The environmental opportunity of fermentation-derived ingredients

Leveraging microorganisms to produce food ingredients can help reduce the environmental cost of feeding a growing global population—including resource pressures associated with livestock production and ocean fisheries. Diversifying our food supply with fermentation-derived ingredients can significantly reduce our food system's environmental impacts and improve supply chain security—but only if investment, policy, and infrastructure enable the science.

Overview

Microorganisms are remarkably efficient biological factories. They're capable of producing proteins, oils, and other food ingredients at a fraction of the climate, land, water, and pollution costs of conventional production, while matching or exceeding the nutritional and functional performance of animal-based ingredients.

By converting renewable feedstocks into these ingredients, fermentation also offers a more resilient and diversified alternative to resource-intensive supply chains. Peer-reviewed life cycle assessment (LCA) evidence supports these advantages across biomass fermentation, precision fermentation, and microbial oils.

Fermentation-derived animal fat. Photo credit: ÄIO

What are fermentation-derived food ingredients?

Fermentation is a process in which microorganisms—bacteria, fungi, and yeasts—convert carbon sources into proteins, oils, and other useful compounds. While fermentation is familiar from bread, beer, and yogurt, the food industry is now applying more advanced fermentation processes to produce sustainable alternative proteins, fats, and food ingredients from microbes and diverse feedstocks. Three distinct pathways produce these ingredients:

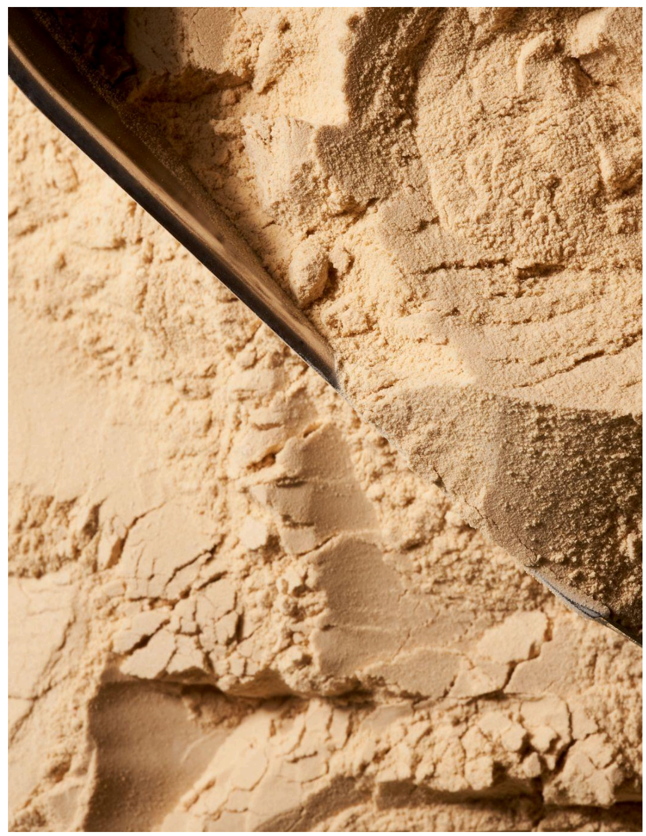
Biomass fermentation, also known as single-cell protein (SCP), leverages the high-protein content and rapid growth of microorganisms to produce large quantities of protein efficiently—without raising animals. Mycoprotein, produced from filamentous fungi such as *Fusarium venenatum*, is the most commercially established example, with decades of production and consumption experience.

Precision fermentation (PF) uses microorganisms as biological factories to produce specific functional proteins and other molecules—including whey protein, egg white protein, casein, heme, and collagen—that are nutritionally and functionally equivalent to their animal-derived counterparts. Unlike biomass fermentation, the microorganism itself is not the end product; instead, it produces a target ingredient that is then purified.

Microbial oils are fat ingredients produced by oleaginous yeasts and microalgae—organisms that naturally accumulate high levels of lipids—and can serve as land-based replacements for omega-3 fish oils extracted from ocean fisheries, including DHA and EPA omega-3s.

What does the evidence show?

A systematic review of LCA evidence conducted by the Good Food Institute, synthesizing findings from over 30 peer-reviewed and industry publications, found that fermentation-derived ingredients have a substantially lower environmental footprint than conventional animal-based ingredients. Environmental advantages—including lower greenhouse gas emissions, land use, and water use—prevail across all three production pathways and across multiple end-product types. The graphical summary below presents headline findings by pathway and comparator.



Fermentation-derived protein powder. Photo credit: MicroHarvest GmBH

Findings at a glance

BIOMASS FERMENTATION • Edible microbial proteins

Protein rich biomass from fungi, yeast, and bacteria — no livestock required

Comparator	GHG emissions	Land use	Water / scarcity
vs Beef	−80 to −98%	−67 to −98%	−78 to −97%
vs Pork	−48% to −86% / +14% †	−58 to −94%	−60 to −70%
vs Chicken	−16% to −75%	−50 to −94%	varies ‡

*See Table 1 for more detail, and appendix for notes and sources.
Biomass: †GHG vs pork: +14% statistically inconclusive vs German pork under current energy grid (Treml et al. 2026). Land savings are robust across both.
‡ Water use vs chicken: +6% (Quorn mince), -23% (Quorn pieces), -55% (Quorn nuggets); Water scarcity vs chicken: -99% (Bacterial SCP)
Sources: Carbon Trust 2021 · Shahid et al. 2024 · Treml et al. 2026 · Järviö et al., 2021

PRECISION FERMENTATION • Functional proteins

Functional whey & egg proteins produced by fungi and yeast — identical to animal-derived ingredients

Comparator	GHG emissions	Land use	Water / scarcity
vs Dairy protein	−16% to −97% §	−99%	−68 to −96%
vs Egg-white protein	−31% to −74%	−87% to −94%	varies: −86% to +53% §§

*See Table 2 for more detail, and appendix for notes and sources.
Precision Fermentation: §GHG emission benefit low when compared to more efficient New Zealand dairy (Behm et al. 2022). §§ Water direction reversal in Poland driven by egg comparator feed sourcing assumptions, not PF process. Land advantages consistent across all scenarios and geographies.
Sources: Behm et al. 2022 · Briggs et al. 2021 · Hamelin & Cellier 2024 · Järviö et al. 2021 · Leino et al. 2025

MICROBIAL OMEGA-3 OILS • Nutritional oils

DHA- and EPA-rich fish oil alternatives from microbes — no ocean extraction required.
Fisheries benefit likely underestimated in standard LCA

Comparator	GHG emissions	Land use	Eutrophication	Biotic resource use
vs Wild-caught fish oil	−5 to −271%	varies: -16% up to 32x¶	+255% (fresh) to -66% (marine)	−88%
vs Farmed fish oil	−99%	−99%	−99% (fresh)	NR

*See Table 3 for more detail, and appendix for notes and sources.
Microbial oils: ¶ Land use trade-off: microalgal oils consistently require more land than fish oil when crop-based sugars are used as feedstocks — an inherent cost of terrestrial production. This is reduced with waste or gas-derived carbon sources (Bartek et al. 2021). Importantly, this comparison is structurally asymmetric: land use costs of microalgal production are fully visible in LCA, while the fisheries overexploitation and ecosystem depletion associated with fish oil are not captured in standard LCA frameworks.
Sources: Wild caught: Bartek et al. 2021 · Davis et al. 2021 · Dutra et al. 2024 · McKuin et al. 2021; Farmed fish: Togarcheti et al. 2021

Figure 1. Environmental benefits of fermentation-derived ingredients across biomass fermentation, precision fermentation, and microbial oils. See Tables 1, 2, and 3 for more information.

Biomass proteins: Meat without the environmental cost

Biomass fermentation, also known as single-cell protein (SCP), leverages the high-protein content and fast growth of microorganisms to produce large quantities of protein efficiently. Microbial biomass can be the main ingredient of a food product or serve as one of several ingredients in a blend. A range of microorganisms for biomass fermentation, from yeast to filamentous fungi to microalgae, can be leveraged to produce sustainable protein sources without raising animals.

Biomass fermentation-enabled meat generates fewer GHG emissions

Alternative proteins produced through fermentation have significantly lower greenhouse gas (GHG) footprints compared to methane-emitting livestock and crops grown for feed. Across biomass studies, microbial proteins can reduce GHG emissions by up to 98% compared with beef, 81% compared with pork, and 75% compared with chicken (Figure 2; Table 1). They provide a crucial tool for decarbonizing food systems—which account for over a third of global GHG emissions—and meeting Paris Agreement goals.

> *Across biomass studies, microbial proteins can reduce GHG emissions by up to 98% compared with beef, 81% compared with pork, and 75% compared with chicken*

GHG emissions (kg-$CO_{2\text{-eq}}$ per kg-protein)

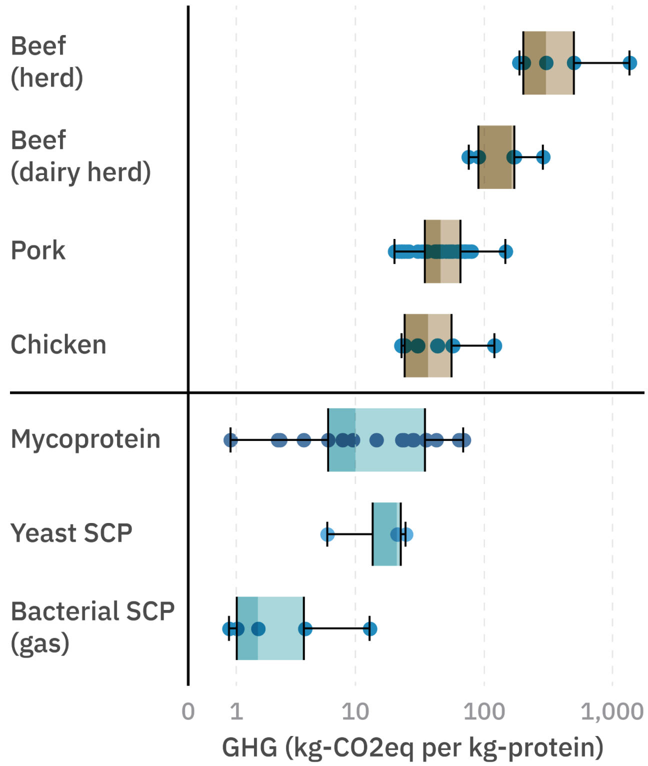


Figure 2. Climate impact (kg-CO_{2eq} per kg protein, log scale) of biomass fermentation-derived ingredients and products relative to animal-based meats. See appendix method notes for data sources.

GHG compared to beef

Fungal mycoprotein has the most extensive LCA evidence base of any fermentation-derived protein. Across multiple independent peer-reviewed studies, replacing animal-derived beef with mycoprotein reduces GHG emissions from 80 to 98%, with reductions against lamb in a similar range (Table 1, Figure 2). Gas fermentation-derived bacterial SCP also offers lower climate impact, demonstrating approximately 94% lower GHG than beef (Järviö et al., 2021) (Figure 2; Table 1).

GHG compared to pork

The GHG advantage compared to pork is also meaningful: studies across multiple locations report reductions ranging from 25–81% (Table 1). However, a recent mycoprotein LCA compared to German pork (Treml et al., 2026) found no clear GHG advantage for mycoprotein under current energy conditions, reflecting the influence of biogas credits in the pork production system which reduce pork's GHG result and introduce uncertainty. The broader evidence base still points to meaningful GHG reduction against most pork production, especially for other microbial SCPs (Figure 2, Table 1).

GHG compared to chicken

The picture compared to chicken is more context-dependent for mycoprotein. Reductions ranging from 16–70% (Shahid et al., 2024) have been reported with clear benefits for mycoprotein when produced with renewable, low carbon intensity electricity grid (Shahid et al., 2024; Wu et al., 2025). Bacterial SCP from gas fermentation offers the most GHG-competitive microbial protein source (Figure 2) with reductions of 75% compared to chicken, depending on energy source (Järviö et al., 2021).

Efficient protein production: Land and water advantages of biomass fermentation

Mycoprotein uses substantially less land and water than conventional meat

Mycoprotein requires approximately 94% less land and 70% less water than pork (Treml et al., 2026), along with up to 96% less land and water than ruminant meat (Table 1). Industry LCAs for Quorn, a long-standing commercial mycoprotein producer (Carbon Trust, 2021), and Nosh.Bio fungal protein (ClimatePoint, 2024) reported similarly lower land use and water deprivation potential compared to conventional beef, while a mycoprotein burger LCA (Smetana et al., 2021) found 67% less land and 78% less water compared to a beef burger patty (Table 1).

Land advantages hold across a range of electricity grids and production contexts. However, water use and water scarcity results are more process and location-dependent, reflecting watershed stress at the production site (Table 1). For instance, Upcraft et al. (2021) found substantially elevated water impacts of mycoprotein production using rice straw feedstock—driven by paddy field irrigation embedded in the rice straw supply chain rather than the fermentation process itself, and not representative of glucose-based mycoprotein production.

Gas fermentation nearly eliminates the agricultural land footprint of protein production

Bacterial SCP produced using hydrogen-oxidizing bacteria requires approximately 98% less land than beef (Järviö et al., 2021), reflecting the ability to bypass crop-based feedstocks almost entirely. Global techno-economic modeling suggests that scaled gas-derived SCP production could decouple protein supply from agricultural land and water constraints almost entirely, with production costs projected to reach competitiveness with conventional plant protein isolates by 2050 (Fasihi et al., 2025).

Sustainable food systems from biomass protein

Modest adoption of mycoprotein and other single-cell proteins could offer significant benefits.

Global scenario modeling (Humpenöder et al., 2022) finds that substituting just 20% of per-capita ruminant meat consumption with microbial protein by 2050 could roughly halve annual deforestation rates and the CO_2 emissions associated with land-use change. This effect is driven by reduced livestock feed demand and avoided forest conversion.

Diet-level modeling further reinforces this. Replacing animal-source foods with alternative proteins, including mycoprotein, can reduce the climate impact, land use, and water use of European diets by more than 80% while still meeting nutritional needs—especially for protein and fiber (Mazac et al., 2022; Finnigan et al., 2019). At the meal level, substituting meat with mycelium-based foods reduced environmental indicators by 13–57% while maintaining protein intake above recommended levels (Zwinkels et al., 2026). Crucially, mycoprotein can be woven into realistic, culturally acceptable sustainable diets (Fu & Irz, 2025).

Sustainability benefits extend beyond environmental impact.

Mycoprotein can enable a genuinely sustainable food system—one that delivers environmental benefits, economic resilience, and positive social outcomes across the value chain. An LCA and social LCA of ABUNDA mycoprotein, produced at commercial scale by ENOUGH, demonstrated a low climate footprint, alongside low land use and eutrophication impacts. ENOUGH's facility is co-located with Cargill's glucose production plant, sharing wastewater infrastructure and returning fermentation process water to Cargill's process—a real-world circular bioeconomy hub that policy frameworks should actively enable (Pignatelli et al., 2026). The social assessment identified positive outcomes including consumer health benefits from high-quality, nutritionally complete protein, improved working conditions, stable employment, local supplier engagement, and community development (Pignatelli et al., 2026).

Fungi have been part of human diets for centuries—from mushrooms to koji and tempeh—and recent consumer research suggests that the sustainability advantages of mycoprotein feel familiar rather than foreign, even where process-specific knowledge remains limited (Hellwig and Taherzahed, 2026). Mycoprotein is increasingly recognized not just as an environmentally sound choice, but as a socially and economically viable one—making it one of the most comprehensively evidenced fermentation-derived protein transitions available today, backed by science and scale (Bertinazzi et al., 2026).

Table 1: Biomass fermentation proteins vs. conventional meat — LCA comparison

Comparative LCA percent difference versus conventional animal protein comparator within-study comparisons only · negative = lower environmental impact · NR = not reported. NC = assessed but not directly compared. ns = not statistically significant · Water as: [1]Water use (blue water), [2]Water scarcity (AWARE); Freshwater pollution as eutrophication; Air pollution as terrestrial acidification . See Appendix for data notes. Full referenced data table available on our website at: gfi.org/fermentation-lca-overview.

Ingredient Type	Instead of	GHG	Land	Water	Freshwater pollution	Air Pollution	Source
vs Beef							
Fungal mycoprotein (F. venenatum) — Quorn mince	Beef	−96%	−93%	−89%[1]	NR	NR	*Carbon Trust, 2021*
Fungal mycoprotein (Y. lipolytica, SSF, potato starch)	Beef	−94%	−97%	-94%[2]	-83%	−97%	*Pasutto et al., 2025*
Fungal mycoprotein (F. venenatum) — ENOUGH	Beef	−89%	NC	−96%	−83%	−99%	*Pignatelli et al., 2026*
Fungal mycoprotein (review, literature range)	Beef	−93 to −98%	NC	NC	NR	NR	*Shahid et al., 2024*
Fungal mycoprotein (F. venenatum) burger patty	Beef burger	−80%	−67%	−78%[1]	0% (ns)	−97%	*Smetana et al., 2021*
Fungal mycoprotein (F. venenatum) from rice straw	Beef	−86%	−98%	+80%[2]*	−73%	−93%	*Upcraft et al., 2021*
Bacterial SCP protein powder	Beef	−94%	−98%	-97%[2]	−98%	−97%	*Järviö et al., 2021*
vs Pork							
Fungal mycoprotein (F. venenatum) — Quorn mince	Pork	−86%	−87%	−55%[1]	NR	NR	*Carbon Trust, 2021*
Fungal mycoprotein (F. venenatum) — Quorn sausages	Pork sausage	−65%	−58%	80%[1]	NR	NR	*Carbon Trust, 2021*
Fungal mycoprotein (Y. lipolytica, SSF, potato starch)	Pork	−25%	−86%	-95%[2]	-60%	−77%	*Pasutto et al., 2025*
Fungal mycoprotein (F. venenatum, review)	Pork	−48 to −81%	NC	NC	NR	NR	*Shahid et al., 2024*
Fungal mycoprotein (F. venenatum)	Pork (Germany)	+14% (ns)	−94%	−70%[2]	NR	NR	*Treml et al., 2026*
Fungal mycoprotein (F. venenatum) from rice straw	Pork	−31%	−85%	10x[2]*	+333%	−59%	*Upcraft et al., 2021*
vs Chicken							
Fungal mycoprotein (F. venenatum) — Quorn pieces	Chicken breast	−71%	−79%	−23%[1]	NR	NR	*Carbon Trust, 2021*
Fungal mycoprotein (F. venenatum) —Quorn nuggets	Chicken nuggets	−29%	−73%	−55%[1]	NR	NR	*Carbon Trust, 2021*
Fungal mycoprotein (F. venenatum) —ENOUGH	Chicken breast (organic)	−33%	NC	−81%	NC	NC	*Pignatelli et al., 2026*
Fungal mycoprotein (review)	Chicken	−16% to −70%	NC	NC	NR	NR	*Shahid et al., 2024*
Fungal mycoprotein (F. venenatum) from rice straw	Chicken	−22%	−80%	9x[2]*	+333%	−42%	*Upcraft et al., 2021*
Fungal mycoprotein (F. venenatum — WT vs FCPD[§])	Broiler chicken (China)	+29%, -31%.[§]	−50%, −73%	+127%[2], +27%[2]	−59%, −79%	−22%, −58%	*Wu et al., 2025*
Bacterial SCP protein powder	Poultry meat	−75%	−94%	−99%[2]	−92%	−91%	*Järviö et al., 2021*

Precision fermentation proteins: Alternative dairy & egg

Precision fermentation uses microorganisms as biological factories to produce specific functional proteins—including whey and egg white protein—that are nutritionally and functionally equivalent to their animal-derived sources, but with fewer resources and emissions.

Precision fermentation dairy and eggs offer reduced GHG emissions, land use, and water use

A growing body of peer-reviewed LCA evidence shows that these proteins can be produced with dramatically lower land requirements and substantially lower GHG emissions, under most energy grid scenarios, than conventional dairy or egg production. Studies report GHG reductions of up to 97% for dairy protein and up to 74% for egg-white protein compared to conventional production (Figure 3; Table 2).

Dairy protein

Three foundational LCAs provided comprehensive evidence for PF dairy protein's environmental sustainability. In a USA production context, Briggs et al. (2021) conducted an ISO-conformant LCA of Perfect Day's whey protein, finding GHG reductions of 62–97% compared to bovine dairy protein, alongside approximately 96–99% lower blue water consumption. The wide range reflects sensitivity to co-product burden allocation, but even the most conservative scenario (100% burden allocated to the whey protein only) still yielded at least 62% lower GHG than the global dairy protein comparator.

On behalf of Verley (formerly Bon Vivant), Hamelin and Cellier (2024) examined a European production context, finding 69–84% lower GHG, 99% lower land use, and 88–96% lower water scarcity than the functionally equivalent cow milk protein system.

Freshwater eutrophication showed high variability (+63% to −103%), driven by canola oil inventory added to match milk's nutritional composition in the comparison, not by the fermentation process itself.

GHG emissions (kg-$CO_{2\text{-eq}}$ per kg-protein)

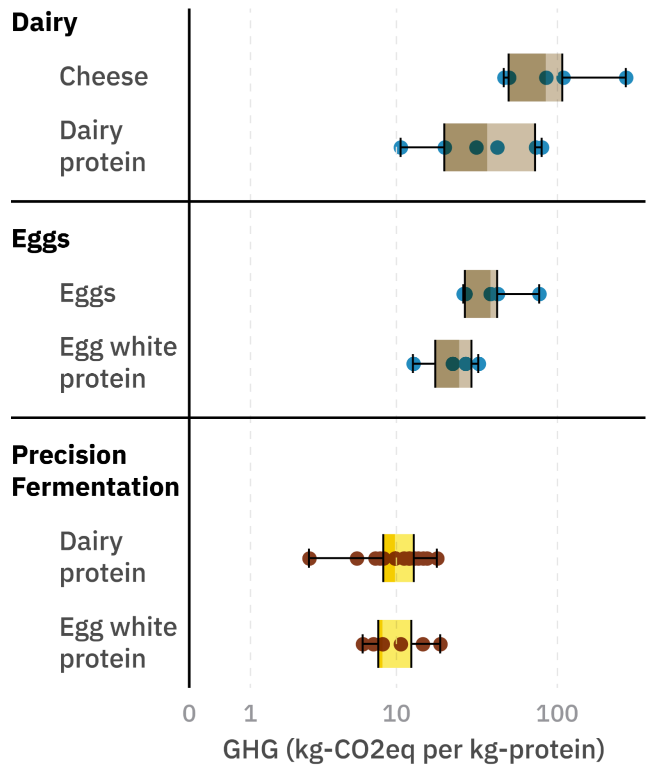
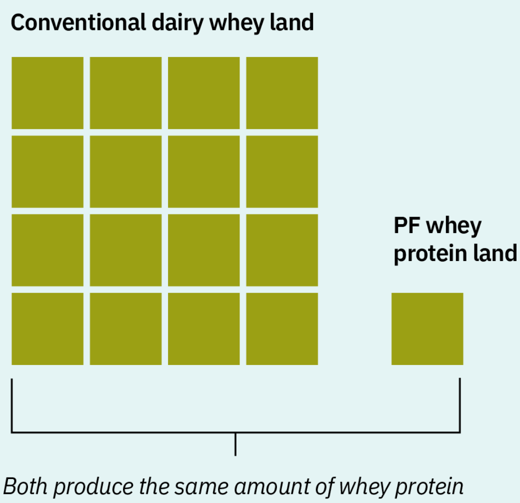


Figure 3. Climate impact (kg-CO_{2eq} per kg protein, log scale) of precision fermentation dairy and egg ingredients relative to animal-based dairy and egg. See appendix method notes for data sources.

Researchers at VTT and Fonterra R&D Centre (Behm et al., 2022) modelled PF whey protein across multiple locations and carbon sources, finding that GHG and water scarcity performance was highly context-dependent. In the New Zealand production scenario, GHG reductions ranged from −45% to −4% lower, while water scarcity impacts varied from −1% to +848% against New Zealand dairy protein, reflecting the difficulty of outperforming one of the lower-impact conventional dairy benchmarks globally. Their results highlight that advantages are possible, but energy source, feedstock choice, and production geography are decisive.

Precision fermentation dairy protein production is more land-efficient

Based on research from Kossmann et al. (2025), redirecting a portion of Germany's current sugar crop production to precision fermentation could theoretically produce 4.5× the country's entire current dairy whey protein output, without expanding agricultural land. More broadly, the researchers found that PF whey protein produced from surplus sugar beet feedstocks requires 4–16× less land than conventional dairy whey protein, using existing German agricultural land.*



**Calculated from Table 4, Kossmann et al. (2025), based on German agricultural statistics and published LCA process data. The 4.5× protein output and 4-16x land figures reflect diversion of surplus sugar above planetary health diet recommended levels; other scenarios modeling full sugar beet or maize acreage diversion yield even greater protein production.*

Egg white protein

Precision egg white proteins offer similar climate, land use, water use, and air pollution benefits over conventional egg whites. Researchers at the University of Helsinki and VTT (Järviö et al., 2021) published the foundational peer-reviewed LCA of precision fermentation ovalbumin egg-white protein (Tr-OVA) produced from *T. reesei*, finding GHG reductions of 55% (Germany) to 31% (Poland) compared to conventional egg white powder, alongside consistent land use reductions of 87–89%. Water scarcity results flip direction in Poland, but this is driven almost entirely by the differences in feed sourcing assumptions for the egg white comparator rather than Tr-OVA's own footprint. This comparator sensitivity is methodologically important: geographic differences in feed supply chains alone can reverse the direction of water-related results.

Leino et al. (2025) updated this analysis using next-generation lignocellulosic feedstocks across Finnish energy scenarios, finding 35–74% lower climate impact and 88–94% lower land use compared to egg white powder. The best results come from low-carbon electricity combined with second-generation carbon sources—the same two levers that dominate performance across all fermentation pathways.

Precision fermentation-derived egg white protein can cut land use by up to 94% and GHG by up to 74% – strong foundational benefits that improve with next-generation feedstocks.

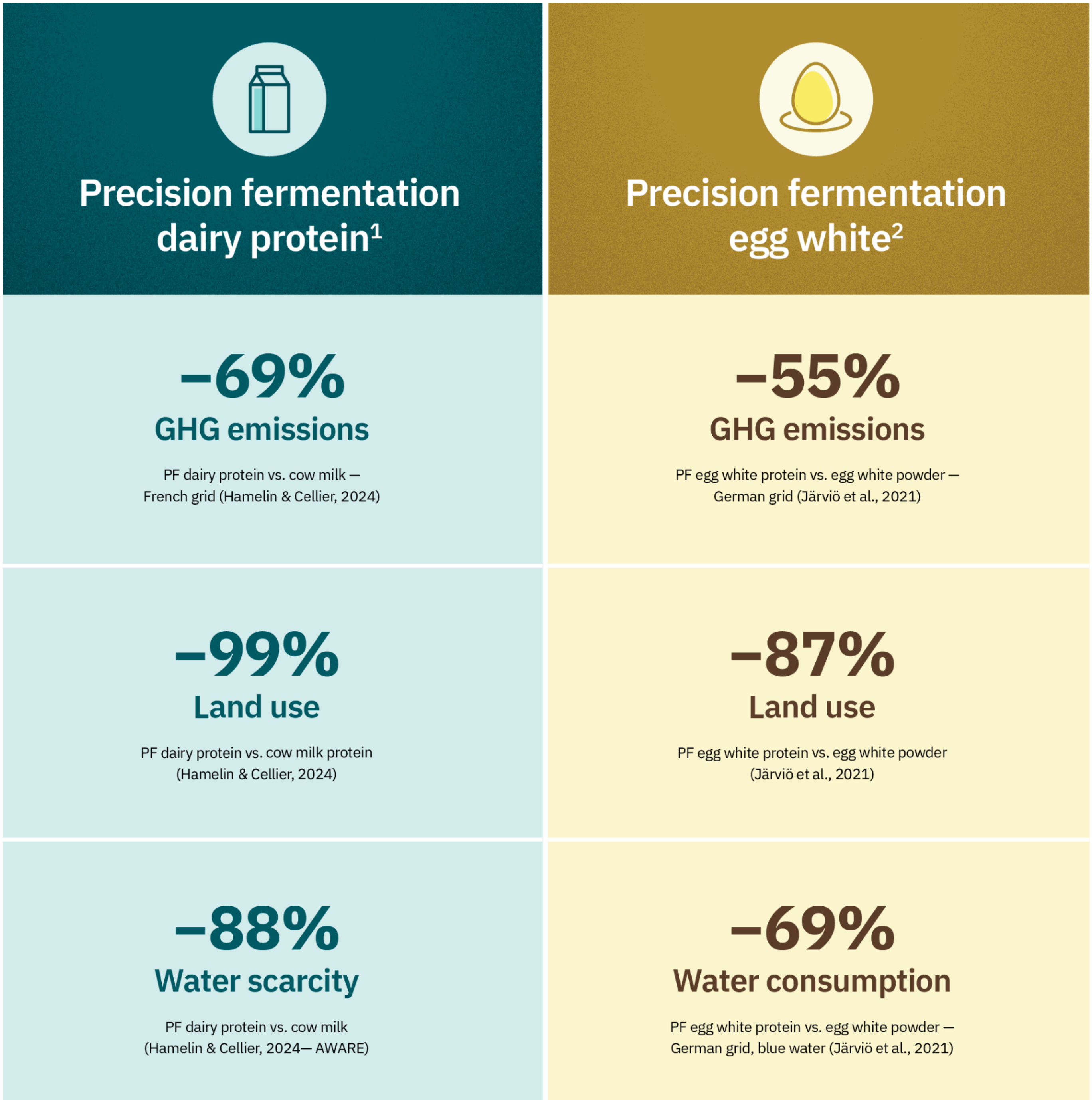


Figure 4. Precision fermentation dairy and egg protein impact reduction

Source: 1 Hamelin and Cellier 2024, on behalf of Verley, based on PF dairy protein versus baseline benchmark cows milk and French grid energy source. 2 Järviö et al. 2021: PF egg white protein versus chicken egg white powder protein production, based on Germany production scenario for both.

Table 2: Precision fermentation proteins vs. conventional dairy and egg — LCA comparison

Comparative LCA percent difference versus conventional animal protein comparator within-study comparisons only · negative = lower environmental impact · NR = not reported. NC = assessed but not directly compared. ns = not statistically significant · Full referenced data table available on our website at: gfi.org/fermentation-lca-overview.

Ingredient Type	Instead of	GHG Emissions	Land Use	Water	Freshwater pollution	Air Pollution	Source
vs Dairy Protein							
PF whey protein (rBLG)— Perfect Day, No allocation vs allocation	Protein in bovine milk (global)	−76%, −94%	NR	−89%[1], −97%[1]	NR	NR	*Briggs et al., 2021*
PF whey protein (rBLG) — Fonterra, NZ comparator	Purified dairy protein (NZ)	−45% to −7%	NR	−1% to +848%[2]	NR	NR	*Behm et al., 2022*
PF dairy protein (rBLG) — Verley/Bon Vivant	Cow milk protein (France)	−69% (−84%)	−99% (-99%)	−88% (−96%) [2]	+63% (−103%)	−71% (-63%)	*Hamelin & Cellier, 2024*
PF whey protein — Bored Cow animal-free milk	2% dairy milk	−44%	−96%	−68%[1]	NR	NR	*Planet FWD., 2023*
vs Egg White Protein							
PF egg protein (Tr-OVA) — Ovalbumin, Germany	Chicken egg white powder (Germany)	−55%	−87%	−69%[1] −86%[2]	124%	−77%	*Järviö et al., 2021*
PF egg protein — Ovalbumin, Poland	Chicken egg white powder (Poland)	−31%	−89%	53%[1] 26%[2]	153%	−66%	*Järviö et al., 2021*
PF egg protein — Ovalbumin, Finland	Chicken egg white powder (Finland)	−35% to −74%	−88% to −94%	NR	NR	NR	*Leino et al., 2025*

Water as: [1]water use (blue water), [2]water scarcity (AWARE); Freshwater pollution as eutrophication unless specified; Air pollution as terrestrial acidification; Briggs et al. (2021) average values shown for no allocation versus allocation to biomass from TableES.1 and Table 9, water as blue water.; Behm et al (2022) values show New Zealand location scenario range versus average comparator impacts with water as water scarcity (AWARE). Hamelin & Cellier (2024) values as baseline and (sensitivity). Leino et al. (2025) values show scenarios range with and without GHG land use and land use change (LULUC) emission assumptions.

Microbial oils: Alternative fish oils

Microbial oils, produced by growing oil-rich microalgae or yeast on land, offer a route to essential omega-3 fatty acids that bypasses ocean extraction entirely—addressing a deepening global shortage of omega-3s. Microbial fish oil alternatives can relieve pressure on overfished marine ecosystems.

Omega-3 fatty acids are increasingly recognised as essential to human health, yet access to adequate, uncontaminated DHA and EPA oils is insufficient in most countries of the world and is projected to worsen as fisheries face mounting pressure from overfishing, ocean warming, and acidification (Ciesielski et al., 2025). Many regions, such as in Europe and the United States, are structurally dependent on imports to meet domestic seafood demand, with domestic supply insufficient to meet omega-3 dietary recommendations (Lofstedt et al., 2021; Gephart et al., 2019). Meanwhile, more than one-third of the world's wild fish stocks are currently fished at unsustainable levels (FAO, 2024), and global fish oil demand continues to intensify pressure on fisheries already stretched beyond sustainable limits. Microbially-produced omega-3 oils offer a scalable terrestrial alternative that eliminates dependence on ocean extraction and removes pressure on fish populations, marine food webs, and the broader ecosystems that depend on them.

Microbial omega-3s demonstrate GHG, pollution, and ecotoxicity advantages

The available LCA evidence shows consistent benefits across multiple impact categories. The strongest case is against farmed fish oil with approximately 99% lower GHG, eutrophication, and acidification (Togarcheti et al., 2021). Against wild-caught fish oil, GHG reduction ranges from 29–32% (Davis et al., 2021) to 73% (Dutra et al., 2024) using glucose and sucrose feedstocks, and 271% lower (Bartek et al., 2021) using a food-waste-derived feedstock.

Marine eutrophication, freshwater eutrophication, terrestrial acidification, and ecotoxicity are reduced across multiple studies (Table 3)—impact categories where fish oil often performs poorly due to fishing vessel emissions and nutrient pollution from aquaculture feed. The notable exception is land use: microalgal oils consistently require more land than fish oil when crop-based feedstocks are used, a trade-off inherent to terrestrial production using agricultural sugar sources that is reduced when waste-derived feedstock sources are used (Bartek et al., 2021; Table 3).

Avoiding marine fisheries depletion is the strongest environmental argument for microalgal oils—but standard LCA methods do not fully measure it

A structural gap exists in how this benefit is quantified. Among the microbial fish oil LCAs, only McKuin et al. (2022) measured biotic resource use, and only Bartek et al. (2021) reported endpoint ecosystem damage—the two metrics that most directly reflect marine ecosystem impacts. More broadly, the overexploitation of living resources remains underrepresented in operational LCA methods (Damiani et al., 2023), in part because biodiversity effects are inherently more complex to quantify than other environmental impacts, and the methods that do exist depend on stock-specific characterisation factors requiring regular recalculation (Bergman et al., 2025). This creates an asymmetric comparison: land use costs of microalgal production are routinely quantified, while the fisheries overexploitation liability of fish oil falls largely outside standard LCA frameworks. The environmental case for microalgal oils is therefore likely stronger than headline LCA figures suggest.

Check out GFI's climate benefits of accelerating global production of alternative seafood report.

Table 3: Microbial oils vs. conventional fish oil — LCA comparison

Comparative LCA percent difference versus conventional animal protein comparator within-study comparisons only · negative = lower environmental impact · NR = not reported. NC = assessed but not directly compared. ns = not statistically significant · Full referenced data table available on our website at: gfi.org/fermentation-lca-overview.

Ingredient Type	Instead of	GHG emissions	Land Use¶	Water	Water pollution	Air pollution	Biotic Resource Use	Source
vs Fish OIl (wild-caught or farmed)								
Microalgal DHA-rich oil (food waste feedstock, Germany)	Fish oil (wild caught)	−271%	−16%	NR	3%	−10%	NR	*Bartek et al., 2021*
Microalgal DHA-rich oil (sugarcane, Brazil)	Fish oil (wild caught)	−32 to −29%	High¶	−77% to +253%[1]	NR	−24% to +65%	NR	*Davis et al., 2021*
Microalgal DHA-rich oil	Fish oil (wild caught)	−73%	High¶	−79%[1]	−66% (marine)	−72%	NR	*Dutra et al., 2024*
Whole-cell DHA-rich microalgal biomass and DHA-rich oil (USA, Brazil)	Fish oil (wild caught)	−5%, +58%	High¶	15x[1]	255% (fresh), 54% (marine)	NR	−96%, −88%	*McKuin et al., 2021*
Microalgal EPA/DHA-rich oil (Europe)	Fish oil (farmed)	−99%	NR	NR	−99%	−99%	NR	*Togarcheti et al., 2021*

Water as: [1]water use (blue water), [2]water scarcity (AWARE); Water *pollution as freshwater eutrophication unless specified; Air pollution as terrestrial acidification; Bartek et al. (2021) also found a -31% reduction in Total Ecosystem Damage (endpoint).; Dutra et al. (2024) also found a -74% reduction in ecotoxicity.; Davis et al. (2021) range reflects agrifootprint vs ecoinvent fish oil LCI.*
¶Land use trade-offs: these studies show 16-32x higher land use - see explainer below.

Depleting marine fisheries versus land use trade-offs

Microalgal oils consistently require more land than wild-caught fish oil when crop-based sugars are used as feedstocks—an inherent cost of terrestrial production that should be considered alongside GHG and marine ecosystem benefits. This tradeoff diminishes by shifting production to alternative feedstocks sourced from waste streams or gas streams, as seen in Bartek et al (2024), which modeled a food-waste-derived feedstock.

Importantly, this comparison is structurally asymmetric: land use costs of microalgal production are fully visible in LCA, while fisheries overexploitation and the depletion of marine living resources is not well reported or quantified in LCA frameworks, as detailed previously.

A growing omega-3 supply gap creates an opportunity for microbial oils

Global demand is outpacing supply with prices rising sharply over the past two decades—driven by stagnating wild catch, rising aquaculture demand, and growing recognition of omega-3s' role in human health. Climate-driven disruptions compound this further: the 2023 El Niño cancelled Peru's first anchovy season entirely, driving global fish oil prices from $2,000–3,000 to over $12,000 per metric ton and briefly making algal oil the cheaper option (GOED, 2024; Glencross et al., 2025). As climate change increases the frequency and severity of such disruptions, microalgal omega-3 oils—grown on land in controlled conditions—offer a supply chain-resilient alternative that is entirely decoupled from vulnerable ocean extraction.

Demand for microbial omega-3 oils is also growing from alternative seafood companies. These companies already cite omega-3 ingredient cost and limited supplier availability as their top sourcing challenges, and anticipate purchasing dramatically larger volumes as their products scale. This presents a significant market opportunity for microbial omega-3 producers across both supplement and alternative seafood sectors.

See GFI's survey report on omega-3 ingredients for alternative meat and seafood.

Check out GFI's climate benefits of accelerating global production of alternative seafood report.

Photo credit: Adnan / Adobe Stock

What drives the environmental performance of fermentation-derived ingredients?

Understanding what drives fermentation's environmental performance matters as much as knowing the headline numbers. The advantages documented above are real, but they are not automatic. Ensuring that fermentation-derived ingredients are manufactured in a lower-impact approach can support stakeholders' environmental, social, and governance (ESG) goals. Three factors consistently determine whether fermentation delivers on its potential, and all three are addressable through deliberate R&D, commercialization, investment, and policy.

Three levers shape outcomes across all fermentation pathways

Energy is the key lever

Electricity and heat are the dominant hotspots across all fermentation pathways. GHG performance is directly tied to grid carbon intensity—land and water advantages are not. Transitioning to renewable energy, or positioning facilities where it is accessible, is the single highest-leverage improvement available—and the clearest target for public and private investment.

Feedstocks shape upstream impact

Carbon feedstock production—glucose, sucrose, and other crop-derived sugars or starches—is the most consistently reported impact driver across both protein and oil LCAs. Next-generation feedstocks, including agricultural sidestreams, food-waste-derived carbon, and CO_2-based sources, can substantially reduce these impacts—though burden-shifting toward energy demand means decarbonizing both levers together delivers the greatest gains.

Where you produce matters

Location shapes results as much as process design. Grid carbon intensity, water scarcity, feedstock sourcing geography, and local infrastructure can each impact the direction of environmental results—even when the production process is identical. Site selection and energy procurement are environmental decisions, not just economic ones.

Policy actions to enable fermentation at scale

Fermentation-derived food ingredients offer a substantial opportunity to reduce the environmental footprint of protein and oil supply chains. Policymakers should invest in alternative proteins for a secure, sustainable food supply: beyond their significant environmental benefits, alternative proteins expand consumer choice and promote national security by increasing supply chain resilience (CSIS 2023; GFI and ETI, 2026).

Fermentation-derived food ingredients deliver environmental and economic value

The evidence reviewed in this fact sheet demonstrates that fermentation-derived ingredients deliver measurable environmental benefits across climate, land, water, and ocean impacts. Alongside this environmental case, a GFI techno-economic analysis shows these ingredients are approaching cost-competitiveness with conventional animal-based ingredients—with feedstock costs, capital expenditures, and raw material processing identified as the primary cost drivers. Investments in sustainable, next-generation feedstocks, production infrastructure, and renewable energy can lower both cost and environmental impact simultaneously.

The barriers to scale are often not scientific, but economic, regulatory, and infrastructure-related. Targeted policy action can close that gap.

Accelerate production to meet sustainability goals

- Fund open-access R&D and commercialization support to drive innovation and competitiveness.
- Incentivize commercial-scale production through loans, loan guarantees, manufacturing grants, transferable tax credits, and procurement commitments.

Deploy incentives to support regional bioeconomy hubs

- Investments in public-private fermentation hubs with shared pilot plants and scale-up facilities to reduce capital expenditure burden on individual companies.
- Create circular bioeconomy hubs by co-locating fermentation facilities with industrial decarbonization projects.
- Prioritize low-cost, renewable electricity access for biomanufacturing facilities.

Bolster regional feedstock supply chains

- Support regionally produced crops, such as corn, sugarcane, and sugarbeet, as primary sugar feedstock sources.
- Develop clean sugar processing and next-generation feedstock infrastructure to meet growing bioproduction demand.
- Connect fermentation facilities to agricultural sidestreams to enable circular resource use and new farmer revenue streams.

Maintain efficient regulatory pathways

- Establish risk-based, proportionate regulatory pathways for novel fermentation-derived ingredients.

For a deeper discussion on policy interventions to support fermentation-derived proteins and oils, review our policy action paper and reach out to GFI.

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About GFI

The Good Food Institute is a nonprofit think tank working to make the global food system better for the planet, people, and animals. Alongside scientists, businesses, and policymakers, GFI's teams focus on making plant-based, fermentation-enabled, and cultivated meat delicious, affordable, and accessible. Powered by philanthropy, GFI is an international network of organizations advancing alternative proteins as an essential solution needed to meet the world's climate, global health, food security, and biodiversity goals. All of GFI's work is made possible by gifts and grants from our global community of donors. If you are interested in learning more about giving to GFI, contact philanthropy@gfi.org. To learn more, please visit www.gfi.org.

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Appendix

Studies: Studies included in this report represent the available peer-reviewed literature and major grey literature sources from a systematic literature review of fermentation LCAs as of early 2026. Excluded studies: Hamelin et al (2022) for Verley and CarbonTrust (2018) for Quorn, which are superseded by 2024 and 2021 updated studies, respectively. These are provided in the reference list.

Data comparison: All percentage comparisons in this report are within-study comparisons only — drawn from the same LCA study using consistent functional units, system boundaries, and impact assessment methods for both the fermentation-derived ingredient and its conventional comparator. Direct comparison of percentage figures across different studies is not appropriate, as studies differ substantially in functional unit (per kg product vs. per kg protein), system boundary (cradle-to-gate vs. cradle-to-grave), LCIA method (ReCiPe, EF, CML, GHG Protocol), and allocation approach. See the data table on our website for more study details. Water results reported in this document include both volumetric blue water consumption and scarcity-weighted water use (AWARE method). These are different quantities measuring different things — process efficiency versus watershed stress — and are not directly comparable across studies. See individual studies referenced in Tables 1-3 for details.

Figure 2 and Figure 3: Climate Impact (kg-CO_{2eq} per kg protein): comparison of median greenhouse gas emissions for biomass fermentation based ingredients and products relative to different types of animal-based meats (Figure 2), and precision fermentation produced dairy and egg white proteins relative to animal based dairy and egg (Figure 3)**.** Data based on impact per kg-protein. Error bars indicate minimum and maximum values from multiple sources.

- Biomass fermentation values sourced from: Fungi: Brancoli et al (2021), Carbon Trust (2018,2022),ClimatePoint NOSH.Bio (2024), ENOUGH (2024), Leino et al. (2025), Pasutto et al. (2025), Smetana et al. (2021), Treml et al. (2026), Upcraft et al. (2021), Wu et al. (2025). Yeast: Kobayashi et al. (2023); Bacteria (gas): Fasihi et al. (2025), Kobayashi et al. (2023), Järviö et al. (2021), Sillman et al. (2021).
- Precision fermentation data sources: Dairy protein: Behm et al. (2022), Briggs et al. (2021); Egg white protein: Järviö et al. (2021), Leino et al. (2025).
- Meat impact data sourced from: Poore and Nemecek (2018) (All); Treml et al. (2026) (Pork); Upcraft et al (2021) (Chicken/Pork); Wu et al. (2025) (Chicken).
- Animal-based dairy & egg impact data sources: Cheese/Milk/Eggs from Poore and Nemecek (2018) after adjusting 100 g protein FU to 1 kg protein, No milk protein nutritional functional unit was available from P&N 2018; Sourced dairy protein impacts from Behm et al. (2022) and Briggs et al. (2021) on a per kg-protein basis; Egg white protein data from Järviö et al. (2021) and Leino et al. (2025).

Tables 1–3: Comparative LCA percent difference versus conventional animal protein comparator within-study comparisons only:

negative = lower environmental impact
NR = not reported
NC = assessed but not directly compared
ns = not statistically significant

Study notes below with more information found on a full referenced data table available on our website at: gfi.org/fermentation-lca-overview.

Biomass study notes below

- Shahid et al., 2024: Range shown is for median animal-based impact versus mycoprotein range.
- *Upcraft et al.(2021) LCA has anomalously high water due to rice irrigation since rice straw is valorized here as a fermentation feedstock. Not representative of glucose-based mycoprotein production.
- §Wu et al., 2025 values shown for wildtype (WT) and CRISPR engineered strain (FCPD) - WT, FCPD. Lower bound = FCPD (CRISPR-engineered, 44% less glucose than WT); upper bound = WT (wild type). Both are modeled under coal-heavy China electricity grid. FCPD is a gene-edited strain of F. venenatum.
- Treml et al. 2026 GHG result (+14% vs pork) is statistically inconclusive per Monte Carlo analysis — pork system has 18× higher variance. Land use (−94%) and water scarcity (−70%) reductions are statistically robust.
- Pasutto et al. 2025: comparison of impacts from more complete data from supplementary inventory "3_All_EF3.1_impacts_no corr" for mycoprotein starch binder scenario. Egg white formulation scenario excluded (lab-scale artifact) as the LCI inventory is unclear and highly elevated - not representative.