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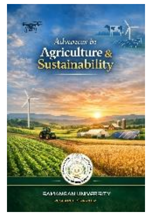

The Impact of Protein Production Systems on Greenhouse Gas Emissions

Mohammad Akbar Muttaqi [1*], Mohammad Nikzad [1], Abdul Basir Sultani [1]

[1] *Department of Agronomy, Agriculture Faculty, Ghor University*
[*] *Corresponding Author: m.akbarghori@gmail.com*

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Abstract

Global demand for protein is rising due to population growth, urbanization, and changing diets. Although protein is essential for human health, its production—from livestock to plant-based and novel sources—has significant environmental impacts, especially greenhouse gas (GHG) emissions. Using the PRISMA method, scientific publications from 2013-2026 were collected, from 43 identified studies, finally 30 relevant articles were selected for analysis. Livestock, particularly cattle and other ruminants, contributes the most to methane and nitrous oxide emissions. Poultry and swine have moderate impacts, mainly from feed and manure management. Plant-based proteins generally produce lower emissions, although processing can increase energy use. Emerging sources such as insect protein, algae, and cultivated meat show strong potential for reducing emissions, with insect protein being especially efficient. Studies from Europe and Asia indicate that shifting diets toward plant-based proteins can significantly reduce GHG emissions, though effects on agricultural incomes differ. The review concludes that no single protein source is sufficient; a diversified approach—improving livestock efficiency, expanding plant-based options, and investing in novel proteins—is essential for balancing nutrition, sustainability, and economic outcomes.

1. Introduction

The global demand for protein continues to rise due to population growth, urbanization, and changing dietary preferences. Protein is essential for human health, yet its production systems, ranging from conventional livestock farming to plant-based alternatives and emerging cultivated proteins, carry significant environmental consequences. Among these, greenhouse gas (GHG) emissions represent one of the most pressing challenges, directly contributing to climate change and threatening planetary sustainability (Nugrahaeningtyas et al., 2024). Understanding how different protein production systems influence GHG emissions is therefore critical for designing sustainable food strategies.

Livestock production remains a major source of methane and nitrous oxide, potent greenhouse gases with high global warming potential (Herrero et al., 2016). While plant-based proteins and novel alternatives are often promoted as environmentally friendly, their production processes-such as protein isolation, crop cultivation (Aimutis & Shirwaiker, 2024), and industrial processing-also generate emissions and resource demands (Leinonen et al., 2013). Moreover, dietary guidelines increasingly emphasize protein diversification, yet they rarely account for the environmental trade-offs associated with different sources (Mozaffarian, 2026; Phillips, 2021). This creates a gap between nutritional recommendations and climate mitigation goals.

Recent studies highlight the potential of alternative proteins to reduce emissions compared to conventional animal sources. For instance, plant-based meat substitutes have been shown to lower cattle inventories and associated GHG outputs (Lusk et al., 2022). Transitioning from animal-based to plant-based food systems in Denmark demonstrated measurable reductions in agricultural emissions (Prag & Henriksen, 2021). Similarly, analyses of European dietary shifts suggest that protein source substitution can influence both emissions and agricultural incomes (Geibel & Freund, 2023).

At the same time, uncertainties remain. The environmental impact of protein concentrates and isolates depends on processing intensity and energy use (Aimutis & Shirwaiker, 2024). Poultry diets incorporating alternative protein crops show variable outcomes depending on cultivation practices and regional conditions (Leinonen et al., 2013). Novel proteins, including cultivated and insect-based sources (Moummou et al., 2026), present promising mitigation pathways but require further life-cycle assessments to validate their sustainability (Quintieri et al., 2023).

Broader reviews emphasize that alternative proteins can contribute to food security and sustainability (Nirmal et al., 2025), but their nutritional quality, safety, and scalability must be carefully considered (Choręziak et al., 2025; Gil et al., 2024). The global protein transition also raises socio-economic and cultural questions, with key unknowns regarding consumer acceptance and long-term climate impacts (Lumsden et al., 2024).

This review aims to synthesize current evidence on the environmental impacts of protein production systems, with a particular focus on GHG emissions. By comparing livestock, plant-based, and novel protein sources, the study seeks to:

- Identify the relative contributions of different systems to GHG emissions.
- Highlight methodological uncertainties and gaps in existing research.
- Assess the alignment between dietary guidelines and climate mitigation strategies.
- Provide insights into pathways for sustainable protein production that balance nutritional needs with environmental goals.

The significance of this work lies in its potential to inform policymakers, researchers, and consumers about the trade-offs inherent in protein production. As nations strive to meet climate targets while ensuring food security, understanding the comparative impacts of protein systems is essential. This review contributes to the broader discourse on sustainable diets and offers a foundation for future innovations in protein production that minimize environmental costs while maximizing human health benefits.

2. Materials and Methods

This study is a review article that draws on information from scientific publications released between 2013 and 2026. In this study, the PRISMA method was used for collecting and selecting scientific article. Literature searches were conducted in different scientific databases using the keywords: Alternative protein, Life Cycle Assessment, Greenhouse Gas Emissions and Food Security. The sources included peer-reviewed scientific articles, reports from international organizations, translations of relevant papers, and technical guidelines. Searches were conducted in databases such as Scopus, Google Scholar, Science Direct, MDPI, as well as organizational websites, including WRI, FAO, and SNV.

Initially 43 relevant articles were downloaded; the articles were then screened according to the PRISMA procedure. Duplicate studies were removed first. Subsequently the titles and abstracts were evaluated based on their relevance to the research topic, namely the impact of protein producers on greenhouse gas emissions.

After full-text assessment, studies with insufficient data or weak relevance were excluded. Finally 30 eligible articles were selected and included in this study.

3. Results

3.1- Greenhouse Gas Emissions from Livestock Systems

Livestock production was consistently identified as a major source of methane and nitrous oxide emissions. Cattle and ruminant systems showed the highest emission intensities, while poultry and swine contributed comparatively lower levels. Mitigation potentials were reported, but variability across regions and production practices remained significant.

Table 1. Estimated greenhouse gas emissions from different livestock systems

Protein Source	Main GHGs	Relative Emission Intensity	Notes
Cattle	CH_4, N_2O	Very High	Enteric fermentation dominant
Sheep/Goats	CH_4, N_2O	High	Similar to cattle, smaller scale
Poultry	CO_2, N_2O	Moderate	Feed production impact
Swine	CH_4, N_2O	Moderate	Manure management significant

3.2 Plant-Based Protein Systems

Plant-based proteins, including legumes, cereals, and isolates, generally showed lower emissions compared to livestock. However, processing of concentrates and isolates introduced additional energy demands. Regional differences in crop cultivation practices influenced emission outcomes.

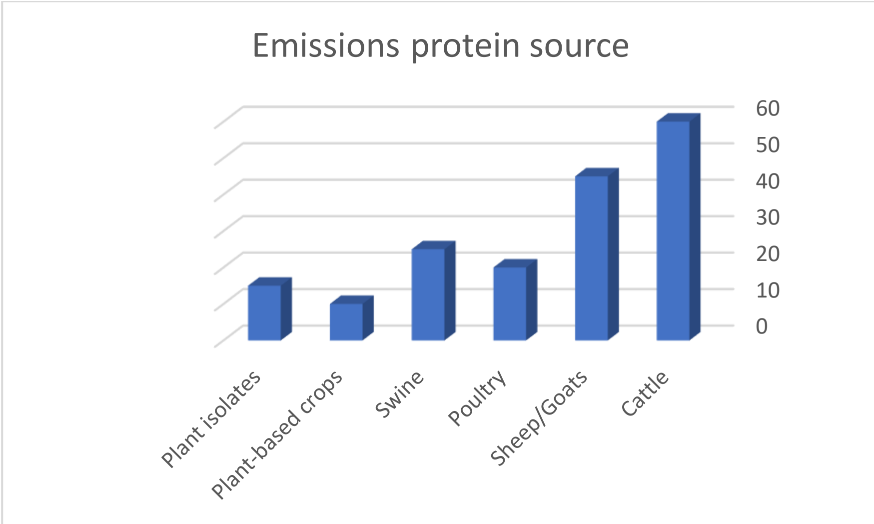

Figure 1. Comparative emissions of plant-based vs animal-based protein systems *(Bar chart showing lower emissions for plant-based proteins compared to livestock, with isolates slightly higher than raw crops due to processing)*.

3.3 Novel and Alternative Proteins

Emerging protein sources such as cultivated meat, insect protein, and algae demonstrated potential for reduced emissions. Life cycle assessments indicated variability depending on technology maturity and energy inputs. Insect protein showed relatively low emissions, while cultivated meat results varied widely depending on production scale and energy source.

Table 2. Emission ranges for novel protein sources

Protein Source	Approximate GHG Emissions	Functional Unit	Reference
Cultivated meat	~1.9-2.24 kg co_2 -eq	Per Kg product	Tuomisto&Teixeira. (2013)
Insect protein	Relatively low emissions	Per Kg edible mass/protein	Choreziak et al. (2025)
Algae/microalgae	Variable; energy demand dependent	Per Kg dry biomass	Gil et al. (2024); Colgrave et al. (2021)
Plant-based proteins	Lower than animal proteins	Per Kg edible product/protein	Aimutis& shirwaiker (2024)
Conventional livestock protein	Higher emissions	Per Kg meat/ product	Herrero et al. (2016)

3.4 Greenhouse gas emissions of different protein sources per gram of protein.

Greenhouse Gas (GHG) Emissions associated with different protein source per gram of protein produced. Plant-based protein source such as wheat, corn, beans, chickpeas, lentils and soy exhibited the lowest climate impact, while animal-based proteins (Beef and lamb) generally produced higher emission (WRI, 2019).

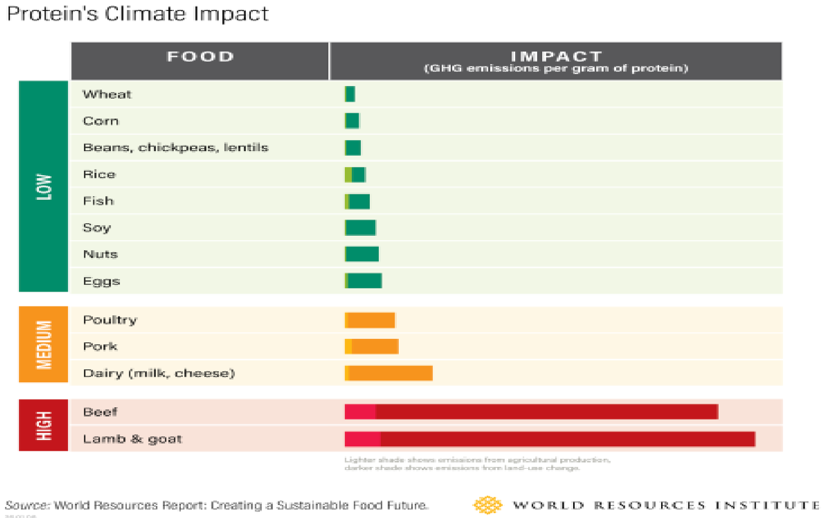

Figure 2. Greenhouse gas emissions of different protein sources per gram of protein.

4. Discussion

The results highlight the substantial differences in greenhouse gas (GHG) emissions across protein production systems. Livestock production, particularly cattle and ruminants, remains the most significant contributor to methane and nitrous oxide emissions. This finding is consistent with prior analyses that emphasize the livestock sector's central role in global warming potential. While mitigation strategies exist, such as improved feed efficiency and manure management, their effectiveness varies across regions and production practices, underscoring the complexity of reducing emissions in traditional animal systems.

Plant-based proteins generally demonstrated lower emissions compared to livestock. However, the environmental benefits are not uniform. Processing steps required to produce protein isolates and concentrates introduce additional energy demands, which can offset some of the advantages of raw crop-based proteins. This aligns with broader assessments that emphasize the importance of considering the full life cycle of plant-based protein products.

Novel protein sources, including cultivated meat, insect protein, and algae, present promising alternatives. Insect protein, for example, showed relatively low emissions due to efficient feed conversion. Cultivated meat, however, exhibited wide variability depending on energy sources and production scale. These findings suggest that while novel proteins may contribute to emission reductions, their sustainability depends heavily on technological maturity and energy infrastructure.

However, these transitions also revealed socio-economic trade-offs, particularly in agricultural incomes and livestock inventories. This highlights the need for integrated policies that balance environmental goals with economic and social considerations.

Overall, the results confirm that no single protein source offers a universal solution. Instead, a portfolio approach that combines emission reductions in livestock systems, expansion of plant-based proteins, and development of novel alternatives appears most effective. Importantly, dietary guidelines must evolve to incorporate environmental dimensions alongside nutritional recommendations, ensuring that protein choices contribute to both human and planetary health.

4.1 Table 1 (Livestock Systems)

- Shows estimated GHG emissions from cattle, sheep/goats, poultry, and swine.
- **Cattle**: Very high emissions (methane from enteric fermentation).
- **Sheep/Goats**: High emissions, similar to cattle but smaller scale.
- **Poultry**: Moderate emissions, mainly CO_2 and N_2O from feed production.
- **Swine**: Moderate emissions, methane and nitrous oxide from manure management. The authors stress that cattle and ruminants dominate global warming potential, while poultry and swine are less intensive but still significant. Regional practices strongly influence outcomes.

4.2 Figure 1 (Plant-Based vs Animal-Based Proteins)

- A bar chart comparing emissions.
- Plant-based crops show the lowest emissions.
- Plant isolates are slightly higher due to processing energy demands.
- Livestock (cattle, sheep/goats) are much higher than plant systems.
- Plant-based proteins generally reduce emissions, but isolates/concentrates can offset some benefits because of energy-intensive processing.

4.3 Table 2 (Novel Proteins)

- Compares cultivated meat, insect protein, and algae.
- **Cultivated meat**: Emissions vary widely depending on energy source and scale.
- **Insect protein**: Low emissions due to efficient feed conversion.

- **Algae/microalgae**: Moderate emissions, highly dependent on cultivation system. Novel proteins are promising but uncertain. Insects are most efficient, while cultivated meat's sustainability depends on technological maturity.

4.4 Figure 2 (Greenhouse gas emissions of different protein sources per gram of protein)

Plant-based proteins such as beans, lentils, chickpeas, wheat and soy generated the lowest emissions, while beef and lamb produced the highest emissions per pram of protein. This figure emphasizes the major environmental differences between animal-based and plant-based protein sources and supports the argument that dietary diversification toward plant proteins can significantly reduce climate impacts.

5. Conclusion

This review demonstrates that protein production systems differ markedly in their greenhouse gas emission profiles. Livestock systems remain the highest contributors, while plant-based proteins generally reduce emissions, though processing requirements can diminish their advantages. Novel proteins show promise but require further technological development and validation of their life cycle. The findings underscore the importance of aligning dietary guidelines with climate mitigation strategies. Sustainable protein production must strike a balance between nutritional adequacy, environmental impact, and socio-economic realities. Policymakers, researchers, and consumers all play a role in advancing this transition.

In conclusion, achieving a sustainable protein future will require coordinated efforts across sectors: improving efficiency in livestock systems, scaling plant-based alternatives responsibly, and investing in novel protein technologies. By integrating these approaches, societies can move toward diets that support both human health and environmental sustainability.

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