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# Environmental impacts of alternatives to animal-source foods: a scoping review

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**Drawing on a comprehensive systematic search of the literature, this scoping Review examined 125 studies on the environmental impacts of alternatives to animal-source foods (Alt-ASFs) compared with conventional animal-source foods. Alt-ASFs generally required fewer natural resources and produced lower greenhouse gas emissions than animal-source foods, with the most consistent advantages observed for plant-based foods. Environmental impacts of insect-based, fungi-based, algae-based, and cell-based alternatives were more variable than plant-based alternatives, reflecting differences in production methods, processing intensity, and energy sources. The evidence base was concentrated in high-income countries, with low coverage of low-income and middle-income contexts. Moreover, analyses of ecological dimensions beyond greenhouse gas emissions, land and water use—such as biodiversity, ecosystem functioning, and resource cycling—were comparatively scarce. Taken together, the evidence suggests that Alt-ASFs can contribute to more sustainable food systems relative to those with higher reliance on animal-source foods (particularly in high-income settings), but the scale and consistency of benefits remain sensitive to production practices and analytical assumptions underlying comparative analyses.**

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## Introduction

Animal-source foods, including meat, fish, eggs, and dairy, are integral to diets worldwide, yet account for some of the most resource-intensive and emission-intensive components of food systems.[1,2] Livestock production contributes disproportionately to climate change, biodiversity loss, freshwater depletion, and soil and air pollution, accounting for 12–18% of global anthropogenic greenhouse gas emissions and extensive land conversion for feed production.[3,4] Global demand for animal-source foods continues to rise, with the steepest increases projected in low-income and middle-income countries, further intensifying pressures on ecosystems.[5,6] Consequently, questions on the role of animal-source food in diets—or which alternative nutrient-dense foods could replace them—have become central to debates on planetary health, with far-reaching implications for climate change mitigation, sustainable land and water use, and the resilience of food systems.

Alternatives to animal-source foods (Alt-ASFs)—including plant-based analogues; fungi-based products; and algae-based, insect-based, and cell-based systems (such as cultured meat and precision fermentation)—are increasingly being positioned as part of the solution.[1,4,7–10] These products are marketed as lower-impact substitutes for conventional livestock and aquatic animals, and have attracted substantial investment, research attention, and consumer interest. Although plant-based alternatives are now mainstream in many high-income markets, fungi-based, algae-based, insect-based, and cell-based foods remain in earlier stages of commercialisation.[4] Despite rapid expansion, however, empirical understanding of the environmental impacts of Alt-ASFs is fragmented. Studies vary widely in scope, assumptions, and methods, thereby restricting the ability of policy makers and other stakeholders to identify the conditions under which Alt-ASFs provide environmental benefits.

The urgency of consolidating this evidence is both scientific and driven by policy. Calls for food-system transformation(s) feature prominently in international fora such as the UN Food Systems Summit and the latest Conference of the Parties climate negotiations, and are widely reflected in academic research, wherein shifts away from conventional animal-source foods are often framed as a protein transition and positioned as a sustainability imperative.[4,7,11,12] Yet, without synthesis, there is a risk that decision making is shaped by selective evidence, commercial claims, or assumptions that might not hold across contexts. Crucial blind spots (including scarce data on emerging categories and on production systems in resource-constrained regions) risk skewing research priorities and policy trajectories.

This scoping review addresses these gaps by systematically mapping the peer-reviewed literature on the environmental impacts of Alt-ASFs, as compared with those of conventional animal-source foods. We characterised the volume and distribution of existing studies, synthesised findings across environmental outcomes, identified methodological and geographical gaps, and highlighted how choices in study design shape reported impacts. By providing a comprehensive synthesis of environmental trade-offs across plant-based, fungi-based, algae-based, insect-based, and cell-based alternatives, we aim to inform evidence-based policy, investment, and product-development strategies. Importantly, we treat Alt-ASFs not as inherently sustainable but as context-dependent innovations whose impacts depend on production systems, energy sourcing, scale, and governance.

## Methods

### Search strategy and selection criteria

Full details on methods, including database-specific search strategies, are provided in appendix 1. A review protocol

See Online for appendix 1

For more information, see https://osf.io/27bze/

See Online for appendix 2

was registered on July 1, 2024, on the Open Science Framework. The steps of this scoping review follow the framework proposed by Arksey and O'Malley.[13] This scoping review was reported in accordance with the PRISMA extension for scoping reviews.[14] Amendments to the protocol are available on the Open Science Framework project page. The review team included subject matter experts in Alt-ASFs and environmental sustainability, and methodological experts in evidence synthesis.

The search strategy included the following key concepts: animal-source foods, environmental impacts, and Alt-ASFs (including plant-based, fungi-based, algae-based, insect-based, and cell-based foods). Search strategies were developed in the Web of Science Core Collection by an evidence-synthesis librarian and then translated to additional databases. Citation chaining was not performed as outlined in the protocol because of the large number of records retrieved and time constraints, which is a limitation of the Review.

The following three databases were searched on July 1, 2024: Web of Science Core Collection, including SCI-EXPANDED, SSCI, AHCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, and IC (Web of Science, 1900–present), CABI: CAB Abstracts (Web of Science, 1910–present), and Environment Index (EBSCOhost, 1888–present). Article screening was performed in two phases: title and abstract screening and full-text screening. Titles and abstracts were screened against predetermined eligibility criteria (appendix 1 p 2) in Covidence by two independent reviewers, and conflicts were resolved by a third reviewer. Peer-reviewed studies were considered eligible when they assessed environmental outcomes of at least one Alt-ASF and included a direct comparison with animal-source foods. To preserve comparability, studies were included only when environmental impacts of Alt-ASFs and conventional animal-source foods were assessed within the same analytical framework, requiring consistent system boundaries, functional units, and methodological assumptions, whether through primary modelling of both product types or harmonised scenario construction within a single study. Any article that met no exclusion criteria was advanced to full-text screening. Full texts were screened against the same eligibility criteria by two independent reviewers, with conflicts resolved by a third reviewer. Only studies meeting all inclusion criteria were advanced to data extraction, and reasons for exclusion were documented.

### Data extraction

Before beginning data extraction, a pilot test of five included articles was conducted to establish inter-rater agreement. A librarian not involved in data extraction selected five random records that passed full-text screening. The pilot test was conducted in Microsoft Excel using a predesigned extraction template (appendix 1 p 1). Results and discrepancies were discussed, and a finalised template was produced. The first batch of studies (n=93) was manually extracted by three independent reviewers into the extraction template. A fourth independent reviewer checked 10% of the included articles for extraction accuracy. For the second batch of studies (n=32), artificial intelligence (AI)-assisted pre-extraction was used to populate fields in the same extraction template. AI-generated entries were treated as preliminary and were systematically verified against the full-text articles by an independent reviewer, with discrepancies corrected as needed. Appendix 2 includes all extracted entities. Classification of ultra-processed foods was conducted as part of data extraction and followed NOVA4 as closely as possible with available information, but is not reported quantitatively due to insufficient details in the included studies.[15]

### Data synthesis

Quantitative data—including the extent, range, and nature of the evidence, and data gaps—were synthesised and analysed using R version 4.4.2. Data were extracted for environmental outcomes, including greenhouse gas emissions, land and water use, eutrophication, acidification, pollution (eg, particulate matter formation and ecotoxicity), biodiversity, and others (appendix 1 pp 23–26). Qualitative data were synthesised descriptively and summarised by Alt-ASF category and environmental indicator. Particular attention was paid to methodological variation in lifecycle assessment (LCA) studies, including system boundaries, functional units, and comparator selection. Wherever possible, findings were grouped to illustrate trends while also noting areas of inconsistency or sparse evidence.

## Results

The search identified 14 675 unique records (figure 1). 9086 records were excluded after title and abstract screening, and 575 full-text articles were screened for eligibility. 183 studies met the inclusion criteria, of which 125 focused on foods for human consumption and have been analysed in this manuscript (appendix 2). Animal feed studies were screened but excluded at extraction, to retain a consistent focus on environmental outcomes of products intended for human diets.

The number of qualifying publications increased substantially over time and varied by Alt-ASF category (figure 2). Plant-based foods were the most frequently compared with conventional animal-source foods (n=93), including 24 on plant-based milks. Cell-based (n=23), insect-based (n=21), fungi-based (n=16), and algae-based (n=11) alternatives were less represented, whereas composite products were rare (n=6). 45 studies covered more than one category.

Comparator choice was uneven across the literature. Across Alt-ASF categories, comparisons were concentrated around specific conventional animal-source foods, particularly red meat and poultry (appendix 1 p 33). Although isolated product substitutions were predominant (n=98), multiple comparator pairings within single studies were

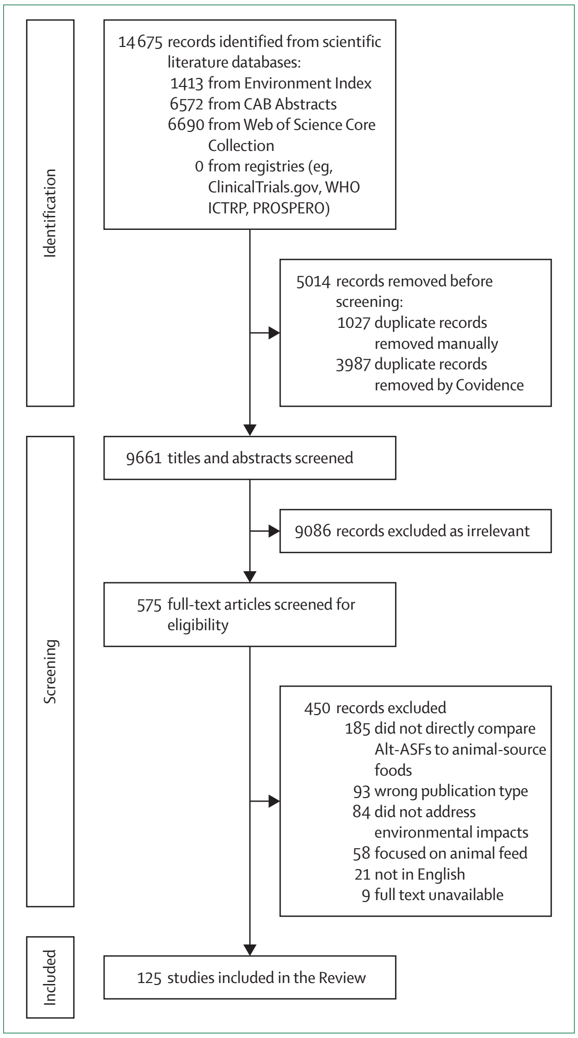


*Figure 1:* **PRISMA flow diagram**
Alt-ASF=alternatives to animal-source food.

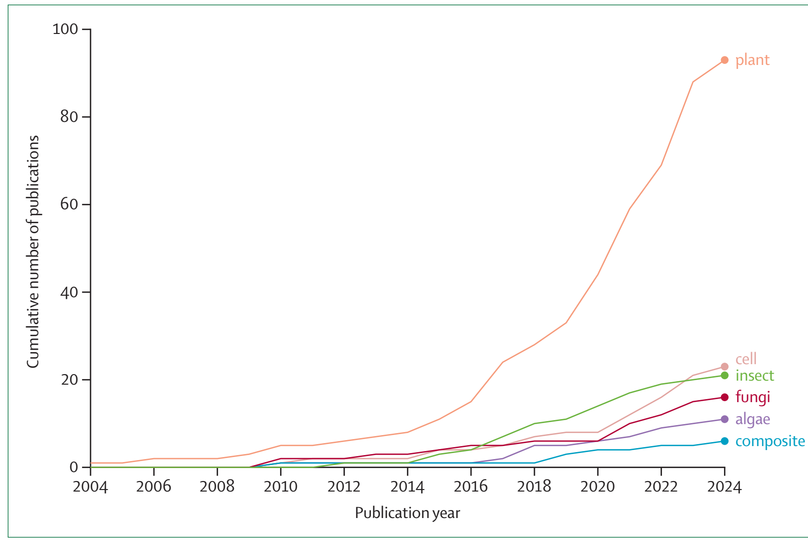


*Figure 2:* **Cumulative publications between 2004–24 by Alt-ASF type**
Alt-ASF=alternatives to animal-source food.

also common (n=26), reinforcing that a meaningful portion of the evidence is based on multiproduct analyses.

Most studies were conducted in high-income countries (n=114), with far fewer from upper-middle-income (n=15), lower-middle-income (n=2), and low-income (n=2) settings—classified according to the World Bank country and lending group definitions.[16] The USA accounted for the largest share (n=28), followed by Germany (n=21), the Netherlands (n=16), the UK (n=13), and Nordic countries such as Sweden (n=10) and Finland (n=9) (figure 3). Contributions from countries outside the Organisation for Economic Co-operation and Development were scarce. Except for China (n=9) and Brazil (n=4), most non-Organisation for Economic Co-operation and Development countries were represented by only one or two studies. A small number of publications spanned multiple countries, including the EU (n=2), sub-Saharan Africa (n=1), and a global analysis (n=1).

Coverage of environmental indicators varied considerably by outcome type and Alt-ASF category. The most assessed indicators were greenhouse gas emissions (n=111), land use (n=85), water use (n=66), eutrophication (n=51), non-renewable resource use (n=51), and acidification (n=44) (appendix 1 p 34). Broader ecological measures, including biodiversity and pollinator services, were assessed only sporadically.

Plant-based foods accounted for the largest absolute number of indicator assessments across nearly all outcome categories (figure 4). In contrast, insect-based, algae-based, fungi-based, cell-based, and composite products were less frequently assessed.

Methodologically, most included studies (n=92) relied on LCA. Several studies (n=40) assessed resource-use efficiency (eg, nitrogen, land, or water), outside the LCA framework. A small number applied geospatial modelling or remote sensing (n=5) or field-based environmental assessments (n=2), with some combining multiple approaches.

Across methods, studies most often reported midpoint indicators (n=121)—metrics that characterise potential environmental pressures—such as greenhouse gas emissions, land use, and water use (appendix 1 p 35). Fewer used activity-based measures (n=39), which quantify raw inputs without translating them into impact assessments, or endpoint indicators (n=30), which estimate downstream effects on ecosystems or human health.

Alt-ASFs generally have lower environmental footprints than conventional animal-source foods across multiple impact categories (figure 5), including greenhouse gas emissions, land use, water demand, and nutrient-use efficiency. Evidence is most abundant and consistent for plant-based alternatives; for other Alt-ASFs, findings also generally indicate environmental advantages, although

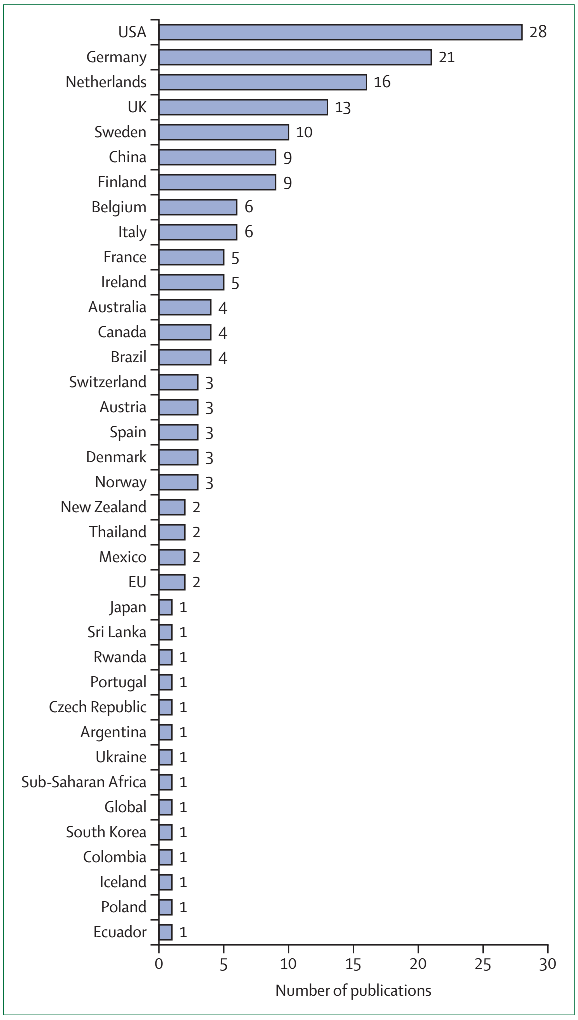


*Figure 3:* **Distribution of publications between 2004–24 across countries**

magnitudes vary with product type, processing intensity, region, and energy mix. Although substitution of animal-source foods with Alt-ASFs—as represented in comparative assessments—typically lowers resource use and climate burdens, gains might be offset in part by energy-intensive processing or ingredient-specific impacts, especially for novel categories.

Plant-based Alt-ASFs consistently present lower burdens than animal-source foods for greenhouse gas emissions, land occupation, and most nutrient-related indicators, including eutrophication potential. Advantages stem largely from lower land use, bypassing enteric methane and manure management, avoiding feed-crop cultivation for livestock, and achieving higher plant-to-protein conversion efficiencies.[17–22] Whole-food formats (eg, tofu, tempeh, minimally processed legumes, and grains) are typically the lowest-impact options—with 80–95% lower emissions and 85–95% less land use than those for beef or pork.[23–25] Formulated meat analogues generally retain a climate and land advantage over beef—and often, over pork and poultry—although processing (extrusion, freezing or refrigeration, emulsification) shifts a larger share of impacts to the factory gate and distribution stages. Performance varies with ingredient choice and sourcing. Legumes usually score well: across LCAs, pea-based, soy-based, and lentil-based burgers or mince typically show 70–95% lower greenhouse gas emissions and 60–90% lesser land use than red meat.[24,26–29] However, risk of land-use change and pesticide profiles in specific soy supply chains can erode benefits;[30–32] cereal-based and pea-based analogues tend to be robust performers wherever yields are high and deforestation risks are low.[25,33] Oil-dominated and nut-dominated recipes can raise water-scarcity or eco-toxicity burdens, and multi-ingredient blends can introduce trade-offs in toxicity categories linked to crop protection chemicals or processing-stage cleaning agents.[29,31,32,34–38] Taken together, the advantages of plant-based alternatives are consistently observed across most contexts, with their magnitude shaped by processing intensity, electricity sources, and ingredient provenance.

Plant-based milk alternatives generally present advantages to the environment over dairy milk, although the extent and direction of benefits vary by impact category. Across LCAs, plant-based drinks consistently present lower greenhouse gas emissions than dairy milk—often around 50–70% lower per litre, and in some cases, even greater,[30,39–41] with soy drinks performing especially well.[42] Studies also show lower land requirements for plant-based drinks versus dairy; for example, oat, soy, and rice drinks require roughly 16–23% of dairy's land footprint.[40,43] Water use differs sharply across plant-based milks. Soy and oat generally require far less water than dairy, whereas almond and rice can be more water-intensive, with rice linked to paddy irrigation.[35,37,40,44] Across studies, plant-based milks generally showed lower nutrient flow and pollution impacts on soils and waterways than dairy, although results varied by product and assessment method.[30,40,45] Fortification and processing can further increase footprints by 15–25%,[46] and transport can add additional impacts;[31,47] yet, overall LCAs consistently present lower burdens for plant-based milk alternatives than for dairy.

Cell-based Alt-ASFs (cultured meat) can offer large potential reductions in land use—typically 80–99% lower than that for conventional beef—by eliminating feed and grazing requirements.[9,10,48–50] However, the industry is nascent and most evidence comes from ex ante, scenario-based LCAs and forward-looking projections, many of which draw on modelled or proprietary process data, with outcomes sensitive to assumptions about feedstock, energy sources, and production scale.[51,52] LCAs generally indicate 70–95% lower greenhouse gas emissions for cell-based Alt-ASFs than for beef, although outcomes depend strongly on electricity source and growth media composition.[49,53,54] Under renewable-energy scenarios, several studies project carbon intensities in the single-digit kg $CO_2$-eq $kg^{-1}$ range—placing cell-based alternatives at or below the lower end of conventional animal-source foods.[48–50] In contrast, studies assuming fossil-dominant or average grid electricity often present substantially higher climate impacts, in some cases approaching those of efficient poultry or dairy systems, underscoring that climate benefits are conditional rather than intrinsic to the production technology.[53,55,56] By eliminating enteric fermentation and manure handling, cultured systems remove major methane sources, but their long-term advantage hinges on low-carbon energy access, and scaling could shift pressures towards rare-earth metal use in bioreactors and renewable infrastructure.[56,57] Water-related impacts vary widely: most ex ante LCAs report 80% or more savings versus beef,[48–50] although outcomes change once bioreactor utilities, cleaning, and regional water-scarcity weighting are included.[55] Eutrophication, acidification, and ecotoxicity generally improve relative to those for beef and pork, but remain sensitive to wastewater treatment and nutrient recycling, with several studies noting that integration with circular-energy or nutrient-recovery pathways could materially influence these outcomes.[52,58,59] Process-waste streams and crucial material demands are still poorly quantified, and current LCAs rely heavily on modelled, proprietary inventories.[49,52]

Insect-based Alt-ASFs generally show consistent environmental advantages over conventional animal-source foods. LCAs indicate that insect production emits substantially lower greenhouse gases than beef (often 70–90% lower) and generally lower emissions than pork or chicken, owing to efficient feed conversion, absence of enteric methane, and lower land requirements.[60–63] However, controlling temperature and humidity in rearing facilities is the dominant energy-using aspect of insect production, causing performance to vary with geography and energy source.[62,64] Land use is dramatically reduced: LCAs show that food-grade mealworm and black soldier fly systems use 60–75% less land than pork or poultry and under one-tenth that of beef,[60–63] with similar reductions observed for grasshoppers and drone brood.[65,66] Across studies, insects typically use 40–80% less freshwater than beef, pork, or chicken, with modelled substitution scenarios showing comparable savings; insect-derived oils also outperform animal fats, underscoring strong overall water efficiency.[10,38,67,68] Both feed sources and downstream processing steps shape outcomes: insects raised on food or agricultural by-products achieve added sustainability gains through waste valorisation,[62,68] although some systems rely instead on conventional feed inputs (eg, wheat bran, maize and brewer's yeast).[63] Energy-intensive processing such as freeze-drying can also offset some benefits.[69] Despite these trade-offs, insect-based foods generally retain strong environmental advantages across major impact categories, including greenhouse gas emissions and land and water use.

Fungi-based Alt-ASFs, primarily mycoprotein (eg, Quorn), generally present lower environmental impacts than conventional meat, owing to efficient conversion of carbohydrate feedstocks into edible microbial mass, rapid growth cycles, and, relative to ruminants, the absence of enteric fermentation. Across LCAs, mycoprotein typically emits 50–80% lower greenhouse gases than beef, largely because of the elimination of feed crops and livestock-related methane.[10,69–72] At large scales, substituting even 20% of ruminant meat with fungi-based products could halve deforestation and related $CO_2$ emissions, highlighting major land use and climate benefits.[9,73] Water use for fungi-based products is generally far lower than that for conventional meats; early LCAs found roughly 70–80% reductions for fungi-based products, as compared with beef,[10,70] although results vary by feedstock: lignocellulosic-based mycoprotein can exceed chicken in water demand,[72] whereas small-scale mushroom systems remain well within ruminant benchmarks.[74] Fermentation for mycoprotein remains energy-intensive relative to other Alt-ASFs,[59] although advances in bioreactor design and heat recovery have substantially lowered energy demands.[70] Emerging systems that use agricultural or chitin-rich waste as substrates show potential to further reduce reactive nitrogen losses (eg, leaching and gaseous emissions) and

| | plant | insect | cell | fungi | algae | composite |
|---|---|---|---|---|---|---|
| Greenhouse gas emissions | 83 | 19 | 21 | 13 | 11 | 5 |
| Land use | 61 | 17 | 17 | 12 | 9 | 3 |
| Water use | 45 | 9 | 11 | 10 | 6 | 4 |
| Eutrophication | 37 | 9 | 8 | 9 | 5 | 4 |
| Non-renewable resource use | 34 | 11 | 8 | 6 | 5 | 3 |
| Acidification | 32 | 8 | 6 | 6 | 5 | 3 |
| Ozone depletion | 21 | 6 | 4 | 3 | 4 | 2 |
| Ecotoxicity | 20 | 4 | 3 | 3 | 2 | 2 |
| Particulate matter formation | 18 | 6 | 4 | 3 | 2 | 1 |
| Ionising radiation | 13 | 6 | 3 | 3 | 1 | 1 |
| Human toxicity | 13 | 4 | 3 | 2 | 2 | 1 |
| Transport | 14 | 3 | 3 | 2 | 2 | 0 |
| Total economic resource use | 13 | 4 | 3 | 3 | 1 | 0 |
| Ecosystem damage | 7 | 5 | 2 | 2 | 2 | 0 |
| Human health | 6 | 5 | 2 | 2 | 1 | 1 |
| Animal feed | 7 | 4 | 4 | 1 | 0 | 0 |
| Fertiliser application | 12 | 0 | 1 | 0 | 1 | 0 |
| Feed conversion ratios | 4 | 6 | 2 | 0 | 0 | 0 |
| Crop yields | 7 | 1 | 1 | 0 | 1 | 0 |
| Pesticide application | 5 | 1 | 0 | 0 | 1 | 0 |
| Biodiversity | 1 | 1 | 1 | 0 | 1 | 1 |
| Manure application | 3 | 0 | 0 | 0 | 1 | 0 |
| Seed application | 3 | 0 | 0 | 0 | 0 | 0 |
| Lime application | 2 | 0 | 0 | 0 | 0 | 0 |
| Pollinator services | 1 | 1 | 0 | 0 | 0 | 0 |
| Animal growth rates | 0 | 1 | 1 | 0 | 0 | 0 |

***Figure 4:*** **Map of the evidence gaps in the included studies**

Note: counts shown in each cell represent the number of studies in which a given indicator was assessed for at least one product, within each Alt-ASF category; many studies evaluated multiple products and outcomes, and therefore, the values are not mutually exclusive and should not be interpreted as additive across rows or columns.

| | Potential environmental benefits | Potential environmental risks |
|---|---|---|
| Plant-based alternatives n=78 | ↓ Greenhouse gas emissions<br>↓ Land use<br>↓ Water use<br>↓ Eutrophication<br>↓ Energy use | ↑ Water use for some inputs (eg, coconut, almond)<br>↑ Energy use with higher processing intensity for some products |
| Plant-based milks n=24 | ↓ Greenhouse gas emissions<br>↓ Land use<br>↓ Water use (except almond milk)<br>↓ Eutrophication | ↑ Water use (almond milk)<br>↑ Methane emissions (rice milk)<br>Level of processing can increase environmental footprint |
| Cell-based alternatives n=23 | ↓ Greenhouse gas emissions<br>↓ Land use<br>↓ Antibiotic use | ↑ Energy use (non-renewable scenarios)<br>↑ Water use<br>Waste-management challenges (bioreactors, media) |
| Insect-based alternatives n=21 | ↓ Greenhouse gas emissions<br>↓ Land use<br>↓ Water use<br>↑ Feed conversion efficiency<br>Can use organic waste streams | Energy needs for climate control<br>Sensitivity to processing intensity and energy source |
| Fungi-based alternatives n=16 | ↓ Greenhouse gas emissions<br>↓ Land use<br>↓ Water use<br>Potential for using waste streams | Energy intensity of fermentation processes (dependent on scale and electricity mix)<br>Requires controlled environments |
| Algae-based alternatives n=11 | ↑ Yield per unit area<br>Can be grown on non-arable land<br>Low freshwater requirements<br>Carbon sequestration potential<br>↓Fertiliser inputs (some species) | High energy demand during harvesting and downstream processing<br>Contamination risks (species-dependent and system-dependent) |

***Figure 5*: Potential environmental benefits and risks of alternatives to animal-source foods**
Note: arrows indicate average decreases (↓) or increases (↑) relative to conventional animal-source foods, wherein directionality is consistently observed across studies; text-only entries denote context-dependent or qualitative risks.

enhance nutrient recycling.[75] Overall, fungi-based foods consistently outperform conventional meat across land, water, and emission indicators, even when accounting for process energy demands.

Algae-based Alt-ASFs, especially microalgae such as Spirulina and Chlorella, have strong potential environmental advantages over conventional animal-source foods, although evidence remains scarce. LCAs indicate that microalgae can be 95–99% more land efficient than beef, producing equivalent protein on only 1–5% of the land area, and can be cultivated on non-arable land using saline or brackish water, reducing the pressure on croplands and freshwater resources.[76–78] Water requirements vary widely: freshwater strains generally use three to six-times less water than beef or pork, whereas marine or saline species can eliminate freshwater needs altogether.[78] Some production systems integrate $CO_2$ capture during cultivation, such as recycling off-gas or flue-gas streams into photobioreactors, achieving partial carbon circularity, although overall sequestration remains uncertain once energy demands are accounted for.[78–80] Environmental burdens for algae Alt-ASFs are dominated by energy-intensive downstream processing—especially biomass drying—and by electricity use in closed photobioreactors, which are required for some microalgae strains, but not all; the use of open-pond and heterotrophic systems can reduce these burdens substantially.[76,80] As with other Alt-ASFs, performance improves markedly when powered by low-carbon energy sources: geothermally powered Spirulina production in Iceland achieved near-zero greenhouse gas emissions, using less than 1% of the land and water required for beef,[77] and integrated biogas-based systems show similarly large reductions in carbon and resource footprints.[79] Overall, microalgae often outperform conventional animal-source foods in terms of land, water use, and—when produced with clean energy—greenhouse gas metrics; however, they do not always surpass leading plant-based Alt-ASFs (eg, soy-based and pea-based products) without circular feedstocks and renewables, and evidence on like-for-like dietary substitution remains scarce.[9,76]

Across the evidence base, direct Alt-ASF-to-animal-source foods comparisons were often constrained by heterogeneity in functional units, system boundaries, and nutritional assumptions. Mass-based or energy-based comparisons (eg, per kg or per kcal) consistently favour plant-based and other Alt-ASFs, whereas nutrient-adjusted metrics—accounting for protein quality, micronutrients, or composite nutrient density—generally reduce, but do not eliminate, the environmental advantage relative to animal-source foods.[34,81,82] The magnitude of this narrowing varies widely by product and nutrient basis: for example, unfortified plant-based milks could approach or exceed dairy impacts when normalised by nutrient density, whereas fortified soy and legume-based products typically retain lower footprints even under nutrient-adjusted units, as compared with dairy.[42,81] These patterns recur across Alt-ASF categories, indicating that conclusions about relative sustainability depend strongly on methodological choices (eg, system boundaries, functional units, and energy assumptions) rather than any single universal metric.

## Discussion

Across the current evidence base focused on high-income contexts, Alt-ASFs generally reduce environmental pressures, but with variation in scale and reliability. The results point to a dual reality: Alt-ASFs can meaningfully lower emissions and land and water demands relative to animal-source foods, but the realised sustainability outcomes depend on production systems and energy inputs, in addition to the choice of the assessment methodology, which influences how those outcomes are interpreted.

Across categories, consistent trends emerge. Alt-ASFs almost universally reduce greenhouse gas emissions relative to conventional animal-source foods, although the magnitude of improvement varies. Reported greenhouse gas emissions for Alt-ASFs varied widely across studies, often spanning an order of magnitude depending on product formulation, energy source, and system boundaries, particularly for cell-based, algae-based, and highly processed plant-based products. The strongest and most consistent climate gains are observed for plant-based and fungi-based products, reflecting the absence of methane associated with rumen microbiomes, reduced manure-related emissions, and avoided feed-based impacts. Outcomes for emerging categories such as (micro)algae and cell-based foods—including precision fermentation approaches—remain largely based on models and appear to be highly dependent on assumptions about process efficiency, energy source, and production design, reflecting their relatively early stage of commercial and product development, whereas insects show context-specific performance linked to feed and temperature control. Highly processed plant-based formulations or fermentation-derived products (whether cell-based or fungi-based products) can narrow the advantages in terms of emissions, although even under such conditions, they still typically retain an advantage in terms of climate change mitigation. As the adoption of renewable energy increases and production efficiencies improve, the gap between Alt-ASFs and conventional animal-source foods in terms of emissions is expected to widen further.

Alt-ASFs show particularly strong gains in land efficiency. Across studies, plant-based, fungi-based, and insect-based products typically require much less land than is needed for ruminant systems, largely because they bypass grazing and feed-crop cultivation and achieve higher conversion efficiencies in fermentation-rearing and insect-rearing systems. Algae-based systems have the potential to further reduce land pressures by operating in tanks or ponds on non-arable land. At the same time, land-use outcomes following dietary or production shifts are not automatic. Land sparing is shaped by governance, markets, and biophysical constraints, and land freed from feed or grazing use is not necessarily restored or repurposed for ecological recovery. Livestock systems can also play a productive role in land-use optimisation by using marginal or non-arable areas—where cropping is not feasible because of soil, topography, or climate—to convert biomass into nutrient-dense foods.[83] Environmental gains from diet diversification might be greatest wherever reductions in feed-intensive livestock production are paired with more targeted, circular livestock systems rather than wholesale displacement. Future assessments should, therefore, distinguish among land types, management regimes, and counterfactual uses to estimate system-level land and ecosystem outcomes more accurately.

Outcomes of water use are more variable than land or climate impacts. Most Alt-ASFs show lower water footprints than animal products, reflecting the absence of feed-crop irrigation and manure management; yet, performance varies markedly by ingredient, system design, and geography. Fungi-based and many plant-based foods generally outperform dairy and several terrestrial and aquatic animal-source foods, whereas water-intensive crops such as almonds or rice narrow these gains. Algae-based and cell-based systems are promising but remain sensitive to cultivation medium and process water recycling. Overall, improvements depend more on where and how production occurs than on product type alone. Because water is a locally constrained resource, context strongly shapes the impact magnitude—scarcity indexes, seasonality, and rainfed versus irrigated conditions are rarely incorporated, but essential for meaningful interpretation. Future assessments should, therefore, shift from volumetric accounting towards water stress-adjusted or source-specific indicators to capture real sustainability implications.

Beyond climate, land, and water, studies looking at eutrophication and acidification outcomes also show fewer nutrient losses for Alt-ASF products than for animal-source food products—largely from avoiding concentrated manure management and synthetic fertiliser use in feed-crop production. Trade-offs do exist. Ecotoxicity and human-toxicity burdens can be higher for some plant-based analogues, driven by pesticide-intensive crop inputs (eg, soy and some oilseed systems), additives, or solvent or cleaning chemicals in processing and ingredient supply chains; however, toxicity-related outcomes remain highly sensitive to data availability, system boundaries, and modelling assumptions, and should be interpreted with caution. Energy-related impacts are highly sensitive to electricity mix and processing intensity; mycoprotein, microalgae, and some insect ingredients can perform worse than simple plant foods when grids are fossil fuel-heavy or when drying and sterilisation demands are high. Insects tend to perform well overall but can show freshwater-eutrophication hotspots tied to feed choice; algae outcomes hinge on cultivation system and nutrient sourcing; and cell-based assessments remain dominated by energy and dependent on the scenario. Nitrogen flows and LCA endpoints such as biodiversity and ecosystem damage are far less frequently quantified, and results are sensitive to modelling choices (eg, allocation, coproducts, and land-use baselines). Together, these patterns support a general advantage for Alt-ASFs while underscoring that toxicity-based and energy-based demands warrant closer monitoring as production scales.

The overall pattern of evidence shows that Alt-ASFs have a strong potential to mitigate the environmental impacts of animal-source food production, but also that performance is highly dependent on context, particularly with respect to production systems, energy inputs, and emerging technologies. Regional variations in energy mixes, agricultural practices, supply-chain infrastructures, and ecological baselines can affect outcomes substantially, underscoring the need for context-specific data and interpretation. Ecological baseline refers to the reference animal-source food production system used for comparison in LCAs; because results depend strongly on the management intensity, geography, and land-use dynamics of the animal-source food production system. For example, livestock can contribute positively within some systems by converting residues and by-products from crops or marginal lands into food, reducing competition with human-edible resources;[84] however, such system-level interactions are typically not captured in product-level LCAs and are specific to context and restricted by the availability of suitable feed streams and land resources. These dynamics warrant nuanced comparisons that acknowledge cases wherein animal systems can perform comparably on select indicators while still reflecting the broader trend of environmental advantage observed for Alt-ASFs.

Several methodological limitations temper the strength and generalisability of the current evidence. LCAs of Alt-ASFs display wide heterogeneity in system boundaries, allocation rules, and coproduct treatment, leading to inconsistent results across studies. Many LCAs remain attributional rather than consequential, omitting systemic feedback such as indirect land-use change, market effects, and nutrient recycling, although a growing body of prospective LCA work seeks to address these dynamics.[85,86] Functional units also differ—by mass, protein, or energy—and assumptions about product composition, energy sources, and end-of-life stages vary substantially. In addition, some LCAs draw on shared or legacy inventory datasets—particularly for emerging products such as mycoprotein—introducing potential dependencies across studies that could overrepresent the apparent strength or consistency of evidence for specific products.

Interpretation of nutrient-use efficiency and recycling outcomes is further complicated by how protein is represented in many LCAs of Alt-ASFs. Several studies model plant-based, fungi-based, or algae-based alternatives using whole-food proxies or mass-based functional units, which can underestimate protein concentration relative to both conventional animal-source foods and commercial Alt-ASF formulations that rely heavily on protein concentrates and isolates. This practice could lead to conservative estimates of protein yield and nitrogen-use efficiency per unit product, while simultaneously obscuring processing-stage losses and energy demands associated with isolate production. For emerging categories such as cell-based and algae-based foods, most results derive from modelled or pilot-scale data, thereby restricting confidence in real-world scalability. Comparator bias (appendix 1 p 33) further constrains interpretation: red meat is frequently used as the sole reference point (n=26), exaggerating relative gains and obscuring comparisons with lower-impact animal-source foods such as poultry, fish, or eggs. Finally, many studies compare products on protein-equivalent bases without accounting for nutritional quality or actual consumption forms, which can distort impact intensities.

Despite rapid growth in research on Alt-ASFs, major evidence gaps remain. The literature is heavily concentrated in high-income countries—particularly the USA and western Europe—with little coverage of lower-middle-income and low-income settings. This geographical skew restricts the understanding of how Alt-ASFs perform under production conditions, energy systems, and resource constraints that differ markedly from those typically measured or modelled, and situations in which environmental trade-offs might play out differently in practice. This geographical skew also reflects broader structural dynamics in global protein transitions, which remain closely tied to income growth, regional food systems, and uneven development of alternative protein production and markets.[87] Few studies examine interactions with smallholder systems, informal markets, or climate-vulnerable production ecologies common in many low-income food systems. Evidence is also uneven across product categories: plant-based alternatives dominate the literature (which could reflect greater commercial maturity and data availability), whereas fungi-based and algae-based systems remain sparsely studied despite growing policy and industry interest. At the outcome level, most studies focus on greenhouse gas emissions, land use and water use, with far less attention to biodiversity, ecotoxicity, or nutrient cycling. The scarcity of integrated, multi-indicator assessments, combined with a paucity of data from emerging economies, constrains the generalisability of the current findings.

Addressing these gaps will require moving beyond fragmented, largely attributional comparisons towards more harmonised, empirically grounded, and system-aware research. Future work would benefit from combining attributional LCAs with consequential or prospective approaches to explore plausible what-if scenarios under different market, technology, and energy-system trajectories. Expanding empirical analyses in under-represented regions and prioritising understudied product categories will be essential as Alt-ASF technologies mature. Scenario-based modelling that incorporates grid decarbonisation, climate change, and technological learning curves will further enhance the policy relevance of future work—particularly for novel Alt-ASFs. Collectively, these efforts would move the field beyond proof-of-concept comparisons towards a more integrated science of sustainable diet transitions—one capable of informing context-specific decisions across diverse food systems.

This Review shows that Alt-ASFs, while heterogeneous in form and maturity, share a common potential to substantially reduce the environmental footprint of food, as compared with animal-source foods. Across 125 studies, the majority of evidence indicates lower greenhouse gas emissions, land use, and water demands, as compared with conventional livestock, particularly terrestrial ruminant systems. Yet, these advantages are not uniform: outcomes depend crucially on production design, energy sourcing, and regional context. By consolidating fragmented evidence, this Review moves beyond categorical debates over better or worse foods, to clarify the conditions under which environmental benefits could be realised. The findings underscore that sustainability gains are attainable—but their credible estimation and translation into practice depend on methodological rigour, transparent assumptions, and thoughtful integration into broader food systems. For researchers, the task ahead is to link environmental metrics with nutritional, economic, and equity dimensions, to better characterise synergies under different production designs and energy pathways. If guided by robust evidence and context-sensitive governance, then Alt-ASFs can contribute meaningfully to climate mitigation and biodiversity goals while supporting more resilient and equitable food systems. The challenge at present is to ensure that innovation aligns with sustainability not only in principle, but in practice as well.

**Contributors**

KS, TB, SN, ED, EL, MX, LMN, and MH conceived the analysis and contributed to the design of the methods. KS, TB, GM, OY, ZG, BQ, and ED conducted the analysis. KS wrote the manuscript, with inputs from GM, ED, and MH; the manuscript was reviewed and edited by TB, OY, ZG, BQ, SN, ED, EL, MX, LMN, and MH. All authors had full access to all data in the study and accept responsibility to submit for publication.

**Declaration of interests**

We declare no competing interests.

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