Global Assessment of Waste Nitrogen Recycling for Microbial Protein Production: A Prospective LCA and Integrated Assessment Model Approach

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Introduction

The rapidly increasing generation of organic residuals due to population growth poses significant environmental and climate-related challenges (Gómez-Sanabria et al., 2022; Javourez et al., 2023). The lack of adequate treatment facilities to manage the large quantities of these feedstocks leads to various environmental and health issues across different countries. High-income countries can implement policies and instruments to handle the rising waste flows, resulting in cleaner and more organized waste management systems. In contrast, low-income countries often face challenges due to insufficient funds, poor planning, inadequate law enforcement, and lack of technology and expertise. As a result, open burning, and poorly managed landfills are common waste disposal methods in these regions, causing adverse effects on the environment, climate, and human health (Hoy et al., 2023).

Furthermore, the global demand for protein feed has steadily increased over the last decade. To achieve the Paris Agreement's targets and reduce fossil carbon dependence, enhancing the utilization of residual streams for edible ingredients is being increasingly promoted to mitigate environmental impacts. However, it remains uncertain whether advanced reuse of residual biomass truly provides net environmental benefits compared to current management practices (Javourez et al., 2022).

This study moves beyond traditional static life cycle assessments (LCAs) by using Prospective Life Cycle Assessment (pLCA) and Integrated Assessment Models (IAMs). Unlike previous studies that rely on static LCAs, which fail to capture the dynamic nature of industrial processes and energy systems (Marami et al., 2022; Zheng et al., 2024), this research leverages the predictive capabilities of pLCA and the comprehensive future scenarios provided by IAMs. By integrating Shared Socioeconomic Pathways (SSPs) and implementing the "premise" tool to align life cycle inventories with IAM outputs, this methodology allows LCA practitioners to generate and conduct pLCI (Sacchi et al., 2022; Šimaitis et al., 2025).

The study aims to quantify the environmental benefits and impacts of microbial protein production from various feedstocks (i.e., food waste, crop residue, livestock manure, wastewater) compared to traditional disposal methods and soybean production as feed on a global scale. It also evaluates the potential and impact of emerging technologies such as nitrogen recovery systems and biogas upgrading. Additionally, future energy scenarios, including changes in energy sources, efficiency, and availability, are considered.

Material and methods

This analysis conducts a global assessment of waste nitrogen for microbial protein production using a future perspective and an IAM approach. The feedstocks considered as nitrogen and carbon sources in this study include food waste, livestock manure, crop residues, and wastewater.

The anaerobic digestion (AD) pathway, which provides carbon and energy for microbial fermentation, is considered and modeled. Additionally, nitrogen, which is a major component of the digestate and is essential for protein production, is extracted using recovery technologies from the liquid fraction of the digestate.

To project the future potential for microbial protein production, the resource availability of selected biowaste in each country for the years 2030, 2040, and 2050 is estimated using IAMs. Greenhouse gas (GHG) savings in this context refer to the emissions avoided by using biowaste in microbial production facilities rather than sending it to conventional waste management systems. The environmental emissions related to different waste management methods, such as landfill disposal, agricultural waste burning, and wastewater treatment, are predicted using IAMs.

Additionally, to estimate GHG emissions from soy production, we project the demand for soy feed and associated emissions for the years 2030, 2040, and 2050 under SSP scenarios and IAMs. These projections offer a comprehensive perspective on the potential environmental benefits of microbial protein production on a global scale.

Results and discussion

Based on the results, the potential amount of microbial protein production that could offset soy protein as animal feed varies across regions. In regions with larger populations and higher Gross Domestic Product (GDP), more waste is generated as a nitrogen source, leading to greater microbial protein production capacities. In some regions, the higher amount of microbial protein production not only substitutes the need for soy protein but also provides surplus microbial protein for the market.

Additionally, in the global application of converting different types of waste to microbial protein, the hierarchy of waste management approaches in different countries is notable. In low-income countries, where open dumping or uncontrolled landfilling is common, converting waste to microbial protein offers greater benefits compared to high-income countries, where anaerobic digestion technologies for converting waste to energy are more prevalent.

Since this study aims to provide a global assessment, it evaluates the global impact of microbial protein production by considering energy inputs in different sectors based on the type of energy supply in each region. By using IAMs for the energy consumption sector, which is the most significant factor in future environmental impacts, we accurately represent the carbon intensity of power systems in different regions. This approach aligns with regional variations and future energy supply scenarios, similar to those presented in the IPCC's models for 2030, 2040, and 2050 ((IPCC), 2021).

Conclusions

This study emphasizes the potential of microbial protein production from different organic wastes as a sustainable solution for waste management and protein supply, offering various environmental benefits across different regions. The use of Prospective Life Cycle Assessment (pLCA) and Integrated Assessment Models (IAMs) provides an accurate representation of future scenarios regarding global carbon intensity, making them suitable for addressing global environmental and climate challenges.

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