demonstrates the great potential of biowaste-based microbial protein for sustainable circular food systems and climate mitigation.

Keywords: climate mitigation; microbial protein; circular bioeconomy; land sparing; sustainable development

1. Introduction

Food systems are responsible for about one third of the current anthropogenic greenhouse gas (GHG) emissions[1], and animal products account for almost 60% of those emissions[2]. Future agri-food systems confront the challenge of sustainably meeting growing protein demand, amid increasing pressures from climate change[3–5] and socioeconomic development[6,7]. Ensuring the ability to feed the world without exceeding planetary boundaries will necessitate a fundamental transformation of the food system[8].

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Over the past two decades, dietary change has been repeatedly proposed as a key approach to sustainable food systems[9,10]. A shift from meat toward vegetables, fruits, and nuts or alternative proteins such as plant-based meat and microbial proteins has been shown to considerably reduce the environmental footprint of food systems[11,12]. However, wide-scale adoption of these alternative food products has yet to emerge. On the contrary, per capita meat consumption has been steadily increasing, with further increase expected[13,14]. Dietary choices are made in complex food environments such as groceries stores, restaurants, and school cafeteria, and driven by a multitude of factors such as taste, cost, availability, and culture. They are difficult to shift without substantial interventions to those environments and the drivers that shape food decision making[15,16]. Even if sustainable dietary transitions are successful in the end, it could take a generation or longer as it involves changing the behavior of 8 to 10 billion people. This time horizon, however, may impede the climate goals to limit global warming within 1.5 to 2 degrees[17].

While changing the diets of humans is difficult, changing the "diets" of livestock animals is relatively easy. One approach, which uses methanotrophic bacteria to convert biogas from organic waste into a protein-rich biomass[18], is garnering increasing attention[18,19] (Fig. 1). This circular approach has multiple benefits. First, it can be fully implemented using current technologies and ensures food safety. It converts waste into clean gas and then protein, resolving the issue of toxic compounds often associated with biowaste[19]. Methanotrophic microbial protein has a broadly comparable essential amino-acid profile and high digestibility relative to conventional feed proteins such as soybean meal and fishmeal[20,21], and is already approved for animal and fish feed by China, the EU and the USA[20,22]. Second, it can mitigate the methane emissions of biowaste due to the current unsustainable waste management practices such as landfill[23]. Third, it can curb the global environmental impacts of animal feed, especially soybean, whose more than two-fold expansion in recent decades[24], driven by increased meat consumption, has reduced tropical forests and resulted in considerable carbon and biodiversity loss[25].

Despite growing interest in this circular approach, its global climate mitigation potential remains unquantified, with few studies jointly assessing life-cycle emissions of the production process with their consequential impacts on waste management and land use. Moreover, most studies of the environmental impacts of alternative proteins relied on static scenario analyses[26,27], without considering the dynamic changes in future crop yields, food demand, and, most notably, land use. For instance, promoting microbial protein production could help curb the future expansion of soybean cropland or even free up existing soybean cropland.

Here, we perform an integrated life-cycle assessment to quantify the global climate benefit of developing biowaste-based microbial protein for sustainable circular food systems. We first estimate the life-cycle emissions of microbial protein from livestock manure and food waste by building a detailed model that simulates the material and energy use of the production process. Then, we quantify how much protein could be produced in each country from these biowastes and associated avoided GHG emissions from diverting them away from conventional waste management pathways such as landfilling and manure lagoons. Then, we assess the potential land use-related climate benefits from replacing soybean protein with microbial protein. Finally, based on scenario analysis we explore the global climate benefit of scaling up biowaste-based microbial protein production between 2020 and 2050, accounting for the full life-cycle GHG emissions and mitigation benefits as described above.

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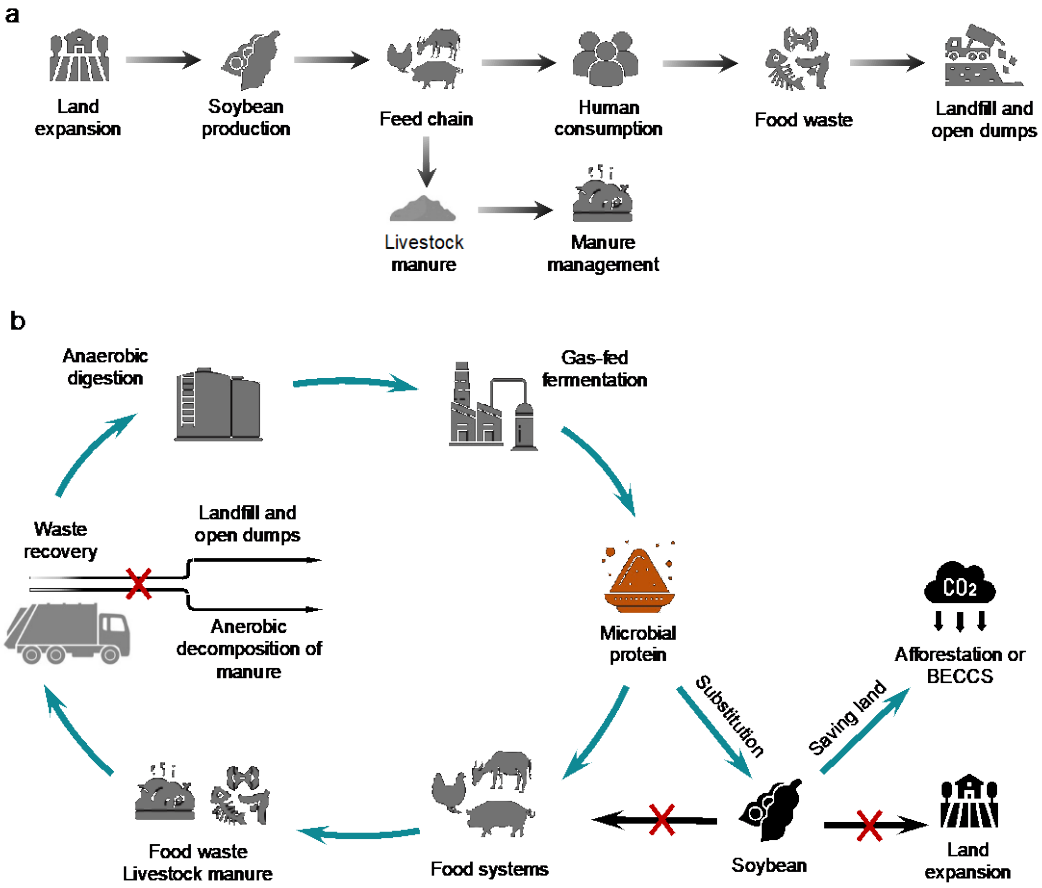


Fig. 1 | Schematic of the current "linear" food system vs a circular food system based on microbial protein made from biowaste. a, The current linear food system, in which large amounts of resources are consumed and wastes generated with little recycling, resulting in massive pollution that harms environmental and human health. **b,** A circular food system that uses biowaste-based microbial protein as animal feed, avoiding, as represented in the red crosses, unsustainable biowaste management and soybean production and associated land use. The spared soybean cropland can be used for afforestation and BECCS (bioenergy with carbon capture and storage).

2. Materials and methods

2.1 Biowaste-based microbial protein production process

This analysis performs a process-based model to evaluate the product-level life-cycle emissions associated with biowaste-based microbial protein, using methanotrophic microbial protein as a proxy. The industrial production process is outlined in *SI Appendix, Fig. S1*, with emissions calculated based on contributions from biowaste transportation and pretreatment, anaerobic digestion, biogas pretreatment, microbial fermentation, downstream processing (separation, drying), digestate management, and clean-in-place procedures.

Livestock manure from industrial production systems and urban food waste are selected as representative feedstocks. Transportation (~40km) and pretreatment requirements (hygienization) are estimated based on current biowaste management practices[28]. Anaerobic digestion (AD) pathway is modeled as the pretreatment of methanotrophic microbial protein production, responsible for converting biowaste into a clean gaseous substrate that provides carbon and energy for the following microbial fermentation. The AD process accounts for the electricity and heat supply required for the digester operation, including biogas leakage rate, based on previously published life cycle assessments (LCA) and techno-economic

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analyses (TEA). The life-cycle inventory of digestate treatment, including digestate storage and land application, primarily drawing from similar works by Javourez et al[29] and Brockmann et al[30]. Before using in fermentation, all biogas generated from anaerobic digestion undergoes purification to remove contaminants and is pressurized to 5 bar for delivery to the bioreactor, requiring chemical and electricity inputs[31]. See *SI Appendix* for further details.

Microbial fermentation takes place in specialized loop bioreactors, aligned with commercial-scale methanotrophic protein production[32–34]. Electricity inputs for fermentation include power for on-site cryogenic equipment that produces pure oxygen required for the fermentation process, operation of the loop reactor (pumping, cooling), media pumping into the bioreactors, and water recirculation[34]. We surveyed the literature to identify microbial yields for each compound required for growth, including methane (1.38 t CH_4 per t dry-matter microbial biomass), oxygen, nitrogen, phosphorus, and inorganic nutrients, as well as the protein content of microbial biomass (See *Dataset*). The biogenic carbon captured by microorganisms is assumed to be released back into the atmosphere during respiration by both the microorganisms and animals, thus having no net effect on climate change. Downstream processing follows the design and energy requirements from Levett et al[35]. After fermentation, the broth is dewatered to 65% moisture via continuous decanter centrifuges, then further dried to 10% using rotary biomass dryers with steam-heated air entering at 100 °C. Bioreactors, inoculation reactors, and pipelines undergo clean-in-place procedures seven times per year, requiring NaOH and nitric acid solutions[36]. The final single-cell protein product is obtained in the form of a fine powder. See *SI Appendix* for further details.

For the product-level life-cycle assessment, energy and material emission intensities are based on current U.S. industrial standards. For the global-level scenario analysis, we use latest country-level carbon intensity of electricity[37] and assumed its dynamic changes from 2020 to 2050 align with current national climate policies[38]. The biowaste-based microbial protein production model, including interlinked calculations, technical parameters, and data sources, is available as an Excel spreadsheet in *Dataset S1*.

2.2 Biowaste availability, microbial-protein potential, and waste-management baselines

Resource potential of wastes. To estimate the potential for microbial protein production, we first examine the resources potential of selected biowaste in each country. The quantities of waste are then multiplied by the various waste-to-protein conversion rates determined by the model to drive the final protein production potential. We focus on two major biowaste sources: (1) manure from cattle, pigs, and chickens raised in industrial production systems; manure from non-industrial production systems, such as grazing systems, was not considered; and (2) urban food waste directed to landfills and open dumps. Only urban food waste is considered collectable.

For livestock manure in industrial production systems, we first obtain country/region-level stock data on cattle (meat and dairy), chickens (broilers and layers), and pigs (breeding and market) from FAOSTAT dataset[39], together with the shares of livestock raised under different production systems from GLEAM 3.0[40]. We then use the Intergovernmental Panel on Climate Change (IPCC) method[41] (Tire 1a) to estimate the annual country-specific and livestock-specific mass (in volatile solid excretion) of manure within industrial systems. For urban food waste ended up in landfill, we calculate the food waste for 54 food commodities based on food supply and food waste statistics (weight%)[42]. Country-level food supply comes from Food Balance Sheets of the FAOSTAT dataset[39], and food waste statistics at the consumption stage are primarily based on research by Zhu et al[23,42]. The final resource potential of food

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waste is determined by the urbanization rate[43] of each country and the market share of landfills and open dumping systems. The market share of landfill and open dumpsite in various countries/regions is obtained from the literature[42].

To project future biowaste availability, we combined income- and trade-dependent projections of country-specific agricultural production and consumption from the EAT-Lancet Commission[10] with UN population projections[44]. Changes in livestock production are used to project future manure availability, whereas changes in food consumption are used to project future food-waste generation. The share of industrial livestock production systems is conservatively held constant through 2050, while projected changes in urbanization are incorporated into estimates of future urban food-waste availability.

Conventional waste-management baselines and avoided GHG emissions. For each waste stream, the baseline represents the GHG emissions that would occur under its conventional management pathway in the absence of diversion to microbial-protein production. For livestock manure, the baseline includes emissions from conventional manure-management practices within industrial livestock production systems. Country- and livestock-specific shares of manure-management systems are obtained from GLEAM 3.0[40], which distinguishes 19 manure-management systems. Methane (CH_4) and nitrous oxide (N_2O) emissions are estimated using the IPCC Tier 2 methodology, accounting for differences among livestock types, production systems, manure-management practices, and regional climatic conditions[41]. The distribution of manure-management systems within industrial livestock production is assumed to remain at its 2020 level through 2050.

For food waste, the baseline includes emissions from urban food waste sent to managed landfills and open dumps. CH_4 emissions are estimated using the IPCC Tier 2 methodology[41], whereas N_2O emissions are excluded because they are considered negligible. Country-specific methane recovery rates of landfill are obtained from government reports and literature reviews[45,46], and no methane recovery is assumed for open dumps. Default values given in the IPCC (2019) report are used for the methane correction factor, methane volume fraction, and oxidation factor[41]. For future projections, landfill management in low-, lower-middle-, and upper-middle-income countries is assumed to improve progressively, such that the overall GHG emission intensity of food-waste disposal gradually converges toward that of high-income countries by 2050. Non-CO_2 emissions are converted to CO_2e using 100-year global warming potentials. See *SI Appendix* for further details.

2.3 Soybean substitution and land-use-related climate impacts

Soybean-protein substitution. Consistent with previous life-cycle assessment studies of alternative protein sources[21,47], we assume a 1:1 substitution of microbial protein for soybean protein on a protein-mass basis. Methanotrophic microbial protein has a broadly comparable essential amino-acid profile and high protein and amino-acid digestibility relative to conventional feed protein sources, including soybean meal and fishmeal[20,48]. Feeding trials across livestock and aquaculture species have further demonstrated substantial substitution potential without adverse effects on animal performance[20,49] (see SI Appendix for details).

Emissions avoided by preventing soybean expansion. The use of microbial proteins can curb future expansion of soybean cropland, thereby avoiding associated land-use change emissions. We assess this by examining the pattern of GHG emissions resulting from the recent soybean expansion.

Here, we estimate carbon emissions from soybean expansion during 2000-2020 at 0.1° resolution, focusing on the carbon loss in the biomass carbon (the sum of aboveground and belowground biomass)

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and soil organic carbon (SOC) during the conversion of natural land to cropland for soybean planting. We used a "space for time" substitution to estimate the biomass loss from soybean expansion[50,51]. For each 0.1°×0.1° grid cell, the biomass loss from the conversion of the natural land to soybean cropland is assumed to be the difference in averaged biomass density between natural land pixels and cropland pixels. A 300-m harmonized global map of biomass carbon density in the year 2010[52] and the 300-m ESA CCI-LC land cover map in the same year[53] are combined to estimate the biomass carbon loss due to soybean expansion. SOC loss after soybean expansion is estimated by an initial SOC density map before human-induced land-use change and the SOC stock change ratio due to the conversion from natural land to cropland[54]. The land sources of soybean expansion were assumed to be the dominant land cover type that had converted to cropland during the last 20 years. By combining biomass carbon loss and SOC loss, we obtained the total carbon emissions from soybean expansion per unit area at the 0.1° × 0.1° grid-cell level (called emission factors of soybean expansion, *SI Appendix, Fig. S3*). Country-level emission factors (EFs) were then estimated by averaging the 0.1° gridded EFs weighted by a gridded soybean expansion map during 2000 and 2020 (see *SI Appendix, Fig. S4*). The gridded soybean expansion map was derived from Spatial Production Allocation Model (SPAM)[55] in year 2000 and 2020. See *SI Appendix* for further details.

Bioenergy with carbon capture and storage (BECCS). The climate mitigation potential of BECCS implementation on soybean cropland at 0.1° resolution relies on the optimal combination of miscanthus and switchgrass, which is found by identifying the energy crops with highest energy yield per grid cell. First, the gridded yield dataset for lignocellulosic bioenergy crops is derived from research by Li et al.[56], based on current technological, climatic, and atmospheric CO_2 conditions. This dataset was developed from a global yield observation dataset using a random forest algorithm based on climatic and soil conditions. Yield growth over the next 30 years is consistent with historical trends, with grass bioenergy crop production increasing by an average of 1.0% per year[57]. Second, life-cycle inventories are developed for biofuel production and CCS based on literature. Energy crops are modelled to produce Fischer-Tropsch (FT) diesel, a common type of biofuel expected to be produced in the future to mitigate climate change in the transport sector[57]. The whole life-cycle GHG balance considers nitrous oxide emissions due to nitrogen fertilizer inputs, supply chain emissions from well to tank for FT fuel production, avoided fossil fuel emissions, soil organic carbon sequestration, and net CO_2 sequestration from CCS. The increase in soil carbon is calculated as current SOC stocks of soybean land multiply by relative change (%) in SOC when land transitions occur. Current SOC stocks of soybean land are derived from Global Soil Organic Carbon Sequestration Potential Map (GSOCseq V1.1)[58] created by FAO. Relative changes in soil organic carbon are based on a recent meta-analysis of global soil organic carbon[59]. See *SI Appendix* for further details.

Afforestation (AF). We use the CO_2 uptake and storage densities map[60] for afforestation combined with the global spatial distribution dataset of soybean cropland to estimate the climate mitigation potential by afforestation. This density map is derived from a recent study by Gvein et al[60], providing afforestation dynamics of coniferous and non-coniferous forests for each grid. Their study utilized Global Forest Model (G4M) driven by SSP2-RCP4.5 multi-ensemble mean climate data from the EC-Earth3 model to quantify the afforestation potentials. G4M has been widely used in the international scientific community and is coupled to the integrated assessment model MESSAGE and the land-based economic model GLOBIOM. The mean annual increment (t C ha^{-1} yr^{-1}) of aboveground stem biomass and a default

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standard factor of 20% of extra biomass (such as branches and roots) are used to estimate the 30-year average carbon sink potential up to 2050[60]. For SOC sequestration through afforestation, we utilize recent studies by Bossio et al.[61] and Powers et al[62].These analyses estimated average SOC accumulation rates of 0.4 Mg C ha^{-1} yr^{-1} in tropical and subtropical afforestation and 0.23 Mg C ha^{-1} yr^{-1} in temperate biomes. See *SI Appendix* for further details.

2.4 Future scenarios of biowaste-based microbial protein

Projecting GHG emissions under business as usual. Business-as-usual (BAU) emissions associated with soybean production include emissions from soybean cultivation and future cropland expansion. We first project the global soybean-feed demand in 2050 based on EAT-lancet projections of future meat demand[10]. This feed demand is then divided by the proportion of global soybean use allocated to animal feed to estimate total soybean demand, yielding approximately 498 Mt in 2050, similar to the previous FAO estimate[63]. Second, dividing the total production of each country in 2050 by its projected yields[64] in 2050 provides the estimated soybean cropland area. Finally, the net change in soybean cropland area in each country is multiplied by the corresponding country-level land-use emission factor to obtain the future emissions from land-use change due to soybean expansion. We assume that land-use emission factors for future soybean expansion will follow the trajectory of the past 20 years. Emissions of soybean production (excluding land use change) are derived from the references[65–67]. Due to the potential for significant uncertainty, sensitivity analyses were conducted on the projected soybean production and soybean yield, as detailed in the Sensitivity Analyses section. See *SI Appendix* for further details. BAU waste-management emissions include emissions from conventional management of industrial livestock manure and urban food waste sent to landfills and open dumps. Current and future biowaste availability and the corresponding waste-management baselines are described in Section 2.2.

GHG emissions under alternative scenarios. In four alternative scenarios, soybean protein is progressively replaced by biowaste-based microbial protein under different deployment trajectories and land-management pathways. All scenarios reach 97 Mt of soybean-protein substitution by 2050. By 2035, substitution reaches 49 Mt in the gradual-deployment scenarios and 78 Mt in the rapid-deployment scenarios, with substitution increasing linearly from 2020 to 2035 and from 2035 to 2050. Overall, the GHG balance comprises five accounting components: emissions from microbial-protein production, avoided emissions from soybean production, avoided emissions from future soybean cropland expansion, avoided emissions from conventional waste management, and carbon removal from afforestation or BECCS on released soybean cropland. GHG emissions for each component were calculated annually from 2021 to 2050 and summed over the study period to obtain cumulative mitigation for each scenario.

Because soybean meal production is associated with the co-production of soybean oil, reducing soybean production also decreases the supply of soybean oil used for food and biofuel[68]. To account for this co-product loss, part of the released soybean cropland is reallocated to oil palm cultivation to compensate for reduced edible soybean oil[27,69], while lignocellulosic bioenergy crops are used to compensate for reduced soybean oil available for biodiesel production[70]. The land required for these co-product replacements is deducted before the remaining released soybean cropland is allocated to afforestation or BECCS. By overlaying the spatial distribution of soybean cropland55 with yield maps of oil palm[71] and lignocellulosic bioenergy crops[56] at 0.1° resolution, we estimate the amount of released soybean

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cropland required for co-product compensation. The proportions of soybean oil used for food and biofuel are derived from FAOSTAT[72]. See *SI Appendix* for further details.

2.5 Sensitivity analyses

The sensitivity analyses were conducted to provide additional insights into the impacts of certain assumptions on the climate mitigation potential of biowaste-based microbial protein. First, projecting emissions from future land use change (LUC) is inherently complicated, and we essentially assumed that future LUC emission factors would be similar to those of the past 20 years (in the BAU scenario). This means we assumed that future land expansion would take place where it has occurred. Here, we developed four alternative scenarios to examine how LUC emission factors would affect our key results. The scenarios considered, based on a review of agricultural land use literature[17,73], were (1) 20% decrease in emission factors for all countries; (2) 20% increase in emission factors for all countries; (3) national-level emission factors from a recent study by Lobell et al.[73]; (4) a single value (333 t CO_2/ha) applied to all countries to represent an extreme scenario where all countries have the same land-use change emission intensity [17]. See *SI Appendix, Supplementary Discussion 2.4* for further details. Second, projections of soybean production and yield in 2050 also influence the amount of additional soybean land needed and the amount of land potentially saved by microbial protein. Greater soybean yields mean less future land expansion and less land savings. We performed sensitivity analyses to understand the effects of different production levels and yields, including a lower[74] (3.24 t ha^{-1}) and a higher[75] (3.8 t ha^{-1}) bound of global soybean yield, as well as a ±10% variation in soybean production. See *SI Appendix, Supplementary Discussion 2.5* for further details.

3. Results

3.1 Life-cycle emissions of biowaste-based microbial protein

We first quantify the carbon footprint, or life-cycle GHG emissions, of biowaste-based microbial protein, as the process is not carbon neutral and is essential for assessing its net climate impact (Fig. 2). Details of unit operations and process flow diagrams are given in *Dataset S1*. The life-cycle GHG emissions per kilogram of protein derived from food waste and manure are found to be less than 6.0 kg CO_2e, with small variation between different waste feedstocks. The primary contributors come from the electricity input required for microbial fermentation processes and anaerobic digestion of waste. Electricity input to microbial fermentation processes, including energy for inlet gas compression, pumping, dehydration, and drying, accounts for 36%–42% of total emissions. Anaerobic digestion processes contribute approximately one-quarter to one-third of the total emissions, mainly due to biogas leakage and energy inputs at the industrial scale. Transportation, bioreactor cleaning, and gas cleanup processes have a negligible impact on the overall emissions footprint.

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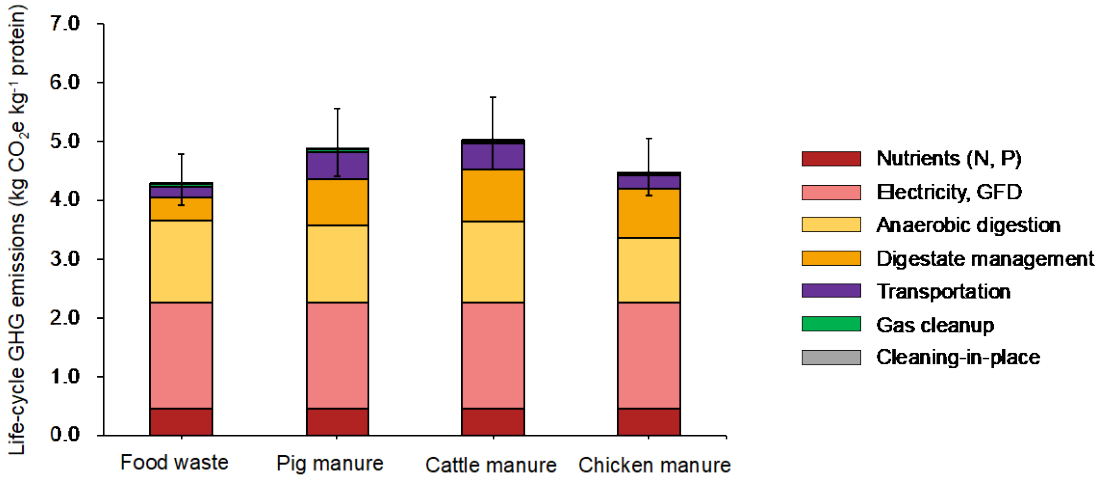


Fig. 2 | Life-cycle GHG emissions of biowaste-based microbial protein by waste feedstock and production stage. The bars show GHG emissions per unit of protein produced from food waste and cattle, pig, and chicken manure, with emissions disaggregated across the major stages of the production process. GFD includes gas pretreatment, fermentation and downstream processes. Error bars indicate the 95% confidence intervals of total life-cycle GHG emissions.

3.2 Biowaste-based protein production potential and GHG savings

After establishing the low carbon intensity of producing biowaste-based microbial protein, we determine its production potential in each country and associated GHG savings obtained by redirecting biowaste from landfill or other conventional systems to microbial protein production facilities (see *Methods*). The biowastes we focus on here are two major sources: 1) livestock manure from cattle, pigs, and chickens raised in industrial production systems, and 2) urban food waste delivered to landfills and open dumps (that is, unmanaged landfills). Prioritizing these two sources of biowaste could yield considerable environmental benefits, because they have a high carbon footprint, pollute the environment, and affect human health[76,77]. Additionally, these wastes are often contaminated[78], but can be safely utilized within the waste-to-protein pathway, with gas as an intermediate.

Fig. 3a shows the microbial protein production potential in major soybean feed protein-consuming countries in 2020. We find that microbial protein produced in most countries could offset more than half of the soybean protein currently used in domestic animal feed. Countries with abundant and concentrated biowaste supply, such as well-developed domestic livestock farming (producing more livestock manure through industrial systems) and larger urban populations (generating more food waste) typically have higher microbial protein production capacities. China, the United States, Brazil all fall into this category. Countries that primarily rely on imported feed proteins, such as China and the EU, can replace 41%–59% of their imported soybean protein with biowaste-based microbial protein (see *SI Appendix, Supplementary Methods 1.2*). This indicates that microbial proteins produced through circular bioeconomy could help to increase the food self-sufficiency of these importing countries and reduce the risk of deforestation associated with soybean trade[79,80].

Repurposing biowastes into microbial protein can help avoid substantial GHG emissions resulting from current unsustainable waste management practices (Fig. 3a). The GHG savings per tonne of protein derived from biowaste range from < 6 t CO_2e (e.g., in Australia) to >14 t CO_2e (e.g., in India). This wide range reflects variations in current waste management practices. For example, high-income countries like

Australia and the United States generally have a lower proportion of open dumps relative to most other income groups, and unmanaged open dumps typically emit more methane (CH_4) to atmosphere[81]. Globally, around 62 Mt of protein could be produced from the studied biowastes in 2020 (Fig. 3b), equivalent to 57% of soybean protein used for animal feed that year, while also saving 840 Mt CO_2e of GHG emissions. This GHG saving potential surpasses the total emissions from global rice cultivation[82] (Fig. 3c). Notably, there is a large disparity in GHG emissions intensities among various types of waste and waste management practices, prioritizing certain wastes to produce microbial proteins might avoid more emissions. For example, food waste contributes less than half of the microbial protein production potential, but accounts for about two-thirds of GHG savings. Overall, repurposing biowastes into microbial protein can contribute to achieving the Global Methane Pledge, which aims to curb 30% of global CH_4 emissions by 2030[83].

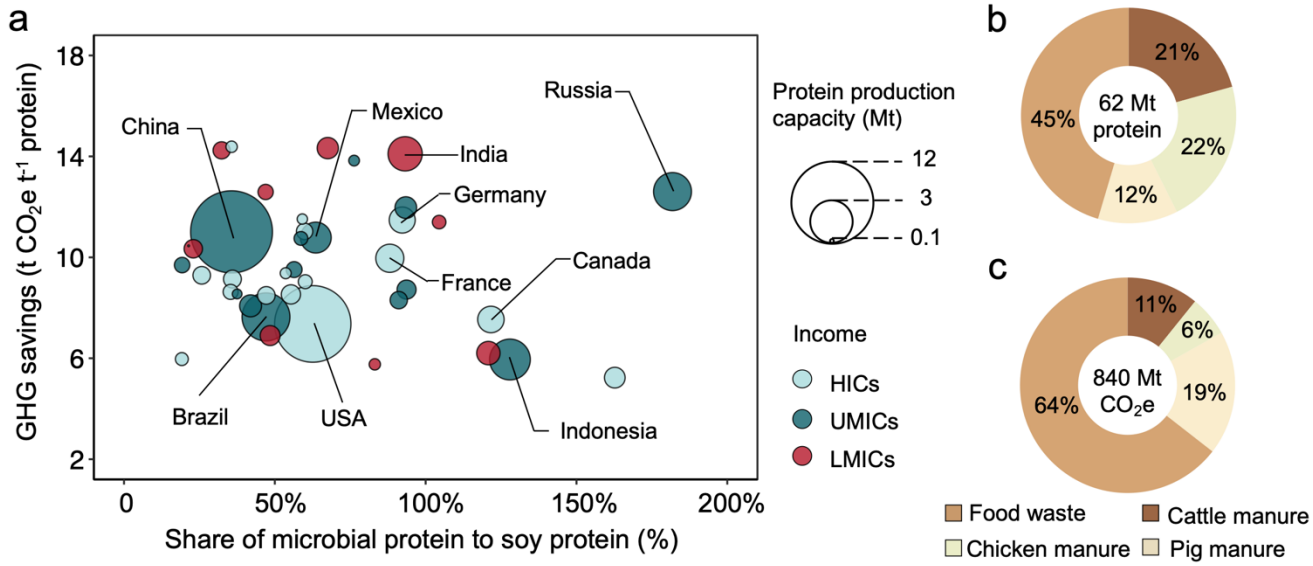


Fig. 3 | Biowaste-based protein production potential and related GHG savings. a, Microbial protein production potential in major soybean feed consuming countries in 2020. Circle size represents the production potential of biowaste-based protein. The x-axis represents the ratio of microbial protein produced in each country to its domestic consumption of soybean protein for feed. The y-axis depicts GHG savings by diverting the waste to microbial protein production facilities instead. **b,** Global microbial protein production potential in 2020. **c,** Global GHG savings due to biowaste diversion in 2020. HIC = high-income countries, UMICs = upper-middle-income countries, LMICs = lower-middle-income countries.

3.3 Land-saving benefits from reduced soybean production

In addition to avoiding GHG emissions from conventional waste management, use of biowaste-based microbial protein to replace soybean protein as animal feed could curb projected soybean expansion and associated land-use change emissions. We assess this by examining the historical carbon emissions from recent soybean expansion using the latest soybean planting area data and a harmonized biomass density dataset (see *Methods*). The cumulative carbon emissions (including losses of biomass and soil organic carbon) due to soybean expansion from 2000 to 2020 amounted to 11.1 Gt CO_2 (see *SI Appendix, Supplementary Methods 1.3*), or about 553 Mt CO_2 a year, which is 15.3% of the global deforestation emissions reported by FAO during the same period[84]. Brazil, the United States, and Argentina were the largest contributors, accounting for about 73.3% of the global land use change emissions from soybean

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expansion. Fig. 4a shows land-use change carbon footprint per tonne of soybean protein produced in each country due to land expansion. In some countries, like the United States and Argentina, the carbon footprint per tonne of soybean protein is relatively low because of higher soybean yields and lower carbon costs of land. In contrast, countries with relatively low yields, such as Russia, exhibit a higher carbon footprint.

The large potential supply of microbial protein could not only avoid future soybean expansion but also displace existing production. This will free up cropland for climate change mitigation opportunities via restoration to native ecosystems or bioenergy production[85–87]. We estimate the mitigation potential of two widely discussed land-management approaches: afforestation (Fig. 4b) and bioenergy with carbon capture and storage (BECCS; Fig. 4c). For these land-based mitigation estimates, the baseline is continued soybean cultivation. Under afforestation, countries such as the United States and Canada, where soybean yields are high and afforestation carbon-sequestration potential is relatively limited, tend to achieve lower mitigation per tonne of soybean protein replaced. On the other hand, using released soybean cropland for BECCS can provide greater mitigation than afforestation while reducing the land-use pressures often associated with large-scale BECCS deployment, such as expansion into natural ecosystems and competition with food production. Overall, the climate mitigation potential per tonne of soybean protein replaced in each country depends on the amount of cropland released and its subsequent management.

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Fig. 4 | Potential land use-related climate benefits from replacing soybean protein (per tonne) with microbial protein in 2020. a, Emissions from soybean expansion during 2000 to 2020. **b, c,** GHG mitigation from freeing up existing soybean cropland for afforestation (**b**) or bioenergy with carbon capture and storage (**c**).

3.4 Global climate mitigation potential

Based on the above analyses, we design five scenarios to analyze the global climate impacts of partially replacing soybean with microbial protein between 2020 and 2050 (see *Methods*). We first project soybean protein demand by 2050 based on global socioeconomic dynamics, such as population and economic growth, and associated land expansion and carbon emissions (i.e., the business-as-usual (BAU) scenario). In four alternative scenarios, we examine the GHG saving potentials of progressively replacing soybean protein with biowaste-based microbial protein, accounting for varying replacement speeds and land management practices. However, soybean protein is associated with the co-production of soybean oil, which is widely used for cooking and biodiesel production. Thus, a decrease in soybean

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protein production due to microbial protein could reduce soybean oil supply, increasing the need for alternative oils. In this case, we assume that part of the released soybean cropland would be repurposed for oil palm fruit cultivation to offset the reduction in soybean oil for food, while lignocellulosic bioenergy crops are introduced to compensate for the decreased soybean oil available for biodiesel production (see *Methods*). As a result, only the remaining land is available for afforestation or BECCS services.

In the BAU scenario, soybean production is projected to rise from 355 to 498 Mt, with global yields increasing from 2.8 to 3.5 Mg ha^{-1}, leading to an expansion of global soybean cultivation by 16 Mha in the next 30 years, reaching a total of 142 Mha by 2050. If soybean cultivation continues to expand along the patterns of land use change and production in the past 20 years, it will result in additional emissions of 11.0 Gt CO_2e during the next 30 years (Fig. 5a), comprising 7.2 Gt CO_2e from the soybean production supply chain and 3.8 Gt CO_2e from land-use change. At the same time, the conventional management of biowaste will generate significant GHG emissions of about 39 Gt CO_2e cumulatively, or about 1.3 Gt CO_2e per year (Fig. 5b).

Fig. 5 | Cumulative GHG mitigation from replacing soybean protein with biowaste-based microbial protein from 2020 to 2050 under different scenarios. a. Mitigation associated with microbial-protein production and soybean replacement, including microbial-protein production emissions, avoided soybean cultivation emissions, avoided future cropland-expansion emissions, and carbon removal from afforestation or BECCS on released soybean cropland. Shaded regions indicate 95% confidence intervals. **b.** Additional mitigation from avoided conventional waste management, including avoided emissions from manure management and food-waste disposal. c, Cumulative GHG mitigation relative to BAU. Positive contributions indicate climate benefits, whereas negative contributions represent emissions

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from microbial-protein production. BAU denotes the baseline scenario. In the Gra.AF and Gra.BECCS scenarios, microbial-protein deployment increases linearly from 2020 and reaches its full modeled potential by 2050, with released soybean cropland used for afforestation and BECCS, respectively. In the Rap.AF and Rap.BECCS scenarios, microbial-protein deployment proceeds more rapidly, with released cropland similarly used for afforestation and BECCS. (see Methods for scenario details).

In the alternative scenarios, manure from industrial livestock systems and urban food waste that would otherwise be landfilled could support the production of approximately 97 Mt of microbial protein by 2050. This amount could replace about 55% of total global soybean protein demand in 2050, corresponding to approximately 68% of the soybean protein projected to be used in animal feed. Although all alternative scenarios reach the same substitution level by 2050, they differ in the pace of microbial-protein deployment.

Reduced soybean demand would first avoid future soybean cropland expansion and, with further substitution, release existing soybean cropland from production. Across the alternative scenarios, microbial-protein substitution could avoid approximately 16 Mha of land clearing for future soybean expansion and spare about 63 Mha of existing soybean cropland by 2050, resulting in a total reduction of approximately 79 Mha in soybean land use relative to BAU. Around 22% of the spared land would be required for palm-oil and biofuel production to compensate for the reduced supply of soybean-oil co-products in global markets.

Figure 5a quantifies afforestation and BECCS as two explicit land-management scenarios for the remaining released cropland. Relative to BAU, soybean replacement together with these land-management pathways could reduce cumulative GHG emissions by approximately 13 Gt CO_2e in the Gra.AF scenario and up to 33 Gt CO_2e in the Rap.BECCS scenario over 2020–2050. These estimates account for emissions from microbial-protein production, avoided soybean cultivation emissions, avoided emissions from future soybean cropland expansion, and carbon removal from afforestation or BECCS on released cropland. Faster deployment results in earlier avoidance of soybean expansion and earlier release of existing cropland, thereby increasing cumulative mitigation over the study period. BECCS provides greater carbon-removal potential than afforestation in our modeled scenarios.

Meanwhile, diverting livestock manure and urban food waste from conventional management systems could avoid an additional 17–23 Gt CO_2e over 2020–2050 (Fig. 5b). These reductions arise from avoided emissions from manure management and food-waste disposal and depend primarily on the pace of microbial-protein deployment. High-income and upper-middle-income countries contribute the largest shares of these avoided waste-management emissions.

Considering both soybean-replacement mitigation and avoided conventional waste-management emissions, the transition to biowaste-based microbial protein could provide 17.1–21.4 Gt CO_2e of cumulative mitigation over 2020–2050 without accounting for carbon removal from afforestation or BECCS (open diamonds in Fig. 5c). When the additional carbon-removal potential of afforestation or BECCS on released soybean cropland is included, cumulative mitigation increases to 29.8–55.6 Gt CO_2e (solid diamonds in Fig. 5c). The magnitude of this mitigation depends jointly on the pace of microbial-protein deployment and the subsequent management of spared soybean cropland.

4. Discussion

In this study, we highlight and demonstrate that biowaste-based microbial protein can contribute to sustainable circular food systems and has a large climate mitigation potential. While microbial protein

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could replace human food directly[88], our analysis focuses on it being a feed substitute, because in the short term this can be more likely to scale. Future research could explore broader environmental benefits and applications. For instance, reducing soybean production may lower risks from extreme weather[89] and trade disruptions[80], decrease pesticide impact on human health[90], and reduce pollution from conventional waste management[76]. Additionally, biowaste-based microbial protein can replace fishmeal, offering higher economic value while supporting sustainable aquaculture and ocean conservation[91].

Innovative technologies such as microbial proteins can help support the transition to sustainable waste management and food system, but their implementation often involves trade-offs among environmental, social and economic outcomes. Economically, biowaste-based microbial protein is currently more expensive than soybean protein, with costs 1.8–2.8 times higher on a pure protein basis. However, when considering social costs, such as carbon emissions, microbial production can become cost-competitive, with food waste-derived microbial protein costing over 70% less than soybean protein, and manure-derived microbial protein being comparable to soybean protein (see *SI Appendix, Supplementary Discussion 2.2*). To move forward, more pilot-scale demonstrations and thorough techno-economic analyses are needed to determine the minimum viable scale of biowaste-based microbial protein production at the regional level, which is essential for enhancing local feasibility. This analysis must cover the entire supply chain, including all costs and revenues, government subsidies, avoided costs (e.g., manure management and landfill fees), external environmental costs, and collection and transportation expenses and so on.

Beyond cost competitiveness, the widespread adoption of biowaste-based microbial protein systems will require both technological advances and policy support. This study assumes that, by 2050, manure from industrial livestock systems and urban food waste sent to landfills or open dumps can be fully utilized for microbial protein production. Industrial livestock systems, with their high-density production and centralized management, facilitate manure collection. Because we conservatively hold the share of industrial livestock production systems constant through 2050, future collectable manure availability could be underestimated if livestock production becomes more industrialized. Food waste, in contrast, is more dispersed and requires stronger collection policies and infrastructure.

Practical constraints related to waste collection, transport, facility capacity, and supporting infrastructure could limit the fraction of available waste that can ultimately be utilized. We considered a more constrained scenario in which only 50% of the available waste included in our analysis is utilized for microbial-protein production by 2050, with utilization increasing linearly over time. Under this scenario, approximately 39.2 Mha of soybean cropland is released by 2050, about half of that under full utilization, while cumulative climate mitigation declines to 14.8–18.7 Gt CO_2e, depending on subsequent land management. The proportionally larger reduction in cumulative mitigation reflects the slower release of cropland and the shorter period available for land-based carbon removal before 2050. This highlights the importance of relatively rapid scale-up for realizing the mitigation potential estimated in our main scenarios. Our scenarios should be interpreted as estimates of potential mitigation under large-scale deployment rather than forecasts of realized adoption. Achieving such scale-up will require stronger waste-collection systems, transport and processing infrastructure, and sufficient production capacity. South Korea, for example, has achieved a 98% food-waste recycling rate following implementation of a nationwide landfill ban in 2005[92], illustrating the potential role of supportive policy and infrastructure. Low- and middle-income countries may require greater financial and infrastructure

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support, while global initiatives such as the Lowering Organic Waste Methane Initiative could help accelerate biowaste recovery and microbial-protein development[93]. Modular fermentation technologies may further improve the scalability of production associated with small- and medium-sized anaerobic digesters[33].

Our findings demonstrate that transitioning to microbial protein can free up cropland for land-based mitigation strategies. However, the climate benefit ultimately depends on how this land is subsequently used. Released cropland could be allocated to afforestation or BECCS, as modeled here, but could also be repurposed for other agricultural production. Our supplementary analysis suggests that the mitigation potential of such alternative uses would likely fall between those of continued soybean cultivation and dedicated land mitigation strategies (afforestation and BECCS), particularly if they reduce pressure for agricultural expansion and associated land-use change elsewhere[73] (see *SI Appendix, Supplementary Discussion 2.3).* Similar spatial displacement could occur for compensatory oil-palm production: although our scenarios assume that oil palm is cultivated directly on released soybean cropland, production could occur elsewhere in practice, leading to unintended land-use consequences not captured in our analysis. Appropriate land-use planning and safeguards will therefore be important to avoid additional conversion of natural ecosystems and to realize the potential climate benefits of released soybean cropland.

One limitation of our study is related to the land use change emissions due to soybean expansion. Following previous studies[94,95], we assume that future land-use change emission factors of soybean expansion would continue to follow the trajectory of the past 20 years (in the BAU scenario). Projecting future soybean expansion is inherently uncertain. However, our sensitivity analysis, which considers different land-use change emission factors, shows that total climate mitigation potential of scaling up microbial protein ranges from -3% to 20% relative to our main scenario (see *SI Appendix, Supplementary Discussion 2.4*), without affecting our conclusions. Projections for soybean production and yield in 2050 may also influence the potential of biowaste-based microbial protein. Numerous uncertainties, such as adverse climatic conditions and policy changes, can affect future soybean yield and production. To address this, we performed sensitivity analyses using different production and yield scenarios. Results indicate that these uncertainties have a very limited impact on the climate mitigation potential and land-saving benefits of biowaste-based microbial protein (see *SI Appendix, Supplementary Discussion 2.5*).

Discussion around sustainable food systems has recently centered around dietary transition, particularly by reducing meat consumption, to mitigate the adverse environmental impacts of agriculture[10,17,94]. However, the feasibility of sustainable dietary transition, including the scale and pace needed to be meaningful, remains debatable. The potential of biowaste-based microbial protein triggers a rethinking of what strategies we might prioritize in the near term. As we push for diet change, we believe it is crucial to invest in innovations like biowaste-based microbial protein that provide immediate and actionable win-win solutions for food production and climate change mitigation. We should also mobilize more climate finance to unlock other untapped solutions within food systems beyond the commonly discussed ones.

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Author contribution statement

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All the authors have approved the final manuscript.

Data availability

The data that support the findings of this study are included in the article or supplementary Dataset 1 and Dataset 2.

Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

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Use of AI statement

None

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Electronic Supplementary Material

Supplementary material (supplementary methods and discussions on life-cycle assessment, biowaste resources, land-use change, BECCS, afforestation, future scenarios and sensitivity analyses, together with detailed life-cycle inventories and calculation datasets) is available in the online version of this article at https://doi.org/10.26599/CS.2026.9510012.

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