Quantitative assessment of bioeconomy systems' sustainability: strengths, limits and research agenda

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Abstract

Introduction

The bioeconomy aims to replace fossil-based products with bio-based alternatives to ensure the continued provision of food and non-food goods to society, while preserving natural resources and drastically reducing GHG emissions. However, the development of the bioeconomy may lead to significant negative impacts due to increased biomass withdrawals and the expansion of processing and transport activities. Therefore, quantitatively assessing the performance of bioeconomy systems is crucial to ensure that the bioeconomy fulfills its promises of sustainability. Sustainability assessments of bioeconomy systems must consider key processes and dimensions (Wohlfahrt et al., 2019):

(i) the entire bio-based value chain, including biomass production, transport, processing, distribution, consumption, and recycling;

(ii) the bioeconomy as a socio-ecological system shaped by natural and socio-industrial processes that are spatially and temporally structured;

(iii) a multi-criteria perspective, as the bioeconomy must address multiple challenges such as food and non-food provision, GHG mitigation, natural resource and biodiversity preservation, and economic development.

To our knowledge, no comprehensive review has yet provided a detailed analysis of studies dealing with the sustainability of bioeconomy systems. This study aims to fill this gap by reviewing the existing literature on sustainability assessment approaches applied to bioeconomy systems. Specifically, we aimed to describe: (i) the types of value chains studied; (ii) the models and methods used; and (iii) the performance criteria employed.

Materials and Methods

To identify relevant articles, we developed a search query and ran it on the Web of Science Core Collection (WoS CC). The query was built around four dimensions of the bioeconomy and associated keywords:

- "Biomass", to target articles addressing biomass-related activities. We chose this term over "bioeconomy" to focus on bioeconomic activities that inherently involve biomass use.

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- "System", to select articles considering bioeconomy systems rather than isolated activities.
- "Circular," "environment," "sustainability," "GHG," "carbon," and "greenhouse gases", based on the assumption that bioeconomy studies frequently address climate-related issues.
- "Evaluation," "assessment," "model," "indicator," and "LCA", to identify studies applying assessment methodologies.

The query initially returned 5204 articles. After screening for relevance and accessibility, we narrowed the selection to 93 articles.

Results and Discussion

Our findings show that most studies focus on agricultural feedstocks and bioenergy production. No study addressed all stages of bio-based value chains. Most research targets the upstream segment of the value chain-namely biomass production, transport, and transformation-with transformation being the most frequently studied activity (89% of articles). This highlights a prevailing biotechnological vision in bioeconomy research, centered on biomass conversion processes.

The concept of biomass cascading-central to the circular bioeconomy and involving the sequential use of biomass for maximum value-is addressed in only 5 studies. The predominance of bioenergy-focused studies likely contributes to this neglect. Additionally, the limited analysis of multi-product/multi-process value chains may reflect the complexity involved in studying, modeling, and assessing such systems. The vast diversity of potential biomass uses and the proliferation of emerging bio-based products complicate the selection and assessment of cascading pathways. In line with Wohlfahrt et al. (2019), we call on the bioeconomy research community to document existing complex chains and develop frameworks capable of capturing their structure and sustainability implications.

Regarding assessment methods, Life Cycle Assessment (LCA) dominates, used in 83% of studies. Fewer than 10% apply simulation models to represent dynamic biophysical or logistical processes, despite these models being well-suited for simulating and assessing bioeconomy systems. Likewise, few studies are spatially and/or temporally explicit. Only 22 studies (less than one-quarter) account for interactions between soil-climate conditions and land use practices. Although simulation models can effectively capture dynamics, they typically address only one activity-e.g., crop models for biomass production-and do not encompass the full biomass-to-bioproduct cycle. Conversely, LCA addresses entire value chains but lacks the capacity to account for biophysical and sociotechnical specificities and dynamic changes. To overcome the limitations of each of these two assessment approaches, some innovative studies have combined them. For instance, Cirone et al. (2025) coupled the MAELIA platform (Misslin et al., 2019), which simulates agricultural system dynamics at the landscape scale, with LCA to perform a Territorial LCA of local food systems that reflects biophysical and agricultural specificities.

We identified 92 different indicators used to assess bioeconomy system sustainability. The most frequently used were GHG emissions and energy efficiency. Overall, sustainability assessments remain heavily focused on environmental indicators. This reflects the dominant perception of the bioeconomy as a climate change mitigation strategy, primarily through the substitution of fossil resources. However, this focus results in a partial sustainability assessment, overlooking social and economic dimensions. A more balanced, multi-criteria approach is needed to fully assess bioeconomy sustainability.

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