

INTRODUCTION

Global demand for dietary protein is projected to rise by more than 40% by 2050 as the world population approaches 9.7 billion, intensifying pressure on agricultural land, water resources, and food systems already strained by climate change (FAO, 2023). Livestock production alone is estimated to contribute close to 14.5% of anthropogenic greenhouse gas emissions and occupies roughly 77% of global agricultural land while supplying only about 18% of global caloric intake — making the efficiency of animal-protein production a central sustainability concern (Gerber et al., 2013; Poore & Nemecek, 2018). In response, the alternative-protein sector — spanning plant isolates, mycoprotein, insect protein, microalgae and cultured meat — has grown at a compound annual rate above 9%, supported by evolving regulatory frameworks such as the EU Novel Food Regulation (EU) 2015/2283, which governs the safety assessment of non-traditional protein sources before market entry. Protein-quality assessment has itself evolved: the Digestible Indispensable Amino Acid Score (DIAAS), recommended by FAO since 2013, replaced the older PDCAAS method by accounting for true ileal digestibility of individual amino acids rather than fecal crude-protein digestibility — giving a more physiologically accurate basis for comparing protein sources of very different origin.

- Study Aims

To comprehensively compare the nutritional quality (amino acid profile, in vitro digestibility, micronutrient density) and environmental footprint (GHG emissions, land and water use) of conventional and alternative protein sources, and to integrate these dimensions into a multi-criteria framework for evaluating dietary and food-industry strategies.
- Research Hypotheses

1. Alternative proteins carry a substantially lower environmental footprint per kg protein, particularly for GHG emissions and land use.

2. Single plant proteins show lower DIAAS scores due to limiting amino acids (e.g., methionine in legumes), but this gap narrows through complementary blending.

3. Novel sources (mycoprotein, insect protein) combine intermediate footprints with favorable micronutrient profiles (Fe, Zn, B12).

4. A multi-criteria approach integrating nutrition, environment, cost and acceptance favors blended and fermentation-based proteins as the most balanced near-term strategy.

8 sources animal, plant, insect, algae & lab-grown	DIAAS digestible indispensable amino acid score	LCA cradle-to-farm-gate life-cycle assessment	3 blends tested for amino-acid complementation
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METHODOLOGY

Conventional protein sources evaluated in this study included meat, fish, eggs, and dairy products, while alternative proteins comprised plant-based proteins, insects, algae, fungi-derived proteins, and cultivated meat. Nutritional assessment was based on protein content, amino acid profile, digestibility, and the presence of essential micronutrients

■ **Protein sources** Beef, chicken, whey (conventional); pea, soy, lentil (plant isolates); mycoprotein (fermentation-based); mealworm (insect); spirulina (microalgae); cultured meat (emerging).

■ **Amino acid analysis** RP-HPLC with pre-column derivatization; DIAAS calculated against the FAO/WHO/UNU (2013) adult reference amino-acid pattern.

■ **Digestibility** INFOGEST 2.0 harmonized static in vitro digestion protocol, simulating oral, gastric and intestinal phases

■ **Micronutrients & antinutrients** Fe, Zn, Ca and vitamin B12 by ICP-MS/AAS; phytate and trypsin-inhibitor screening in plant sources.

■ **Sustainability (LCA)** ISO 14040/14044-compliant cradle-to-farm-gate LCA; functional unit = 1 kg digestible protein; GHG, land and water footprints.

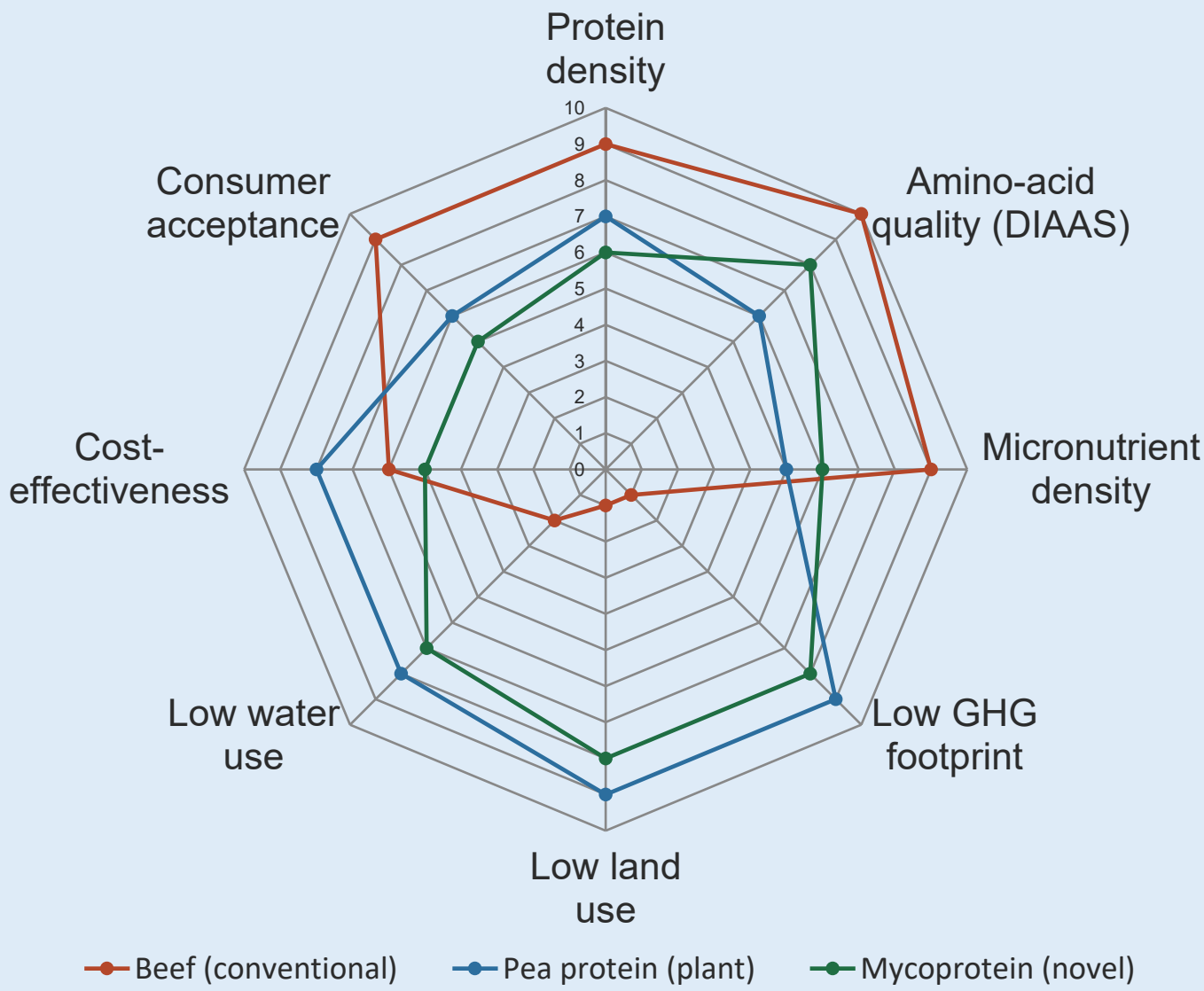
■ **Functional properties** Solubility across pH 3–9, water/oil-holding and foaming/emulsifying capacity, relevant to food reformulation.

■ **Multi-criteria scoring** PCA and weighted multi-criteria decision analysis (MCDA) integrating nutritional and environmental axes into a single comparative score.

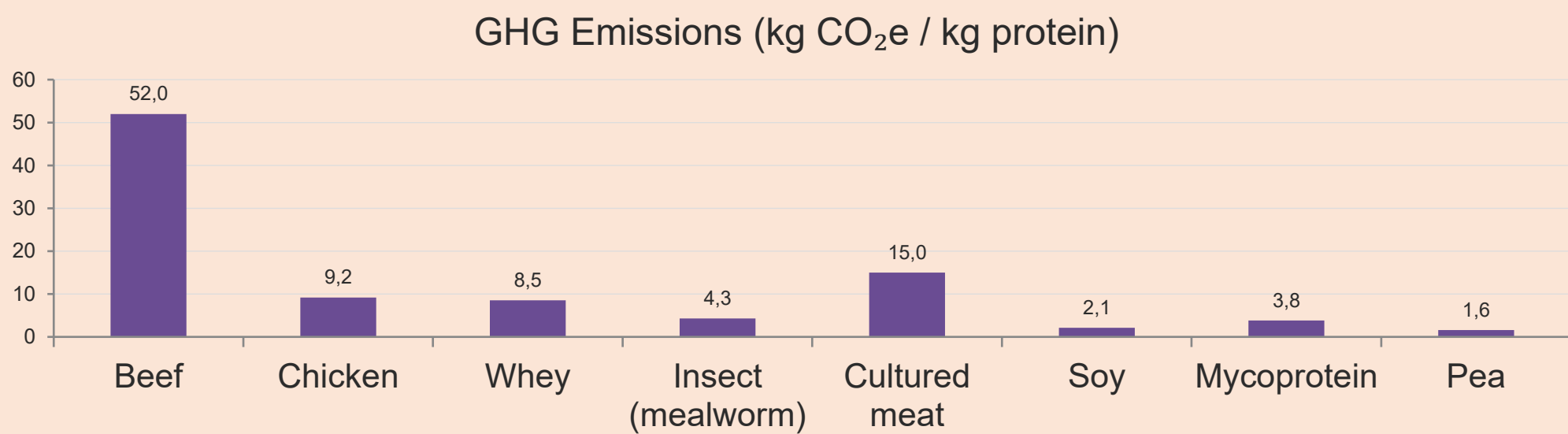
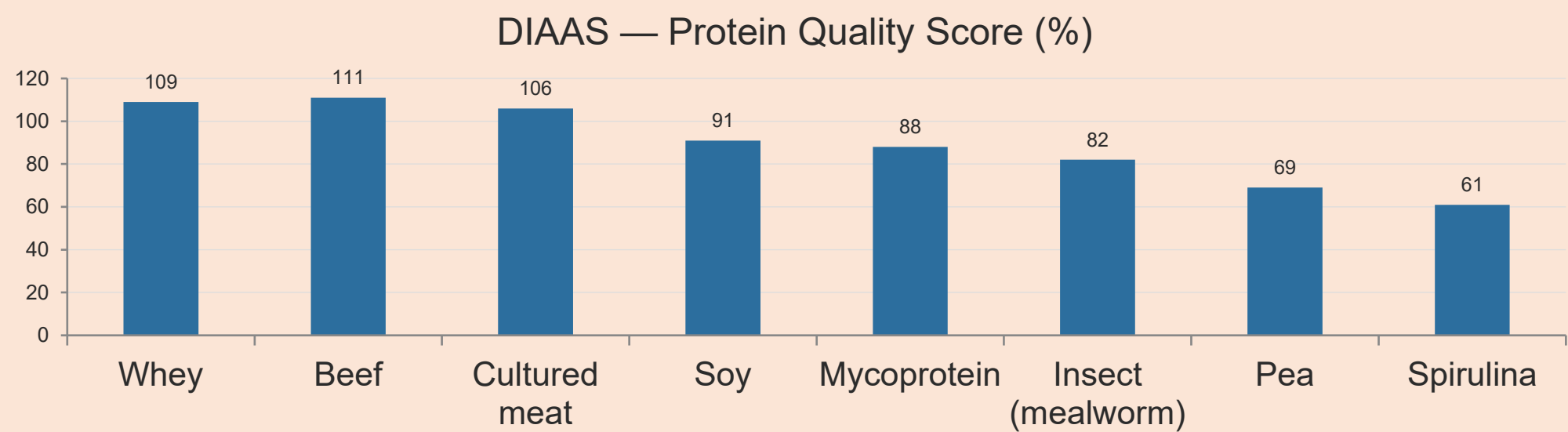
■ **Statistics** ANOVA with Tukey post-hoc tests; Pearson correlation between DIAAS and footprint metrics (R 4.3.2).

Multi-criteria assessment framework

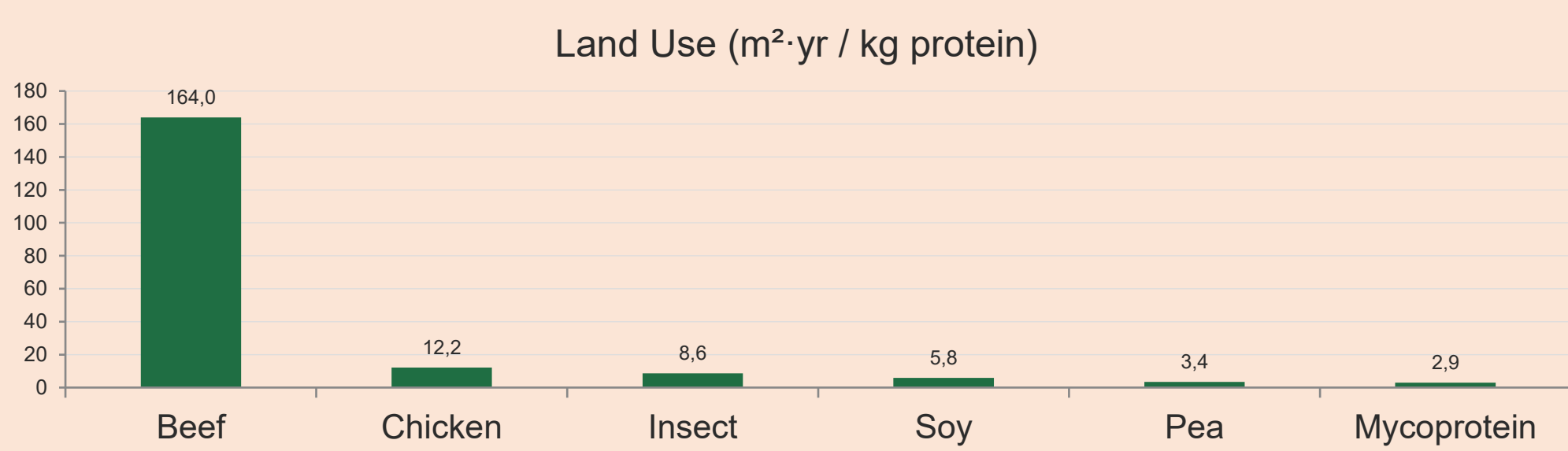
Illustrative scores (0–10) across nutritional and environmental axes for three representative sources



RESULTS & DISCUSSION



Nutritional & Environmental Summary			
Source	Protein (%)	DIAAS (%)	GHG (kgCO ₂ e/kg)
Beef	26	111	52.0
Pea protein	82	69	1.6
Pea + rice blend	80	97	1.8
Mycoprotein	45	88	3.8
Mealworm	50	82	4.3



Key Results: Animal proteins (beef, whey) scored highest on DIAAS (109–111%) but carried the largest environmental footprint — beef required roughly 30× more land and 20–30× more GHG emissions per kg protein than pea or mycoprotein. Single plant proteins scored lower on DIAAS (pea 69%), but a pea + rice blend reached 97% DIAAS — close to animal sources — while keeping GHG emissions near pea-protein levels. Insect and mycoprotein occupied an intermediate position, combining good amino-acid scores with a much smaller footprint than meat.

Significance: Complementary blending of plant proteins is an effective, low-cost route to close the amino-acid gap without sacrificing sustainability gains. Insect protein and mycoprotein additionally provide micronutrients (Fe, Zn, B12) often lacking in plant sources. Cultured meat matched conventional meat on DIAAS but currently carries a higher GHG footprint than most plant and fermentation-based alternatives, reflecting present-day energy-intensive production.

CONCLUSIONS

–97% GHG per kg protein: pea vs. beef	97% DIAAS of pea+rice blend (vs. 69% pea alone)	–30× land use: beef vs. mycoprotein	3 novel sources rich in Fe / Zn / B12
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- Alternative proteins cut environmental footprint dramatically, but single plant sources trail animal proteins on amino-acid quality.

• Blending complementary plant proteins (e.g., pea + rice) closes most of the DIAAS gap while preserving the sustainability advantage.

• Insect protein and mycoprotein offer a favorable middle ground on both nutrition and environmental impact, plus useful micronutrients.
- Policy Perspectives:** Encourage dietary diversification toward blended and fortified protein sources, support labeling standards that report both DIAAS and carbon footprint, and prioritize R&D funding for scaling low-footprint fermentation- and blend-based proteins.

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