

## Environmental Impacts of Alternatives to Animal-Source Foods: A Scoping Review

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### Abstract

Drawing on a broad 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 (ASFs). Across categories, Alt-ASFs generally required fewer natural resources and produced lower greenhouse gas emissions, with the most consistent advantages observed for plant-based foods. Outcomes were more variable for insect-, fungi-, algae-, and cell-based alternatives, reflecting differences in production methods, processing intensity, and energy sources. The evidence base was concentrated in high-income countries, with relatively limited coverage of low- and middle-income contexts, and analyses of ecological dimensions beyond greenhouse gas emissions, land, and water—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 (particularly in high-income settings), but the scale and consistency of benefits remain sensitive to production practices and analytical assumptions underlying comparative analyses.

## Introduction

Animal-source foods (ASFs), including meat, fish, eggs, and dairy, are integral to diets worldwide yet account for some of the most resource- and emission-intensive components of food systems.<sup>1,2</sup> 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 (GHG) emissions and extensive land conversion for feed production.<sup>3,4</sup> Global demand for ASFs continues to rise, with the steepest increases projected in low- and middle-income countries, further intensifying pressures on ecosystems.<sup>5,6</sup> Consequently, questions of the role of ASF 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 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, algae, insects, and cell-based systems (such as cultured meat and precision fermentation)—are increasingly positioned as part of the solution.<sup>1,7–11</sup> These products are marketed as lower-impact substitutes for conventional livestock and aquatic animals, and have attracted significant investment, research attention, and consumer interest. While plant-based alternatives are now mainstream in many high-income markets, fungi, algae, insect and cell-based foods remain in earlier stages of commercialization.<sup>11</sup> Despite rapid expansion, however, empirical understanding of their environmental impacts is fragmented. Studies vary widely in scope, assumptions, and methods, limiting the ability of policymakers and other stakeholders to determine under what conditions Alt-ASFs provide environmental benefits.

The urgency of consolidating this evidence is both scientific and policy-driven. Calls for food system transformation feature prominently in international fora such as the UN Food Systems Summit and recent COP climate negotiations, and are widely reflected in academic research, where shifts away from conventional ASFs are often framed as a ‘protein transition’ and positioned as a sustainability imperative.<sup>7,11–13</sup> Yet without synthesis, decision making risks being shaped by selective evidence, commercial claims, or assumptions that may not hold across contexts. Critical blind spots (including limited 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 compared with conventional ASFs. We characterize the volume and distribution of existing studies, synthesize findings across environmental outcomes, identify methodological and geographic gaps, and highlight how choices in study design shape reported impacts. By providing a comprehensive synthesis of environmental trade-offs across plant-, fungi-, algae-, insect-, 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**

Full details on methods, including database-specific search strategies, are provided in Supplementary Information. A review protocol 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.<sup>14</sup> This scoping review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) extension for scoping reviews.<sup>15</sup> Amendments to the protocol are available on the OSF project page (<https://osf.io/27bze/>). The review team included subject matter experts in alternatives to animal-source foods and environmental sustainability as well as methodological experts in evidence synthesis.

### **Article Screening and Selection**

Article screening was performed in two phases: (1) title and abstract screening and (2) full-text screening. Titles and abstracts were screened against predetermined eligibility criteria in Covidence by two independent reviewers, and conflicts were resolved by a third reviewer. Peer-reviewed studies were eligible if they assessed environmental outcomes of at least one Alt-ASF and included a direct comparison with ASF(s). To preserve comparability, studies were included only if environmental impacts of Alt-ASFs and conventional ASFs 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 harmonized 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**

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), 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. Classification of ultra-processed foods was conducted as part of data extraction and followed NOVA 4 as closely as possible with available information but is not reported quantitatively due to insufficient details in included studies.<sup>16</sup>

### **Data Synthesis**

Quantitative data—including the extent, range, and nature of the evidence as well as data gaps—were synthesized and analyzed using R version 4.4.2. Data were extracted for environmental outcomes including greenhouse gas emissions, land and water use, eutrophication, acidification, pollution (e.g., particulate matter formation and ecotoxicity), biodiversity and others. Qualitative

data were synthesized descriptively and summarized by Alt-ASF category and environmental indicator. Particular attention was paid to methodological variation in LCA studies, including system boundaries, functional units, and comparator selection. Where 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). Title and abstract screening excluded 9,086 of these records, and 575 full-text articles were screened for eligibility. In total, 183 studies met the inclusion criteria, of which 125 focused on foods for human consumption and are analyzed in this manuscript. 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 exponentially over time and varied by Alt-ASF category (Figure 2). Plant-based foods were the most frequently compared to conventional ASFs (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, while composite products were rare (n=6). Forty-five 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. While isolated product substitutions were predominant (n=98), multiple comparator pairings within single studies were also common (n=26), reinforcing that a meaningful portion of the evidence is based on multi-product 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.<sup>17</sup> The United States accounted for the largest share (n=28), followed by Germany (n=21), Netherlands (n=16), the United Kingdom (n=13), and Nordic countries such as Sweden (n=10) and Finland (n=9). Outside the OECD, contributions were more limited. With the exception of China (n=9) and Brazil (n=4), most non-OECD countries were represented by only one or two studies. A small number of publications spanned multiple countries, including the European Union (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 commonly 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), where n denotes the number of studies in which each indicator was measured. 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 3). In contrast, insect-, algae-, fungi-, cell-based, and composite products were less frequently assessed.

Methodologically, most included studies (n = 92) relied on Life Cycle Assessment (LCA). Several studies (n=40) assessed resource-use efficiency (e.g., nitrogen, land, or water), outside

the LCA framework. A small number applied geospatial modeling 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 characterize potential environmental pressures—such as greenhouse gas emissions, land use, and water use. Fewer employed 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.

## Key Findings

Alt-ASFs generally exhibit lower environmental footprints than conventional ASFs across multiple impact categories (Figure 4), 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, though magnitudes vary with product type, processing intensity, region, and energy mix. While substitution of ASFs with Alt-ASFs—as represented in comparative assessments—typically lowers resource use and climate burdens, gains may be partially offset by energy-intensive processing or ingredient-specific impacts, especially for novel categories.

Plant-based Alt-ASFs consistently demonstrate lower burdens than ASF 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.<sup>18–23</sup> Whole-food formats (e.g., tofu, tempeh, minimally processed legumes and grains) are typically the lowest-impact options—exhibiting 80–95% lower emissions and 85–95% less land use than beef or pork.<sup>24–26</sup> Formulated meat analogues generally retain a climate and land advantage over beef—and often over pork and poultry—though processing (extrusion, freezing/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-, soy-, and lentil-based burgers or mince typically show 70–95% lower GHG emissions and 60–90% less land use than red meat.<sup>25,27–30</sup> However, land-use change risks and pesticide profiles in specific soy supply chains can erode benefits<sup>31–33</sup>; cereal- and pea-based analogues tend to be robust performers where yields are high and deforestation risks are low.<sup>26,34</sup> Oil- and nut-dominated recipes can raise water scarcity or ecotoxicity burdens, and multi-ingredient blends may introduce trade-offs in toxicity categories linked to crop protection chemicals or processing-stage cleaning agents.<sup>30,32,33,35–39</sup> Taken together, the advantage for plant-based alternatives is consistently observed across most contexts, with its magnitude shaped by processing intensity, electricity sources, and ingredient provenance.

Plant-based milk alternatives generally exhibit environmental advantages relative to dairy milk, though the extent and direction of benefits vary by impact category. Across life cycle assessments, plant-based drinks consistently show lower greenhouse gas emissions than dairy milk—often around 50–70% lower per liter, and in some cases even greater,<sup>31,40–42</sup> with soy drinks performing especially well.<sup>43</sup> 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.<sup>41,44</sup> Water use differs sharply across plant-based milks. Soy and oat generally require far less water than dairy, while almond and rice can be more water-intensive, with the latter linked to paddy irrigation.<sup>36,38,41,45</sup> Across studies, plant-based milks generally showed lower nutrient flow and pollution impacts on soils and waterways than dairy, though results varied by product and assessment method.<sup>31,41,46</sup> Fortification and processing can further increase footprints by 15–25%<sup>47</sup>, and transport can add additional impacts,<sup>32,48</sup> yet overall LCAs consistently demonstrate lower burdens than dairy.

Cell-based Alt-ASFs (cultured meat) demonstrate large potential reductions in land use—typically 80–99% lower than conventional beef—by eliminating feed and grazing requirements.<sup>9,10,49–51</sup> However, the industry is nascent and most evidence comes from ex ante, scenario-based LCAs and forward-looking projections, many of which draw on modeled or proprietary process data, with outcomes sensitive to assumptions about feedstock, energy sources, and production scale.<sup>52,53</sup> LCAs generally indicate 70–95% lower GHG emissions than beef, though outcomes depend strongly on electricity source and growth media composition.<sup>50,54,55</sup> Under renewable-energy scenarios, several studies project carbon intensities in the single-digit kg CO<sub>2</sub>-eq kg<sup>-1</sup> range—placing cell-based alternatives at or below the lower end of conventional ASFs.<sup>49–51</sup> In contrast, studies assuming fossil-dominant or average grid electricity often find 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.<sup>54,56,57</sup> 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 toward rare-earth metal use in bioreactors and renewable infrastructure.<sup>57,58</sup> Water-related impacts vary widely: most ex-ante LCAs report ≥80% savings versus beef,<sup>49–51</sup> though outcomes change once bioreactor utilities, cleaning, and regional water-scarcity weighting are included.<sup>56</sup> Eutrophication, acidification, and ecotoxicity generally improve relative to 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.<sup>53,59,60</sup> Process-waste streams and critical material demands are still poorly quantified, and current LCAs rely heavily on modeled, proprietary inventories.<sup>50,53</sup>

Insect-based Alt-ASFs generally show consistent environmental advantages over conventional ASFs. LCAs indicate that insect production emits substantially lower greenhouse gases than beef (often by 70–90%) and generally lower emissions than pork or chicken, owing to efficient feed conversion, absence of enteric methane, and lower land requirements.<sup>61–64</sup> 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.<sup>63,65</sup> 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,<sup>61–64</sup> with similar reductions observed for grasshoppers and drone brood.<sup>66,67</sup> Across studies, insects typically use 40–80% less freshwater than beef, pork, or chicken, with modeled substitution scenarios showing comparable savings; insect-derived oils also outperform animal fats, underscoring strong overall water efficiency.<sup>10,39,68,69</sup> Feed sources and downstream processing steps both shape outcomes: insects raised on food or agricultural by-products achieve added sustainability gains through waste valorization,<sup>63,69</sup> though some systems instead rely on conventional feed

inputs (e.g., wheat bran, maize, brewer's yeast).<sup>64</sup> Energy-intensive processing such as freeze-drying can also offset some benefits.<sup>70</sup> Despite these trade-offs, insect-based foods generally retain strong environmental advantages across major impact categories, including greenhouse gas emissions, land use, and water use.

Fungi-based Alt-ASFs, primarily mycoprotein (e.g., Quorn®), generally demonstrate 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 due to the elimination of feed crops and livestock-related methane.<sup>10,70–73</sup> At larger scales, substituting even 20% of ruminant meat with fungi-based products could halve deforestation and related CO<sub>2</sub> emissions, highlighting major land-use and climate benefits.<sup>9,74</sup> Water use for fungi-based products is generally far lower than for conventional meats; early LCAs found roughly 70–80% reductions compared to beef,<sup>10,71</sup> though results vary by feedstock: lignocellulosic-based mycoprotein can exceed chicken in water demand,<sup>73</sup> while small-scale mushroom systems remain well below ruminant benchmarks.<sup>75</sup> Fermentation for mycoprotein remains energy-intensive relative to other Alt-ASFs,<sup>60</sup> though advances in bioreactor design and heat recovery have substantially lowered energy demands.<sup>71</sup> Emerging systems that utilize agricultural or chitin-rich waste as substrates show potential to further reduce reactive nitrogen losses (e.g., leaching and gaseous emissions) and enhance nutrient recycling.<sup>76</sup> Overall, fungi-based foods consistently outperform conventional meat across land, water, and emissions indicators, even when accounting for process energy demands.

Algae-based Alt-ASFs, especially microalgae such as *Spirulina* and *Chlorella*, show strong potential environmental advantages relative to conventional ASFs, though evidence remains limited. 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 pressure on croplands and freshwater resources.<sup>77–79</sup> Water requirements vary widely: freshwater strains generally use three- to six-times less water than beef or pork, while marine or saline species can eliminate freshwater needs altogether.<sup>79</sup> Some production systems integrate CO<sub>2</sub> capture during cultivation, such as recycling off-gas or flue-gas streams into photobioreactors, achieving partial carbon circularity, though overall sequestration remains uncertain once energy demands are accounted for.<sup>79–81</sup> 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.<sup>77,81</sup> As with other Alt-ASFs, performance improves markedly when powered by low-carbon energy sources: geothermally powered *Spirulina* production in Iceland achieved near-zero GHG emissions, using less than 1% of the land and water required for beef,<sup>78</sup> while integrated biogas-based systems show similarly large reductions in carbon and resource footprints.<sup>80</sup> Overall, microalgae often outperform conventional ASFs on land, water, and—if produced with clean energy—GHG metrics; however, they do not always surpass leading plant-based Alt-ASFs (e.g., soy- and pea-based products) without circular feedstocks and renewables, and evidence on like-for-like dietary substitution remains thin.<sup>9,77</sup>

Across the evidence base, direct Alt-ASF-to-ASF comparisons were often constrained by heterogeneity in functional units, system boundaries, and nutritional assumptions. Mass- or

energy-based comparisons (e.g., per kg or per kcal) consistently favor plant-based and other Alt-ASFs, while 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.<sup>35,82,83</sup> The magnitude of this narrowing varies widely by product and nutrient basis: for example, unfortified plant-based milks may approach or exceed dairy impacts when normalized by nutrient density, whereas fortified soy and legume-based products typically retain lower footprints even under nutrient-adjusted units.<sup>43,82</sup> These patterns recur across Alt-ASF categories, indicating that conclusions about relative sustainability depend strongly on methodological choices (e.g., system boundaries, functional units, and energy assumptions) rather than any single universal metric.

## Discussion

Across the current high-income-context-focused evidence base, 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, land, and water demands, but realized sustainability outcomes depend on production systems and energy inputs, as well as on assessment methodological choices that influence how those outcomes are interpreted.

The overall pattern of evidence demonstrates that Alt-ASFs hold strong potential to mitigate the environmental impacts of ASF production, but also that performance is highly context-dependent, 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 significantly affect outcomes, underscoring the need for context-specific data and interpretation. Here, ecological baseline refers to the reference ASF production system used for comparison in LCAs; because results depend strongly on its management intensity, geography, and land-use dynamics. For example, livestock can contribute positively within certain systems by converting residues and by-products from crops or marginal lands into food, reducing competition with human-edible resources<sup>85</sup>; however, such system-level interactions are typically not captured in product-level LCAs and are context-specific and limited by the availability of suitable feed streams and land resources. These dynamics warrant nuanced comparisons that acknowledge cases where animal systems may perform comparably on select indicators while still reflecting the broader trend of environmental advantage observed for Alt-ASFs.

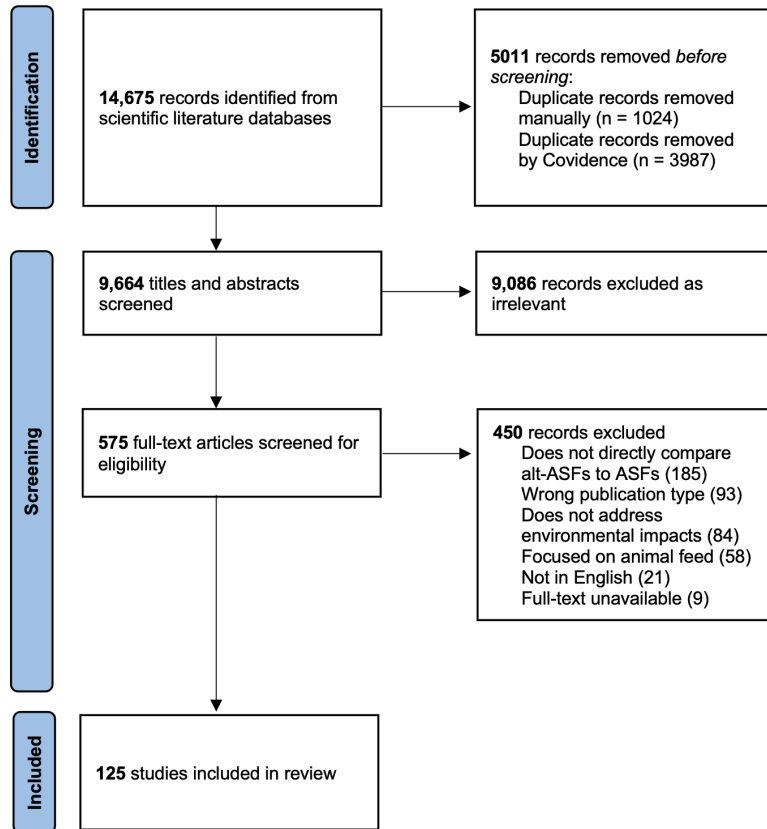
Several methodological limitations temper the strength and generalizability of current evidence. LCAs of Alt-ASFs display wide heterogeneity in system boundaries, allocation rules, and co-product treatment, leading to inconsistent results across studies. Many remain attributional rather than consequential, omitting systemic feedback such as indirect land use change, market effects, and nutrient recycling, though a growing body of prospective LCA work seeks to address these dynamics.<sup>86,87</sup> Functional units also differ—by mass, protein, or energy—while 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 may 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. This may 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 modeled or pilot-scale data, limiting confidence in real-world scalability. Comparator bias (SI-3) further constrains interpretation: red meat is frequently used as the sole reference point (n=26), exaggerating relative gains and obscuring comparisons with lower-impact ASFs like 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.

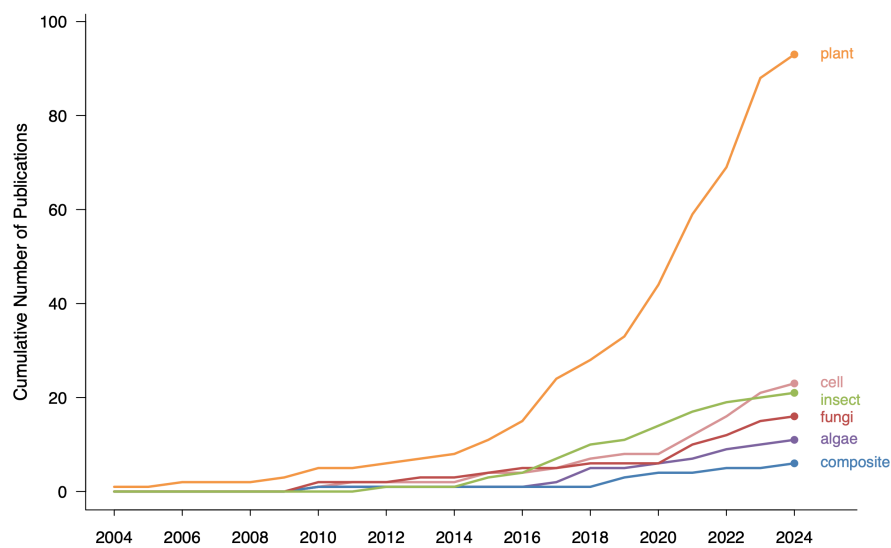
Despite rapid growth in research on Alt-ASFs, major evidence gaps remain. The literature is heavily concentrated in high-income countries—particularly the United States and Western Europe—with limited coverage of lower-middle- and low-income settings. This geographic skew limits understanding of how Alt-ASFs perform under production conditions, energy systems, and resource constraints that differ markedly from those typically measured or modeled, and where environmental trade-offs may play out differently in practice. It 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.<sup>88</sup> 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 may reflect greater commercial maturity and data availability), while fungi- 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 lack of integrated, multi-indicator assessments, combined with limited data from emerging economies, constrains the generalizability of current findings.

This review demonstrates that Alt-ASFs, while heterogeneous in form and maturity, share a common potential to substantially reduce the environmental footprint of food as compared to ASFs. Across 125 studies, the preponderance of evidence indicates lower greenhouse gas emissions, land use, and water demands compared with conventional livestock, particularly terrestrial ruminant systems. Yet these advantages are not uniform: outcomes depend critically 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 realized. The findings underscore that sustainability gains are attainable—but their credible estimation and translation into practice depend on methodological rigor, 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 characterize synergies under different production designs and energy pathways. If guided by robust evidence and context-sensitive governance, Alt-ASFs can contribute meaningfully to climate mitigation and biodiversity goals while supporting more resilient and equitable food systems. The challenge now is to ensure that innovation aligns with sustainability not only in principle—but in practice.

## Figures









**Figure 1. PRISMA Flow Diagram for the review.**



**Figure 2. Cumulative publications by type of alternatives to animal-source foods.**

	plant	insect	cell	fungi	algae	composite
<b>GHG emissions</b>	<b>83</b>	19	21	13	11	5
<b>Land use</b>	<b>61</b>	17	17	12	9	3
<b>Water use</b>	<b>45</b>	9	11	10	6	4
<b>Eutrophication</b>	<b>37</b>	9	8	9	5	4
<b>Nonrenewable resource use</b>	<b>34</b>	11	8	6	5	3
<b>Acidification</b>	<b>32</b>	8	6	6	5	3
<b>Ozone depletion</b>	<b>21</b>	6	4	3	4	2
<b>Ecotoxicity</b>	<b>20</b>	4	3	3	2	2
<b>Particulate matter formation</b>	<b>18</b>	6	4	3	2	1
<b>Ionizing radiation</b>	<b>13</b>	6	3	3	1	1
<b>Human toxicity</b>	<b>13</b>	4	3	2	2	1
<b>Transport</b>	<b>14</b>	3	3	2	2	0
<b>Total Economic Resource Use</b>	<b>13</b>	4	3	3	1	0
<b>Ecosystem damage</b>	<b>7</b>	5	2	2	2	0
<b>Human health</b>	<b>6</b>	5	2	2	1	1
<b>Animal feed</b>	<b>7</b>	4	4	1	0	0
<b>Fertilizer application</b>	<b>12</b>	0	1	0	1	0
<b>Feed conversion ratios</b>	<b>4</b>	6	2	0	0	0
<b>Crop yields</b>	<b>7</b>	1	1	0	1	0
<b>Pesticide application</b>	<b>5</b>	1	0	0	1	0
<b>Biodiversity</b>	<b>1</b>	1	1	0	1	1
<b>Manure application</b>	<b>3</b>	0	0	0	1	0
<b>Seed application</b>	<b>3</b>	0	0	0	0	0
<b>Lime application</b>	<b>2</b>	0	0	0	0	0
<b>Pollinator services</b>	<b>1</b>	1	0	0	0	0
<b>Animal growth rates</b>	<b>0</b>	1	1	0	0	0

**Figure 3. Evidence gap map of 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 therefore values are not mutually exclusive and should not be interpreted as additive across rows or columns.

	Potential environmental benefits	Potential environmental risks
<b>Plant-based alternatives</b> n=78 	<ul style="list-style-type: none"> <li>• ↓ GHG emissions</li> <li>• ↓ Land use</li> <li>• ↓ Water use</li> <li>• ↓ Eutrophication</li> <li>• ↓ Energy use</li> </ul>	<ul style="list-style-type: none"> <li>• ↑ Water use for some inputs (e.g., coconut, almond)</li> <li>• ↑ Energy use with higher processing intensity for certain products</li> </ul>
<b>Plant-based milks</b> n=24 	<ul style="list-style-type: none"> <li>• ↓ GHG emissions</li> <li>• ↓ Land use</li> <li>• ↓ Water use (except almond milk)</li> <li>• ↓ Eutrophication</li> </ul>	<ul style="list-style-type: none"> <li>• ↑ Water use (almond milk)</li> <li>• ↑ Methane emissions (rice milk)</li> <li>• Level of processing can increase env. footprint</li> </ul>
<b>Cell-based alternatives</b> n=23 	<ul style="list-style-type: none"> <li>• ↓ GHG emissions</li> <li>• ↓ Land use</li> <li>• ↓ Antibiotic use</li> </ul>	<ul style="list-style-type: none"> <li>• ↑ Energy use (non-renewable scenarios)</li> <li>• ↑ Water use</li> <li>• Waste management challenges (bioreactors, media)</li> </ul>
<b>Insect-based alternatives</b> n=21 	<ul style="list-style-type: none"> <li>• ↓ GHG emissions</li> <li>• ↓ Land use</li> <li>• ↓ Water use</li> <li>• ↑ Feed conversion efficiency</li> <li>• Can utilize organic waste streams</li> </ul>	<ul style="list-style-type: none"> <li>• Energy needs for climate control</li> <li>• Sensitivity to processing intensity and energy source</li> </ul>
<b>Fungi-based alternatives</b> n=16 	<ul style="list-style-type: none"> <li>• ↓ GHG emissions</li> <li>• ↓ Land use</li> <li>• ↓ Water use</li> <li>• Potential for utilizing waste streams</li> </ul>	<ul style="list-style-type: none"> <li>• Energy intensity of fermentation processes (dependent on scale and electricity mix)</li> <li>• Requires controlled environments</li> </ul>
<b>Algae-based alternatives</b> n=11 	<ul style="list-style-type: none"> <li>• ↑ Yield per unit area</li> <li>• Can be grown on non-arable land</li> <li>• Low freshwater requirements</li> <li>• Carbon sequestration potential</li> <li>• ↓ Fertilizer inputs (some species)</li> </ul>	<ul style="list-style-type: none"> <li>• High energy demand during harvesting and downstream processing</li> <li>• Contamination risks (species- and system-dependent)</li> </ul>

**Figure 4. Potential environmental benefits and risks of Alt-ASFs.** Note: Arrows (↓ / ↑) indicate average decreases or increases relative to conventional ASFs where directionality is consistently observed across studies; text-only entries denote context-dependent or qualitative risks.

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