Received: 24 September 2025 | Revised: 26 September 2025 | Accepted: 24 November 2025 | Available online: 06 November 2025
DOI: https://doi.org/10.31102/eam.2025.2.2.104-121

REVIEW ARTICLE

Open Access Environmental & Agriculture Management

# Gas-to-feed revolution: a novel review of the microbial conversion of industrial emissions into sustainable livestock feed

**Rezki Amalyadi[1*], Lusia Komala Widiastuti[2]**

[1]Department of Animal Science, Faculty of Animal Science, University of Mataram
[2] Department of Animal Science, Faculty of Agriculture, University of Lampung
**Correspondence**
Rezki Amalyadi, Department of Animal Science, Faculty of Animal Science, University of Mataram
Email: rezkiamalyadi@staff.unram.ac.id



**Abstract**
The livestock sector is a major contributor to greenhouse gas emissions, especially through feed production and processing. As demand for animal products increases, the need for sustainable alternatives becomes more urgent. This review explores how the circular bioeconomy (CBE) can reduce environmental impact by using industrial waste gases, such as $CO_2$, CO, and $CH_4$, as carbon sources for microbial bioconversion. The review discusses key microbial platforms, including autotrophic bacteria, methanotrophs, and hydrogen-oxidizing bacteria, for their ability to convert gases into biofuels and single-cell protein (SCP). These alternatives offer a more ecofriendly approach to conventional livestock feed. The review also highlights successful industrial applications, safety and regulatory challenges, and emerging biotechnological innovations, such as synthetic biology and co-culture systems. Ultimately, integrating the CBE into livestock systems provides a way to achieve more sustainable, resilient, and efficient food production.

KEYWORDS
Circular bioeconomy, Gas fermentation, Microbial bioconversion, Single-cell protein (SCP), Sustainable livestock.

## 1. INTRODUCTION

Recent advances in microbial biotechnology enable the ‘gas-to-feed’ approach, in which industrial waste gases such as $CO_2$, CO, and $CH_4$ are biologically converted into single-cell protein and other feed components, transforming emissions into valuable nutritional inputs. The livestock sector significantly contributes to global greenhouse gas (GHG) emissions and has various environmental impacts, including land use, water use, and pollution (Molden & Khanal, 2025). Beyond contributing to global GHG emissions, gases such as $CO_2$, CO, and $CH_4$ represent untapped carbon reservoirs that can be valorized through microbial fermentation. Converting these waste gases into feed ingredients repositions them from pollutants to productive inputs within a circular carbon economy. Feed production and processing alone account for 45% of the sector's total GHG emissions. Feed production dominates livestock-related emissions because it involves intensive use of land, energy, and fertilizers for crop cultivation and processing. Consequently, decarbonizing feed supply chains provides the most strategic leverage point for emission reduction both by minimizing land-use change and by introducing novel feed inputs, such as microbial protein synthesized from waste gases. Other sources include enteric methane and manure management (Makkar, 2016). The growing demand for livestock products exacerbates these environmental issues, underscoring the importance of sustainable feed practices and efficient resource utilization (Mamphogoro et al., 2024; Place, 2024). The circular bioeconomy (CBE) integrates the principles of the circular economy with the use of biological resources to create sustainable, resource-efficient production systems (Mabee, 2022; Molden et al., 2025). In livestock production, this involves using outputs from one sector as inputs for another. For example, agricultural by-products and food waste can be used as feed (Puente-Rodríguez et al., 2022). The CBE aims to minimize waste, optimize resource use, and reduce environmental impacts by promoting practices such as nutrient recycling, using alternative feed sources, and implementing integrated farming systems (Garrett et al., 2020; Wyngaarden et al., 2020).

This review explores the potential of the circular bioeconomy to address sustainability challenges in livestock production. Specifically, this review examines how circular bioeconomy principles can be operationalized by converting industrial emissions ($CO_2$, CO, and $CH_4$) into microbial biomass for livestock feed, identifying technological pathways, industrial examples, and policy enablers that support this gas-to-feed transition. It will examine current practices and innovations, highlighting successful implementations of circular bioeconomy (CBE) principles in livestock feed and production systems (Parodi et al., 2022), as well as the barriers and opportunities. The circular bioeconomy (CBE) represents a systems-based approach that integrates biological resource cycles into a broader framework of environmental sustainability, economic resilience, and social equity. It emphasizes closing nutrient and energy loops across sectors through valorization of waste streams and renewable carbon flows. Globally, feed manufacturing contributes significantly to $CO_2$ emissions through fertilizer use, energy consumption, and land conversion. Simultaneously, industrial processes emit billions of tonnes of $CO_2$ annually, representing an overlooked carbon source that could offset feed-related emissions. The convergence of these two systems industrial emissions and livestock feed production presents an opportunity for integrated mitigation through microbial conversion technologies. It will identify the challenges faced by farmers and other stakeholders in adopting circular practices and potential solutions to overcome these barriers (Pink et al., (2025); and policy and regulatory frameworks, discussing the role of policies and regulations in facilitating the transition to a circular bioeconomy in the livestock sector (Domènech & Bahn-Walkowiak, 2019; Marku et al., 2024). By synthesizing insights from recent research, the review will provide a comprehensive understanding of how CBE principles can enhance the sustainability of livestock production, contributing to global food security and environmental conservation. Despite its holistic framework, the practical application of the circular bioeconomy in livestock remains constrained by technological and structural barriers. Efficient bioconversion of industrial gases requires advanced reactor systems, reliable gas capture, and integration with existing feed supply chains. Moreover, the lack of supportive policies and limited technological readiness for industrial-scale microbial fermentation hinder broader implementation.

## 2. MATERIALS AND METHODS

This review uses a systematic literature review (SLR) approach to summarize existing research on applying circular bioeconomy principles to sustainable livestock feed production. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework guided the review process to ensure methodological transparency, rigor, and replicability. This study adopts a Systematic Literature Review (SLR) approach following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological rigor, transparency, and reproducibility. Scopus was selected as the primary database because it comprehensively indexes peer-reviewed scientific publications relevant to environmental sciences, biotechnology, and livestock production.

Scopus was used as the primary database because it comprehensively indexes peer-reviewed research across biotechnology and agricultural sciences. Search strings combined keywords such as '*circular bioeconomy*,' '*gas fermentation*,' '*industrial emissions*,' 'microbial bioconversion,' '*single-cell protein*,' and '*livestock feed*,' using Boolean operators (AND/OR). The search was limited to English-language publications from 2003–2025. Articles were included if they reported microbial or biotechnological utilization of industrial gases for feed or bioresource production; purely conceptual or non-livestock studies were excluded. A literature search was conducted using combinations of keywords and Boolean operators, including terms such as "*circular bioeconomy*," "*livestock*," "*microbial bioconversion*," "industrial gases," "gas fermentation," "single-cell protein," "*methanotrophs*," and "*Clostridium autoethanogenum*." The search was limited to English articles published between 2003 and 2025. To maintain focus, the search strategy explicitly targeted studies addressing microbial bioconversion of industrial gases ($CO_2$, CO, $CH_4$) for feed or bioresource applications. Broader circular bioeconomy or livestock sustainability papers without microbial or gas-conversion components were excluded during full-text screening. This filtering step ensured the review concentrated on microbial biotechnology pathways relevant to gas-to-feed innovations rather than general CBE concepts. Only articles focusing on practical or experimental applications of microbial or biotechnological innovations in livestock feed systems were considered to ensure relevance. Articles were included if they met the following criteria: they were published in peer-reviewed journals indexed in Scopus; they focused on the microbial conversion of industrial gases or the circular bioeconomy in the context of livestock production; and they provided empirical data, applied reviews, or techno-economic assessments. Articles were excluded if they were non-English publications, opinion pieces, conference proceedings, or unrelated to microbial feed production or livestock sustainability.

The initial search yielded 312 records. After removing duplicates and screening the titles and abstracts preliminarily, 161 articles remained for full-text evaluation. Each article was assessed against the inclusion and exclusion criteria, resulting in a final selection of 93 relevant articles. The selection process was documented using a PRISMA flow diagram (see Appendix A). Key information from each selected article was extracted and entered into a standardized data matrix. This information included authorship, year of publication, microbial platform or pathway used, types of industrial gases utilized (e.g., $CO_2$, CO, $CH_4$), target products (e.g., single-cell protein, ethanol, polyhydroxyalkanoates), scale of implementation (laboratory, pilot, or industrial), and major findings. A thematic analysis was then performed to categorize the findings as microbial bioconversion strategies, gas-to-feed pathways, nutritional and safety evaluations of microbial protein, regulatory frameworks, or future technological directions. This structured synthesis aims to provide a comprehensive overview of how microbial and biotechnological innovations contribute to sustainable livestock systems within a circular bioeconomy framework.

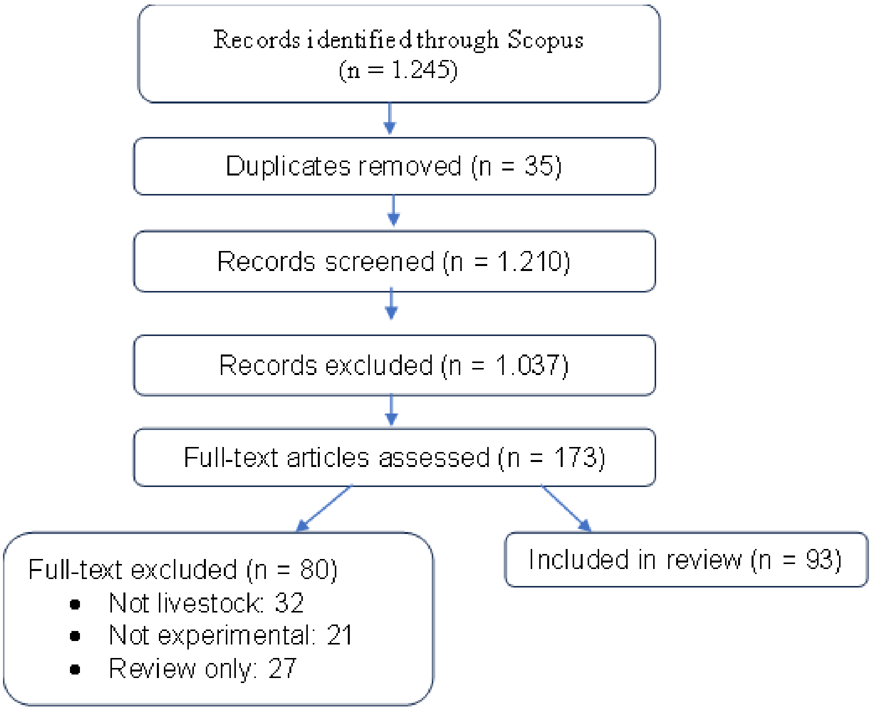


Figure 1. PRISMA flow diagram for literature review.

## 3. RESULT AND FINDING

### 3.1 Industrial Emissions and Their Environmental Impact

Various gases are emitted from industrial activities, including carbon dioxide ($CO_2$), which is produced from the burning of fossil fuels in power plants, automobiles, and industrial processes (El-Nemr, 2011; Kannan & James, 2009); carbon monoxide (CO), which is produced from the incomplete combustion of fossil fuels in power plants, vehicles, and industrial processes (Kocasoy & Yalin, 2004; Majstorović et al., 2020); methane ($CH_4$), released from natural gas production, coal mining, and agricultural activities (Aydin & Karakurt, 2024; Mohajan, 2011); nitrous oxide ($N_2O$), emitted from industrial processes and agricultural activities; and halocarbons, which are gases containing fluorine, chlorine, and bromine that are linked to carbon and are often used in industrial applications (El-Nemr, 2011). Industrial emissions significantly contribute to climate change by increasing the concentration of greenhouse gases (GHGs) in the atmosphere. Typical industrial off-gases contain 40–80% CO, 10–30% $CO_2$, and trace $CH_4$, often with impurities such as NOx, $SO_2$, or heavy metals that can inhibit microbial growth. Gas–liquid mass transfer remains a key bottleneck in large-scale fermentations, with volumetric mass-transfer coefficients (kLa) typically ranging from 100–400 $h^{-1}$ depending on reactor design. Addressing these constraints through gas purification and reactor optimization is essential to ensure consistent SCP yields and process safety. Global warming occurs when GHGs, such as $CO_2$, $CH_4$, and $N_2O$, trap heat in the atmosphere, leading to a rise in global temperatures (Talaei et al., 2020). Climate impacts: increased GHGs result in more extreme weather events, such as storms, floods, droughts, and rising sea levels (Fu et al., 2021). Historical context: since the Industrial Revolution, human activities have significantly increased GHG emissions, primarily from fossil fuel combustion and deforestation (Kannadhasan & Nagarajan, 2023).

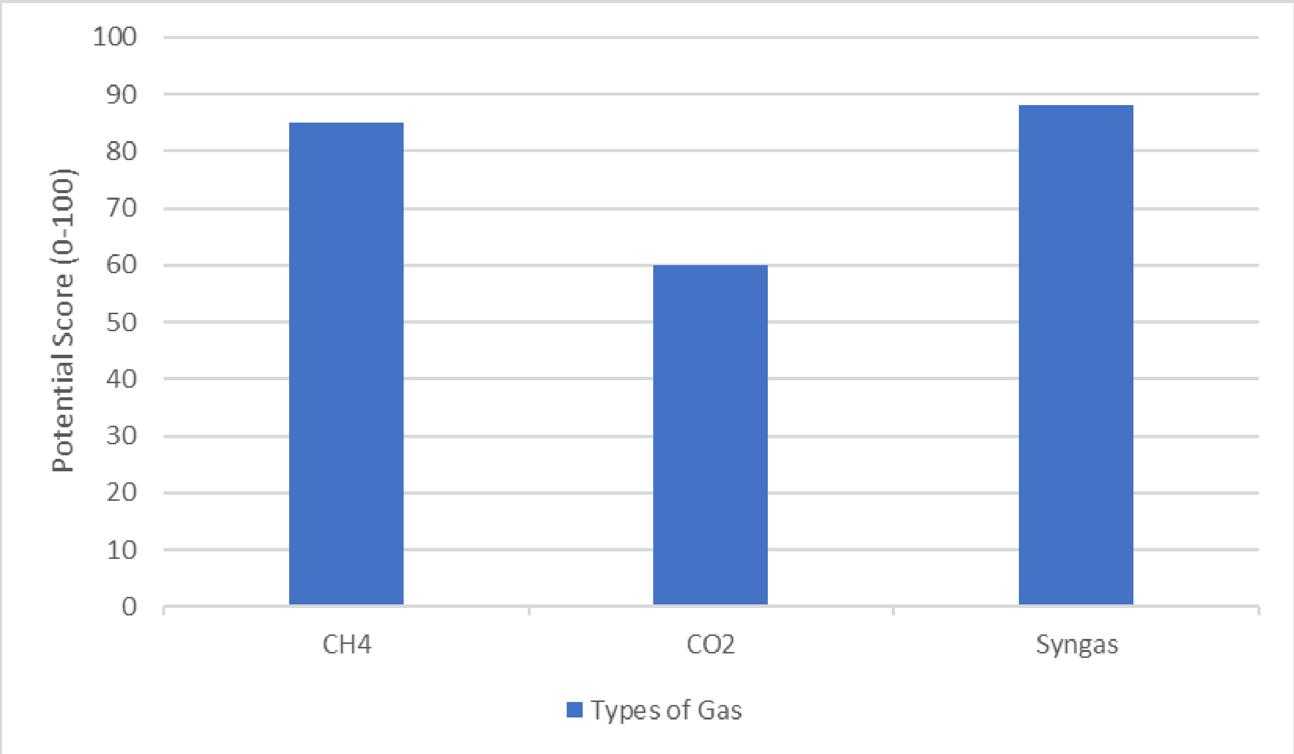


Figure 2. Potential use of gas for feed production.

Using industrial gases as carbon feedstocks for microbes offers several benefits. Abundant and inexpensive gases, such as $CO_2$, CO, and $CH_4$, are ideal for microbial biomanufacturing (Baumschabl et al., 2024; Yaverino-Gutiérrez et al., 2024). Additionally, utilizing these gases can mitigate their environmental impact by converting them into valuable products, thus reducing greenhouse gas (GHG) emissions (Bae et al., 2022; Federici et al., 2023). Biotechnological Potential: Microbes can be engineered to efficiently convert one-carbon (C1) compounds into biofuels and chemicals, supporting a circular carbon economy (Yao & Zhou, 2023). Challenges and Advances: While natural C1-utilizing microbes have limitations, recent advancements in microbial engineering and synthetic biology are improving their efficiency and productivity (Neto et al., 2024).

*Using industrial gases as carbon feedstocks for microbes offers several benefits*

Table 1. Characteristics of industrial gases and their bioconversion potential

| Aspect | Details |
|---|---|
| Types of Gases | $CO_2$, CO, $CH_4$, $N_2O$ and halocarbons |
| Sources | Sources: fossil fuel combustion, industrial processes, agriculture, natural gas production, and coal mining |
| Climate Impact | Global warming, extreme weather events, rising sea levels |
| Utilization Rationale | Abundance, low cost, environmental mitigation, and biotechnological potential |
| Challenges | Efficiency of natural microbes and the need for advanced microbial engineering |

### 3.2 Microbial Platforms for Gas Bioconversion

Notable autotrophic bacteria, such as *Clostridium autoethanogenum* and *Acetobacterium woodii,* convert CO and $CO_2$ into valuable products via the Wood-Ljungdahl pathway. For instance, Clostridium autoethanogenum can convert CO and $CO_2$ into ethanol and other bioproducts. The efficiency of this process is enhanced by supplementing hydrogen (Davin et al., 2024). *Methanotrophs*, such as *Methylococcus capsulatus* and *Methylomicrobium buryatense*, can convert methane ($CH_4$) and $CO_2$ into biomass and other valuable products. Methylococcus capsulatus utilizes both $CH_4$ and $CO_2$, and carbonic anhydrase isoforms play a crucial role in its metabolism (Henard et al., 2021). Genetic engineering has improved the efficiency of these processes. For example, overexpressing carbonic anhydrase enhances the conversion of $CH_4$ to biomass (Lee et al., 2024). M. *buryatense* has been studied for its robust growth and ability to produce various biochemicals under different growth conditions (Garg et al., 2018; Gilman et al., 2015). Hydrogen-oxidizing bacteria (HOB), such as *Cupriavidus necator* and *Hydrogenobacter thermophilus*, use hydrogen ($H_2$) to fix $CO_2$, producing valuable compounds, including polyhydroxyalkanoates and single-cell proteins (Ueda et al., 2007). These bacteria show promise for $CO_2$ capture and waste recovery; recent advances in metabolic engineering have enhanced their productivity (Lin et al., 2022; J. Yu, 2018).

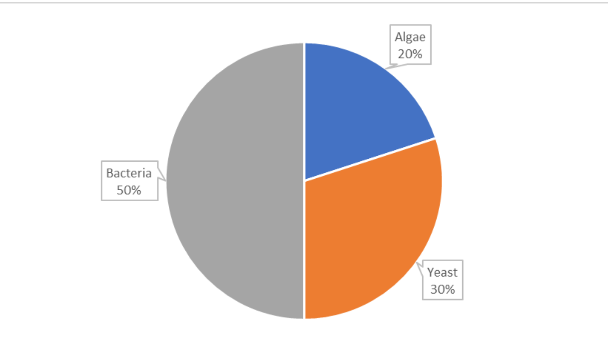


Figure 3. The role of microbes in SCP production

While autotrophic bacteria such as Clostridium autoethanogenum or Methylococcus capsulatus are primarily engineered for bulk protein and biofuel production, algae and cyanobacteria occupy a complementary niche as functional feed ingredients. Their high pigment, lipid, and antioxidant content makes them valuable for enhancing feed quality and animal health rather than serving as primary protein replacements. Thus, they complement rather than compete with bacterial C1 platforms in the gas-to-feed ecosystem. Algae and cyanobacteria efficiently convert $CO_2$ into biomass and biofuels through photosynthesis. These organisms are integral to sustainable biofuel production because they can fix $CO_2$ and produce high-value products (Bardhan et al., 2019). Genetic and metabolic engineering have significantly advanced the capabilities of gas-fermenting microorganisms. For example, methanotrophs have been engineered to increase their efficiency in converting methane and their yield of products. Synthetic promoters and plasmids have been developed to enhance gene expression in methanotrophs such as Methylococcus capsulatus and Methylosinus trichosporium (Bhat et al., 2024; Nath et al., 2022). Furthermore, the Wood-Ljungdahl pathway in Clostridium autoethanogenum has been optimized through metabolic engineering for improved $CO_2$ utilization (Davin et al., 2024).

*Genetic and metabolic engineering have significantly advanced the capabilities of gas-fermenting microorganisms*

Table 2. Microbial strategies for gas-to-product conversion

| Microbial Platform | Key Organisms | Key Processes | Applications |
|---|---|---|---|
| *Autotrophic Bacteria* | *Clostridium autoethanogenum* and *Acetobacterium woodii* | Conversion of CO and $CO_2$ via the Wood-Ljungdahl pathway | Ethanol, bioproducts (Davin et al., 2024) |
| *Methanotrophs* | Methylococcus capsulatus and Methylomicrobium buryatense | $CH_4$ and $CO_2$ conversion | Biomass, biochemicals (Garg et al., 2018; Gilman et al., 2015; Henard et al., 2021; Lee et al., 2024) |
| *Hydrogen-oxidizing bacteria* | *Cupriavidus necator* and *Hydrogenobacter thermophilus* | $H_2$ oxidation and $CO_2$ fixation | Polyhydroxyalkanoates, single-cell proteins (Lin et al., 2022; Ueda et al., 2007; J. Yu, 2018) |
| *Algae* and *cyanobacteria* | Various species | $CO_2$ fixation via photosynthesis | Biomass, biofuels (Bardhan et al., 2019) |
| *Genetic* and *metabolic engineering* | Various gas-fermenting microorganisms | Enhanced gene expression and metabolic pathways | Improved conversion efficiency, product yield (Bhat et al., 2024; Nath et al., 2022) |

### 3.3 Gas-to-Feed Conversion Pathways and Feed Products

Single cell protein (SCP) production involves cultivating microorganisms, such as algae, bacteria, fungi, and yeast, to produce protein-rich biomass. The mechanisms of SCP production are influenced by the choice of microorganisms and substrates, as well as by the optimization of fermentation conditions. For example, photosynthetic bacteria can use volatile fatty acids (VFAs) from food waste fermentation liquids to increase SCP production via metabolic pathways such as the tricarboxylic acid cycle (Zhu et al., 2022). SCP production can also be optimized by adjusting the sources of carbon and nitrogen, pH, temperature, and other cultivation conditions (Koukoumaki et al., 2024; Raita et al., 2022). SCP is rich in protein and contains essential amino acids, lipids, vitamins, and minerals. For instance, SCP derived from various microorganisms contains essential amino acids, such as lysine, methionine, and threonine, as well as lipids and vitamins (Sharif et al., 2021). The fermentation process can improve the nutritional value of SCP by increasing its essential nutrient content (Salazar-López et al., 2022; Sharif et al., 2021). Furthermore, SCP production from food waste results in biomass rich in amino acids, vitamins, and minerals, making it a valuable feed component (Salazar-López et al., 2022).

*The fermentation process can improve the nutritional value of SCP by increasing its essential nutrient content*

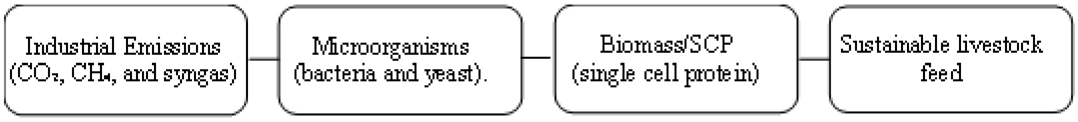


Figure 4. Conceptual diagram: gas bioconversion to feed.

The nutritional profile of SCP makes it a suitable alternative to traditional protein sources, such as fishmeal and soybean meal, in livestock feed. It contains high levels of protein, essential amino acids, carbohydrates, nucleic acids, fats, minerals, and vitamins (Koukoumaki et al., 2024; Sharif et al., 2021). Studies have shown that SCP can replace traditional protein sources in animal diets without negative effects, offering a sustainable, nutritious feed option (Bratosin et al., 2021). Including SCP in livestock feed enhances its nutritional value and supports animal growth and health. While SCP offers numerous nutritional benefits, its safety and palatability are critical for its acceptance in animal feed. However, SCP may contain toxic substances, such as nucleic acids, mycotoxins, and bacterial toxins, necessitating further purification steps to ensure its safety (Salazar-López et al., 2022). Additionally, the palatability of SCP-enriched feed must be evaluated to ensure its acceptability to animals. Studies have shown that including SCP in animal diets does not adversely affect feed intake or animal performance (Bratosin et al., 2021; Sharif et al., 2021). For example, SCP-enriched bread was found to be acceptable up to a certain concentration, suggesting its potential use in animal feed (Khan et al., 2022).

*the palatability of SCP-enriched feed must be evaluated to ensure its acceptability to animals. Studies have shown that including SCP in animal diets does not adversely affect feed intake or animal performance*

### 3.5 Industrial Applications and Case Studies

*LanzaTech* has developed an improved strain of *Clostridium autoethanogenum* that can convert industrial waste gases, primarily CO and $CO_2$, into valuable products, such as ethanol and 2,3-butanediol, via gas fermentation (Chen et al., 2018). This process utilizes the bacteria's acetogenic capabilities to fix carbon and produce biofuels and biochemicals, promoting sustainable industrial practices (Allaart et al., 2023; L. Zhang et al., 2020). *LanzaTech*: Commercial scale; utilizes CO-rich steel off-gas (≈60–70% CO); reported carbon conversion efficiency up to 90% in continuous gas fermentation. Deep Branch: Pilot scale; uses syngas ($CO_2$:$H_2$ ≈1:3) in hydrogen-oxidizing bacterial systems; yields ~60% crude protein (dry basis) in the final single-cell biomass. UniBio: Demonstration/commercial hybrid scale; operates on $CH_4$-dominant natural gas (>95% $CH_4$); achieves biomass productivity of 1.5–2.0 g $L^{-1}$ $h^{-1}$ under optimized conditions.

*LanzaTech has developed an improved strain of Clostridium autoethanogenum that can convert industrial waste gases, primarily CO and $CO_2$, into valuable products, such as ethanol and 2,3-butanediol, via gas fermentation*

The technology has been commercialized, and operational plants use CO-rich off-gas from the steel industry (Gunes, 2021). Deep Branch Biotechnology focuses on converting $CO_2$ into protein using hydrogen-oxidizing bacteria. This process uses hydrogenotrophic bacteria that use hydrogen as an energy source and $CO_2$ as a carbon source to produce single-cell protein (SCP) (Jain et al., 2023; Jiang et al., 2022). While the production of SCP from syngas (a mixture of $CO_2$ and $H_2$) has been demonstrated to be feasible, the presence of CO can inhibit growth. This indicates the need to optimize gas compositions (Jiang et al., 2022). UniBio uses methanotrophic bacteria to convert methane into microbial protein. Methanotrophs, such as *Methylococcus capsulatus*, can use methane as a carbon and energy source to produce biomass, which can serve as a protein source (Engel et al., 2025). This approach provides an alternative protein source and helps mitigate methane emissions, contributing to environmental sustainability (Gao et al., 2024).

*Deep Branch Biotechnology focuses on converting $CO_2$ into protein using hydrogen-oxidizing bacteria. This process uses hydrogenotrophic bacteria that use hydrogen as an energy source and $CO_2$ as a carbon source to produce single-cell protein (SCP)*

The economic viability of these bioconversion processes varies. For example, *LanzaTech's* gas fermentation process reduces production expenses and greenhouse gas emissions, making it economically attractive (Gao et al., 2024; Günes, 2021). Similarly, using hydrogen-oxidizing bacteria to produce SCP is promising but requires further innovation to become cost-effective (Jain et al., 2023). The scalability of these technologies is a critical factor. *LanzaTech's* process has been successfully scaled to commercial levels, demonstrating its feasibility. However, scaling hydrogen-oxidizing bacteria for SCP production and methanotrophic processes remains challenging, particularly in optimizing gas compositions and reactor designs (Engel et al., 2025; Jiang et al., 2022). Techno-economic assessments emphasize the importance of optimizing operational conditions to enhance productivity and reduce costs. For instance, integrating biofilm reactors into syngas fermentation can enhance mass transfer rates and process stability, both of which are essential for commercial scalability (Gunes, 2021). Furthermore, the economic feasibility of producing microbial protein from methane and hydrogen hinges on the market value of the protein and the associated costs of gas purification and reactor operation (Verbeeck et al., 2021).

Table 3. Commercial applications of microbial gas fermentation technologies

| Company | Process Description | Key Microorganism | Key Considerations |
|---|---|---|---|
| LanzaTech | CO to ethanol and biochemicals via gas fermentation | *Clostridium autoethanogenum* | Commercially viable, reduces GHG emissions, scalable (Chen et al., 2018; Gunes, 2021) |
| Deep Branch | Conversion of CO to ethanol and biochemicals via gas fermentation<br>-$CO_2$ to protein via hydrogen-oxidizing bacteria | *Hydrogenotrophic bacteria* | Requires optimization for cost-efficiency, promising but needs further innovation (Jain et al., 2023; Jiang et al., 2022) |
| UniBio | Methane to microbial protein using methanotrophs | *Methylococcus capsulatus* | Mitigates methane emissions, scalable with optimization (Engel et al., 2025; Gao et al., 2024) |

### 3.5 Safety, Regulation, and Public Acceptance

Ensuring the safety of feed is crucial for ensuring the safety of food of animal origin. Feed risk management involves addressing biological, chemical, and physical hazards that can affect human and animal health and welfare (Bouxin, 2023). Risk assessment models, including systematic reviews and meta-analyses, are used to evaluate these risks. However, refining these models for systematic reviews can be challenging (Aiassa et al., 2015). The Codex Alimentarius has developed guidelines for assessing the risk of feed safety, which are implemented through Hazard Analysis and Critical Control Points (HACCP)-based Feed Safety Assurance Schemes (Gorris & Yoe, 2014). The EU's food safety regulations are based on a risk analysis framework, and the European Food Safety Authority (EFSA) provides independent scientific advice (Smith, 2024). The EU has stringent food safety regulations, including the General Food Law (Regulation 178/2002/EC), which ensures high standards (Mandato et al., 2018). Additionally, the EU emphasizes separating risk assessment and risk management to maintain transparency and independence (Holm & Halkier, 2009; Silano, 2005).

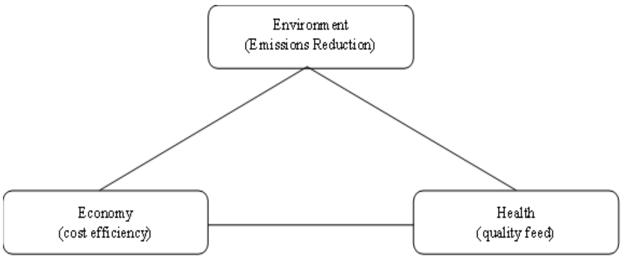


Figure 5. One health/sustainability

The United States' regulatory framework includes the 2011 Food Safety Modernization Act (FSMA), which focuses on preventing food safety issues rather than responding to them. The FSMA requires comprehensive, science-based preventive controls throughout the food supply chain (Gordon et al., 2020). In Asia, food safety regulations are influenced by the WTO's Sanitary and Phytosanitary (SPS) and Technical Barriers to Trade (TBT) agreements. ASEAN and SAARC countries are working to harmonize their food legislation to facilitate trade and ensure food safety (Hoejskov, 2017). Consumer perceptions of food safety significantly influence purchasing decisions and willingness to pay for safer foods. These perceptions are shaped by factors such as trust in food safety information, personal experiences, and demographic characteristics (Sharma et al., 2012; Tonsor et al., 2009; H. Yu et al., 2017). In developing regions such as the MENA, consumer knowledge and awareness are crucial for shaping food safety practices and influencing market readiness (Raad & Bou-Mitri, 2024). Effective risk communication and transparency in the food supply chain are essential for building consumer confidence (De Jonge et al., 2004; Martinez, 2010).

Ethical considerations in food safety include animal treatment, genetically modified organisms, and the precautionary principle (Millstone, 2012; Veflen-Olsen & Motarjemi, 2014). As sustainability concerns grow, the focus is on reducing food waste, ensuring resource-efficient food production, and addressing the environmental impact of food systems (Guillier et al., 2016). Integrating ethical evaluations into sustainability frameworks can address these concerns and promote a holistic approach to food safety and sustainability (Rollin, 2006; Vinnari et al., 2017).

### 3.6 Future Directions

Synthetic biology has advanced strain improvement significantly by developing tools for mutagenesis, screening, and creating novel genetic circuits. These innovations allow for high-throughput screening and selection, resulting in more efficient phenotypic engineering (Yang et al., 2019). Modern genetic technologies, such as recombinant DNA technology, further enhance strain improvement by optimizing metabolic pathways and increasing product yields (Konar & Datta, 2022). Integrating omics approaches, such as transcriptomics and proteomics, with synthetic biology tools has improved the prediction of genes responsible for metabolite overproduction (Sanghavi et al., 2020). Modular co-culture engineering, which uses multiple microbial strains to divide biosynthetic tasks, has emerged as a promising bioproduction performance improvement strategy. This strategy reduces the metabolic burden on individual strains and enhances production efficiency (Pang et al., 2022; Zhao et al., 2023). Co-culture systems have been successfully applied in various fields, including wastewater treatment, soil remediation, and the production of high-value products (Rosero-Chasoy et al., 2021; L. Zhang et al., 2020). Future research should focus on optimizing population dynamics and maintaining robust flux routes to realize the full potential of co-culture engineering (Jones & Wang, 2018; H. Zhang & Wang, 2016).

Producing microbial protein (MP) using renewable energy sources, such as electrolytic hydrogen and oxygen, offers a sustainable alternative to traditional protein sources. Power-to-Protein and *electromicrobial* production technologies can convert $CO_2$ and renewable electricity into high-value proteins with minimal environmental impact (Schmitz et al., 2024; Wise et al., 2022). These methods can significantly reduce reliance on arable land and water resources, making protein production more efficient and environmentally friendly (Fasihi et al., 2025; Sillman et al., 2019). Integrating renewable energy with microbial electrosynthesis also shows promise for producing commodity chemicals and biofuels (Altin & Akay, 2024; Rabaey et al., 2010). Successful adoption of alternative protein sources, such as microbial proteins, requires comprehensive socioeconomic and policy-driven models. These models must address environmental, economic, and social aspects of protein production to ensure balanced outcomes (Søndergaard et al., 2023). Public policies should support the development of sustainable protein sources by promoting research, providing incentives, and ensuring regulatory alignment (Hundscheid et al., 2024). Furthermore, overcoming public acceptance and regulatory challenges is essential for the commercialization of microbial proteins (Matassa et al., 2023).

## 4. CONCLUSION

Industrial waste gases such as $CO_2$, CO, and $CH_4$ represent viable carbon inputs for microbial bioconversion into single-cell protein and other feed ingredients. The gas-to-feed framework links emission mitigation with sustainable feed supply, offering dual environmental and nutritional gains. Successful implementation depends on advancing bioreactor efficiency, lowering production costs, and ensuring supportive policy and regulatory conditions for safe adoption. Strengthening these enabling environments will accelerate the integration of gas-based microbial feed systems within a circular bioeconomy, advancing both livestock sustainability and climate resilience. The livestock sector is under increasing pressure to reduce its environmental footprint, especially regarding greenhouse gas emissions associated with feed production. The circular bioeconomy offers a promising solution: transforming industrial waste gases, such as $CO_2$, CO, and $CH_4$, into valuable products through microbial bioconversion. Microorganisms such as *Clostridium autoethanogenum*, *methanotrophs*, and *hydrogen-oxidizing* bacteria have been engineered to produce biofuels and single-cell protein (SCP), providing sustainable alternatives to traditional feed sources. Companies such as *LanzaTech*, *Deep Branch*, and *UniBio* are commercializing gas fermentation technologies, though challenges in cost, scalability, and regulatory compliance remain. SCP is a nutrient-rich, low-impact feed option; however, safety, public acceptance, and regulatory frameworks are crucial for its adoption. Future directions include synthetic biology, co-culture systems, and integrating renewable energy to efficiently produce protein. With the right policies and innovations, circular bioeconomy practices could enhance the sustainability of livestock and contribute to global food and environmental security.

## CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Rezki Amalyadi: Writing – original draft, Conceptualization. Lusia Komala Widiastuti: Conceptualization, Supervision, Methodology, Data curation.


## ACKNOWLEDGMENT

The authors would like to thank all co-authors for their valuable contributions and collaboration that made the publication of this article possible.


## ETHICS APPROVAL

No ethical approval was needed for this study.


## FUNDING

None declared.


## CONFLICT OF INTEREST

The authors state no conflict of interest.

## DATA AVAILABILITY STATEMENT

No new data were generated or analyzed in this study. All data supporting the findings of this review were obtained from previously published articles and publicly accessible databases cited within the manuscript. Additional bibliographic information or extraction tables used for analysis are available from the corresponding author upon reasonable request.

## REFERENCES


Aiassa, E., Higgins, J. P. T., Frampton, G. K., Greiner, M., Afonso, A., Amzal, B., Deeks, J., Dorne, J.-L., Glanville, J., & Lövei, G. L. (2015). Applicability and feasibility of systematic review for performing evidence-based risk assessment in food and feed safety. *Critical Reviews in Food Science and Nutrition*, *55*(7), 1026–1034.

Allaart, M. T., Diender, M., Sousa, D. Z., & Kleerebezem, R. (2023). Overflow metabolism at the thermodynamic limit of life: How carboxydotrophic acetogens mitigate carbon monoxide toxicity. *Microbial Biotechnology*, *16*(4), 697–705.

Altin, N., & Akay, R. G. (2024). Components used in microbial fuel cells for renewable energy generation: a review of their historical and ecological development. *Journal of Electrochemical Energy Conversion and Storage*, *21*(2), 20801.

Aydin, G., & Karakurt, I. (2024). Methane emission from coalbed. In *Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion* (pp. 3–30). Elsevier.

Bae, J., Jin, S., Kang, S., Cho, B.-K., & Oh, M.-K. (2022). Recent progress in the engineering of C1-utilizing microbes. *Current Opinion in Biotechnology*, *78*, 102836.

Bardhan, P., Gupta, K., & Mandal, M. (2019). Microbes as bio-resource for sustainable production of biofuels and other bioenergy products. In *New and future developments in microbial biotechnology and bioengineering* (pp. 205–222). Elsevier.

Baumschabl, M., Ata, Ö., & Mattanovich, D. (2024). Single carbon metabolism–A new paradigm for microbial bioprocesses? *Synthetic and Systems Biotechnology*, *9*(2), 322–329.

Bhat, E. H., Henard, J. M., Lee, S. A., McHalffey, D., Ravulapati, M. S., Rogers, E. V, Yu, L., Skiles, D., & Henard, C. A. (2024). Construction of a broad-host-range Anderson promoter series and particulate methane monooxygenase promoter variants expand the methanotroph genetic toolbox. *Synthetic and Systems Biotechnology*, *9*(2), 250–258.

Bouxin, A. (2023). Management of safety in the feed chain. In *Food Safety Management* (pp. 19–35). Elsevier.

Bratosin, B. C., Darjan, S., & Vodnar, D. C. (2021). Single cell protein: A potential substitute in human and animal nutrition. *Sustainability*, *13*(16), 9284.

Chen, J., Daniell, J., Griffin, D., Li, X., & Henson, M. A. (2018). Experimental testing of a spatiotemporal metabolic model for carbon monoxide fermentation with Clostridium autoethanogenum. *Biochemical Engineering Journal*, *129*, 64–73.

Davin, M. E., Thompson, R. A., Giannone, R. J., Mendelson, L. W., Carper, D. L., Martin, M. Z., Martin, M. E., Engle, N. L., Tschaplinski, T. J., & Brown, S. D. (2024). Clostridium autoethanogenum alters cofactor synthesis, redox metabolism, and lysine-acetylation in response to elevated H2: CO feedstock ratios for enhancing carbon capture efficiency. *Biotechnology for Biofuels and Bioproducts*, *17*(1), 119.

De Jonge, J., Frewer, L., Van Trijp, H., Jan Renes, R., De Wit, W., & Timmers, J. (2004). Monitoring consumer confidence in food safety: an exploratory study. *British Food Journal*, *106*(10–11), 837–849.

Domenech, T., & Bahn-Walkowiak, B. (2019). Transition towards a resource efficient circular economy in Europe: policy lessons from the EU and the member states. *Ecological Economics*, *155*, 7–19.

El-Nemr, A. (2011). *Environmental pollution and its relation to climate change*.

Engel, D., Hoffmann, M., Kosfeld, U., & Mann, M. (2025). Online monitoring of methane transfer rates unveils nitrogen fixation dynamics in Methylococcus capsulatus. *Biotechnology and Bioengineering*, *122*(1), 110–122.

Fasihi, M., Jouzi, F., Tervasmäki, P., Vainikka, P., & Breyer, C. (2025). Global potential of sustainable single-cell protein based on variable renewable electricity. *Nature Communications*, *16*(1), 1496.

Federici, F., Orsi, E., & Nikel, P. I. (2023). From rags to riches: exploiting the calvin-benson-bassham cycle for biomanufacturing. *ChemCatChem*, *15*(23), e202300746.

Fu, J., Zhou, Q., Zou, R., & Zhang, D. (2021). Mitigation & Adaptation—China's Evolving Policy Framework. In *Climate Mitigation and Adaptation in China: Policy, Technology and Market* (pp. 3–33). Springer.

Gao, Z., Guo, S., Chen, Y., Chen, H., Fu, R., Song, Q., Li, S., Lou, W., Fan, D., & Li, Y. (2024). A novel nutritional induction strategy flexibly switching the biosynthesis of food-like products from methane by a methanotrophic bacterium. *Green Chemistry*, *26*(12), 7048–7058.

Garg, S., Wu, H., Clomburg, J. M., & Bennett, G. N. (2018). Bioconversion of methane to C-4 carboxylic acids using carbon flux through acetyl-CoA in engineered Methylomicrobium buryatense 5GB1C. *Metabolic Engineering*, *48*, 175–183.

Garrett, R. D., Ryschawy, J., Bell, L. W., Cortner, O., Ferreira, J., Garik, A. V. N., Gil, J. D. B., Klerkx, L., Moraine, M., & Peterson, C. A. (2020). Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecology and Society*, *25*(1), 24.

Gilman, A., Laurens, L. M., Puri, A. W., Chu, F., Pienkos, P. T., & Lidstrom, M. E. (2015). Bioreactor performance parameters for an industrially-promising methanotroph

Methylomicrobium buryatense 5GB1. *Microbial Cell Factories*, *14*(1), 182.

Gordon, A., DeVlieger, D., Vasan, A., & Bedard, B. (2020). Technical considerations for the implementation of food safety and quality systems in developing countries. In *Food safety and quality systems in developing countries* (pp. 1–40). Elsevier.

Gorris, L. G. M., & Yoe, C. (2014). *Risk analysis: risk assessment: principles, methods, and applications*.

Guillier, L., Duret, S., Hoang, H.-M., Flick, D., Nguyen-Thé, C., & Laguerre, O. (2016). Linking food waste prevention, energy consumption and microbial food safety: the next challenge of food policy? *Current Opinion in Food Science*, *12*, 30–35.

Gunes, B. (2021). A critical review on biofilm-based reactor systems for enhanced syngas fermentation processes. *Renewable and Sustainable Energy Reviews*, *143*, 110950.

Henard, C. A., Wu, C., Xiong, W., Henard, J. M., Davidheiser-Kroll, B., Orata, F. D., & Guarnieri, M. T. (2021). Ribulose-1, 5-bisphosphate carboxylase/oxygenase (RubisCO) is essential for growth of the methanotroph Methylococcus capsulatus strain Bath. *Applied and Environmental Microbiology*, *87*(18), e00881-21.

Hoejskov, P. S. (2017). History of Asian Food Policy. In *International Food Law and Policy* (pp. 1263–1294). Springer.

Holm, L., & Halkier, B. (2009). EU food safety policy: localising contested governance. *European Societies*, *11*(4), 473–493.

Hundscheid, L., Voigt, C., Bergthaler, D., Plank, C., Wurzinger, M., & Melcher, A. H. (2024). Policy mix for the sustainable protein transition in Austria-Addressing repercussions of regime shifts as a prerequisite for acceleration. *Environmental Innovation and Societal Transitions*, *51*, 100819.

Jain, S., Heffernan, J., Joshi, J., Watts, T., Marcellin, E., & Greening, C. (2023). Microbial conversion of waste gases into single-cell protein. *Microbiology Australia*, *44*(1), 27–30.

Jiang, Y., Yang, X., Zeng, D., Su, Y., & Zhang, Y. (2022). Microbial conversion of syngas to single cell protein: The role of carbon monoxide. *Chemical Engineering Journal*, *450*, 138041.

Jones, J. A., & Wang, X. (2018). Use of bacterial co-cultures for the efficient production of chemicals. *Current Opinion in Biotechnology*, *53*, 33–38.

Kannadhasan, S., & Nagarajan, R. (2023). Green house gases: Challenges, effect, and climate change. In *Biomass and Bioenergy Solutions for Climate Change Mitigation and Sustainability* (pp. 65–74). IGI Global Scientific Publishing.

Kannan, R., & James, D. A. (2009). Effects of climate change on global biodiversity: a review of key literature. *Tropical Ecology*, *50*(1), 31.

Khan, M. K. I., Asif, M., Razzaq, Z. U., Nazir, A., & Maan, A. A. (2022). Sustainable food industrial waste management through single cell protein production and characterization of protein enriched bread. *Food Bioscience*, *46*, 101406.

Kocasoy, G., & Yalin, H. (2004). Determination of carboxyhemoglobin levels and health effects on officers working at the Istanbul Bosphorus Bridge. *Journal of Environmental Science and Health, Part A*, *39*(4), 1129–1139.

Konar, A., & Datta, S. (2022). Strain improvement of microbes. In *Industrial Microbiology and Biotechnology* (pp. 169–193). Springer.

Koukoumaki, D. I., Tsouko, E., Papanikolaou, S., Ioannou, Z., Diamantopoulou, P., & Sarris, D. (2024). Recent advances in the production of single cell protein from renewable resources and applications. *Carbon Resources Conversion*, *7*(2), 100195.

Lee, S. A., Henard, J. M., Alba, R. A. C., Benedict, C. A., Mayes, T. A., & Henard, C. A. (2024). Overexpression of native carbonic anhydrases increases carbon conversion efficiency in the methanotrophic biocatalyst Methylococcus capsulatus Bath. *Msphere*, *9*(9), e00496-24.

Lin, L., Huang, H., Zhang, X., Dong, L., & Chen, Y. (2022). Hydrogen-oxidizing bacteria and their applications in resource recovery and pollutant removal. *Science of The Total Environment*, *835*, 155559.

Mabee, W. E. (2022). Conceptualizing the circular bioeconomy. In *Circular Economy and Sustainability* (pp. 53–69). Elsevier.

Majstorović, A., Babić, V., & Todić, M. (2020). Carbon monoxide in the process of uncontrolled combustion-occurrence, hazards and first aid. *Journal of Physics: Conference Series*, *1426*(1), 12008.

Makkar, H. P. S. (2016). Smart livestock feeding strategies for harvesting triple gain–the desired outcomes in planet, people and profit dimensions: a developing country perspective. *Animal Production Science*, *56*(3), 519–534.

Mamphogoro, T. P., Mpanza, T. D. E., & Mani, S. (2024). Animal feed production and its contribution to sustainability of livestock systems: African perspective. *The Marginal Soils of Africa: Rethinking Uses, Management and Reclamation*, 37–54.

Mandato, D., Colarusso, G., Pellicanò, R., Baldi, L., Guarino, A., & Sarnelli, P. (2018). Official Controls According to Integrated Regional Plan in Campania Region 2011/2014. *Italian Journal of Food Safety*, *6*(4), 5708.

Marku, D., Minga, A., & Sosoli, I. (2024). Circular Economy Perspective and Implications for Livestock Farming in Albania. *The Open Agriculture Journal*, *18*(1).

Martinez, M. G. (2010). Enhancing consumer confidence in food supply chains. In *Delivering performance in food supply chains* (pp. 285–302). Elsevier.

Matassa, S., Papirio, S., Esposito, G., & Pirozzi, F. (2023). Protein from microscopic sources—a realistic scalable solution? In *Future Proteins* (pp. 195–220). Elsevier.

Millstone, E. (2012). Food safety: the ethical dimensions. In *Food ethics* (pp. 84–100). Routledge.

Mohajan, H. (2011). *Dangerous effects of methane gas in atmosphere*.

Molden, L., & Khanal, P. (2025). Establishing a circular economy-based livestock sector using alternative feeding resources requires a broader collaboration between local and global partners. In *Research Handbook of Innovation in the Circular Bioeconomy* (pp. 181–198). Edward Elgar Publishing.

Molden, L., Modic, D., Rasmussen, E., Jakobsen, S., & Vanhaverbeke, W. (2025). Introduction: harnessing innovation for advancing a circular bioeconomy. In *Research Handbook of Innovation in the*

*Circular Bioeconomy* (pp. 2–14). Edward Elgar Publishing.

Nath, S., Henard, J. M., & Henard, C. A. (2022). Optimized tools and methods for methanotroph genome editing. In *Engineering Natural Product Biosynthesis: Methods and Protocols* (pp. 421–434). Springer.

Neto, A. S., Wainaina, S., Chandolias, K., Piatek, P., & Taherzadeh, M. J. (2024). Exploring the potential of syngas fermentation for recovery of high-value resources: a comprehensive review. *Current Pollution Reports*, *11*(1), 7.

Pang, Q., Han, H., Qi, Q., & Wang, Q. (2022). Application and population control strategy of microbial modular co-culture engineering. *Sheng Wu Gong Cheng Xue Bao= Chinese Journal of Biotechnology*, *38*(4), 1421–1431.

Parodi, A., Valencia-Salazar, S., Loboguerrero, A. M., Martínez-Barón, D., Murgueitio, E., & Vázquez-Rowe, I. (2022). The sustainable transformation of the Colombian cattle sector: Assessing its circularity. *Plos Climate*, *1*(10), e0000074.

Pink, M., Kiełbasa, B., Niewiadomski, M., & Piecuch, K. (2025). Barriers and Challenges Faced in the Deployment of Principles of the Circular Bioeconomy: Awareness, Knowledge and Practices Based on the Example of Polish Agriculture. *Sustainability*, *17*(10), 4729.

Place, S. E. (2024). Environmental Sustainability of Livestock Systems. *Meat and Muscle Biology*, *8*(1).

Puente-Rodríguez, D., van Laar, H., & Veraart, M. (2022). A circularity evaluation of new feed categories in the Netherlands—squaring the circle: a review. *Sustainability*, *14*(4), 2352.

Raad, M., & Bou-Mitri, C. (2024). Food Safety and Risk Perception of Consumers in the Middle East and North African Region. In *Consumer Perceptions and Food* (pp. 457–472). Springer.

Rabaey, K., Johnstone, A., Wise, A., Read, S., & Rozendal, R. (2010). Microbial electrosynthesis: from electricity to biofuels and biochemicals. *BIOTECH INTERNATIONAL*, *22*(June).

Raita, S., Kusnere, Z., Spalvins, K., & Blumberga, D. (2022). Optimization of yeast cultivation factors for improved SCP production. *Rigas Tehniskas Universitates Zinatniskie Raksti*, *26*(1), 848–861.

Rollin, B. E. (2006). Food Safety—Who Is Responsible? *Foodbourne Pathogens & Disease*, *3*(2), 157–162.

Rosero-Chasoy, G., Rodríguez-Jasso, R. M., Aguilar, C. N., Buitrón, G., Chairez, I., & Ruiz, H. A. (2021). Microbial co-culturing strategies for the production high value compounds, a reliable framework towards sustainable biorefinery implementation–an overview. *Bioresource Technology*, *321*, 124458.

Salazar-López, N. J., Barco-Mendoza, G. A., Zuñiga-Martínez, B. S., Domínguez-Avila, J. A., Robles-Sánchez, R. M., Ochoa, M. A. V., & González-Aguilar, G. A. (2022). Single-cell protein production as a strategy to reincorporate food waste and agro by-products back into the processing chain. *Bioengineering*, *9*(11), 623.

Sanghavi, G., Gupta, P., Rajput, M., Oza, T., Trivedi, U., & Singh, N. K. (2020). Microbial strain engineering. In *Engineering of microbial biosynthetic pathways* (pp. 11–32). Springer.

Schmitz, L. M., Kreitli, N., Obermaier, L., Weber, N., Rychlik, M., & Angenent, L. T. (2024). Power-to-vitamins: producing folate (vitamin B9) from renewable electric power and CO2 with a microbial protein system. *Trends in Biotechnology*, *42*(12), 1691–1714.

Sharif, M., Zafar, M. H., Aqib, A. I., Saeed, M., Farag, M. R., & Alagawany, M. (2021). Single cell protein: Sources, mechanism of production, nutritional value and its uses in aquaculture nutrition. *Aquaculture*, *531*, 735885.

Sharma, A., Sneed, J., & Beattie, S. (2012). Willingness to pay for safer foods in foodservice establishments. *Journal of Foodservice Business Research*, *15*(1), 101–116.

Silano, V. (2005). Scientific activities and perspectives of the European Food Safety Authority (EFSA). *AGRO FOOD INDUSTRY HI-TECH*, *16*(1), 4–5.

Sillman, J., Nygren, L., Kahiluoto, H., Ruuskanen, V., Tamminen, A., Bajamundi, C., Nappa, M., Wuokko, M., Lindh, T., & Vainikka, P. (2019). Bacterial protein for food and feed generated via renewable energy and direct air capture of CO2: Can it reduce land and water use? *Global Food Security*, *22*, 25–32.

Smith, A. I. M. (2024). *European Food Safety Authority—Providing scientific advice for EU food safety since 2002*.

Søndergaard, N., Fernandes, J. F. A., Potent, J., Karl, K., Furtado, M., & Baethgen, W. (2023). A governance framework to manage the food-environment-livelihood trilemma of alternative proteins. *One Earth*, *6*(7), 843–853.

Talaei, A., Gemechu, E., & Kumar, A. (2020). Key factors affecting greenhouse gas emissions in the Canadian industrial sector: A decomposition analysis. *Journal of Cleaner Production*, *246*, 119026.

Tonsor, G. T., Schroeder, T. C., & Pennings, J. M. E. (2009). Factors impacting food safety risk perceptions. *Journal of Agricultural Economics*, *60*(3), 625–644.

Ueda, Y., Yamamoto, M., Urasaki, T., Arai, H., Ishii, M., & Igarashi, Y. (2007). Sequencing and reverse transcription-polymerase chain reaction (RT-PCR) analysis of four hydrogenase gene clusters from an obligately autotrophic hydrogen-oxidizing bacterium, Hydrogenobacter thermophilus TK-6. *Journal of Bioscience and Bioengineering*, *104*(6), 470–475.

Veflen Olsen, N., & Motarjemi, Y. (2014). Food safety assurance systems: food safety and ethics. *Encycl Food Saf*, *4*, 340–344.

Verbeeck, K., De Vrieze, J., Pikaar, I., Verstraete, W., & Rabaey, K. (2021). Assessing the potential for up-cycling recovered resources from anaerobic digestion through microbial protein production. *Microbial Biotechnology*, *14*(3), 897–910.

Vinnari, M., Vinnari, E., & Kupsala, S. (2017). Sustainability matrix: Interest groups and ethical theories as the basis of decision-making. *Journal of Agricultural and Environmental Ethics*, *30*(3), 349–366.

Wise, L., Marecos, S., Randolph, K., Hassan, M., Nshimyumukiza, E., Strouse, J., Salimijazi, F., & Barstow, B. (2022). Thermodynamic constraints on electromicrobial protein production. *Frontiers in Bioengineering and Biotechnology*, *10*, 820384.

Wyngaarden, S. L., Lightburn, K. K., & Martin, R. C. (2020). Optimizing livestock feed provision to improve the efficiency of the agri-food system. *Agroecology and Sustainable Food Systems*, *44*(2), 188–214.

Yang, J., Kim, B., Kim, G. Y., Jung, G. Y., & Seo, S. W. (2019). Synthetic biology for evolutionary engineering: from perturbation of genotype to acquisition of desired phenotype. *Biotechnology for Biofuels*, *12*(1), 113.

Yao, L., & Zhou, Y. (2023). Progress in microbial utilization of one-carbon feedstocks for biomanufacturing. *Chemical Industry and Engineering Progress*, *42*(1), 16.

Yaverino-Gutiérrez, M. A., Wong, A. Y. C.-H., Ibarra-Muñoz, L. A., Chávez, A. C. F., Sosa-Martínez, J. D., Tagle-Pedroza, A. S., Hernández-Beltran, J. U., Sánchez-Muñoz, S., Santos, J. C. dos, & da Silva, S. S. (2024). Perspectives and progress in bioethanol processing and social economic impacts. *Sustainability*, *16*(2), 608.

Yu, H., Gibson, K. E., Wright, K. G., Neal, J. A., & Sirsat, S. A. (2017). Food safety and food quality perceptions of farmers' market consumers in the United States. *Food Control*, *79*, 266–271.

Yu, J. (2018). Fixation of carbon dioxide by a hydrogen-oxidizing bacterium for value-added products. *World Journal of Microbiology and Biotechnology*, *34*(7), 89.

Zhang, H., & Wang, X. (2016). Modular co-culture engineering, a new approach for metabolic engineering. *Metabolic Engineering*, *37*, 114–121.

Zhang, L., Song, X., Chen, L., & Zhang, W. (2020). Recent progress in photosynthetic microbial co-culture systems. *Sheng Wu Gong Cheng Xue Bao= Chinese Journal of Biotechnology*, *36*(4), 652–665.

Zhang, L., Zhao, R., Jia, D., Jiang, W., & Gu, Y. (2020). Engineering Clostridium ljungdahlii as the gas-fermenting cell factory for the production of biofuels and biochemicals. *Current Opinion in Chemical Biology*, *59*, 54–61.

Zhao, S., Li, F., Yang, F., Ma, Q., Liu, L., Huang, Z., Fan, X., Li, Q., Liu, X., & Gu, P. (2023). Microbial production of valuable chemicals by modular co-culture strategy. *World Journal of Microbiology and Biotechnology*, *39*(1), 6.

Zhu, Z., Wu, Y., Hu, W., Zheng, X., & Chen, Y. (2022). Valorization of food waste fermentation liquid into single cell protein by photosynthetic bacteria via stimulating carbon metabolic pathway and environmental behaviour. *Bioresource Technology*, *361*, 127704.