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Challenges and opportunities to a sustainable bioenergy utilization in climate mitigation: a global perspective

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Bioenergy is perceived to play a vital role in climate mitigation, transition to renewable energy consumption, energy security, and local and rural socio-economic development. However, exploiting renewable bioenergy resources may need to be more sustainable in the current predominant paradigm. In this study, we raise two broad research questions: (1) what are the significant challenges to the current global bioenergy production and consumption system, and (2) what are the opportunities for a sustainable and circular bioenergy system? We qualitatively analyzed how the current bioenergy production and consumption system results in unintended negative consequences. Taking the example of biofuels, this research exemplifies some critical systemic flaws in how bioenergy is currently utilized in the transportation sector. We do this by broadening the system boundaries to identify the social, economic, and environmental consequences often distant in time and space. We conducted semi-structured interviews, workshops, and literature studies to gather data on the significant bioenergy production and consumption drivers, socio-economic factors, and ecological impacts. The causal loop diagram technique illustrates this broader system's systemic cause-effect and feedback relationships. In the current system of bioenergy production and consumption, negative socio-economic and ecological consequences limit the potential of exploiting bioenergy for climate mitigation. Firstly, bioenergy is neither carbon neutral nor renewable from a broader systems perspective, given that biomass cultivation, feedstock refining, and processing are closely coupled with natural resource use (e.g., water, energy, chemicals, and fertilizers) and other nutrient cycles (e.g., nitrogen, and phosphorus). Secondly, large-scale bioenergy developments negatively impact food security, land use change, ecosystem services, and biodiversity in certain regions. Thirdly, the current globalized bioenergy economy is fundamentally unsustainable due to the displacement of bioenergy production's negative social and ecological impacts from consumer to producer regions. We identify and discuss the critical system interventions to be placed throughout the system as significant leverages for managing the unintended negative consequences of the present dominant bioenergy production and consumption regimes.

KEYWORDS

bioenergy, climate mitigation, challenges, energy policy, impacts, just transitions

1 Introduction

1.1 Sustainability implications of bioenergy

Increasing energy consumption globally drives carbon emissions and contributes to climate change (Tilman et al., 2009; Péreau et al., 2012; Hammond and Li, 2016; Wang et al., 2017). To address this sustainability challenge, bioenergy is recognized as an essential short- to medium-term solution for addressing climate mitigation by replacing fossil energy and contributing to sustainable development (Blair et al., 2021). The International Energy Agency (2023a) forecasts an expansion of biofuel demand from 22% over 2022–2027 to 35,000 million liters per year, saving significant annual carbon dioxide emissions compared to the continuous utilization of petroleum-based fossil fuels. Further, bioenergy provides added benefits, such as pollution reduction (Wang et al., 2017), energy security, diversification of the energy supply mix, and local economic development through employment and infrastructure development in selected sectors (Humpenöder et al., 2018; Qaim et al., 2020; Sibhatu, 2023).

However, bioenergy production and consumption are only partially carbon-neutral and sustainable from a broader systems perspective, as the production (and consumption) processes of bioenergy require significant resource inputs. For instance, land-based bioenergy cultivation is closely linked to local, regional, and global nutrient cycles, the use of non-renewable fossil resources (e.g., phosphorus), and agricultural inputs impacting ecosystem services and biodiversity (Wang et al., 2017). Indeed, resource inputs and life cycle emissions needed to cultivate biomass, process feedstocks, and transport bioenergy offset (partial or complete) the positive benefits of bioenergy (Staples et al., 2017; Humpenöder et al., 2018). Further, rapid economic growth and urbanization have intensified demand for land, land-use competition, and negative impacts on food security, ecosystem services, and biodiversity (Tilman et al., 2009; Witcover et al., 2013; Essl et al., 2018; Humpenöder et al., 2018). Furthermore, the globalized bioenergy value chains have displaced the bioenergy production's negative socioeconomic and ecological impacts on other regions (Brose et al., 2010; Brinkman et al., 2019). Indeed, the bioenergy policymaking regimes have shaped the global energy sectors and geopolitical landscapes. With the current global socio-economic trends, global energy consumption is expected to increase nearly 50% compared with 2020 levels by 2050 (The U.S. Energy Information Administration, 2023). Without impeding on competing land uses, the relative contribution of utilizing land (agriculture or forest) resources for bioenergy purposes will likely be very limited (Wang et al., 2017). Therefore, the broad sustainability challenges linked to bioenergy production and consumption need to be scrutinized to avoid any unintended negative social, economic, and ecological consequences.

1.2 Systems thinking and policymaking

In today's globalized world, sustainability problems facing policymakers are interconnected, ill-defined, and complex. These problems are acknowledged in policymaking as uncertain, unpredictable, ill-structured, or wicked (Bali, 2021). Despite this, the current global policymaking regimes are dominated by reductionist thinking, a linear thinking approach [also called "open loop thinking" (Sterman, 2000)] that addresses these problems in silos (Head, 2019; Hynes et al., 2020; Mueller, 2020; Bali, 2021; Nel and Taeihagh, 2024). Such an approach to policymaking focuses on immediate cause-and-effect, quick-fix decision-making, and short-term outcomes (Sterman, 2000; Ollhoff and Walcheski, 2002). It is prone to failure because it fails to understand the interconnected, multidimensional, and complex nature of these problems (Hynes et al., 2020). This often results in unintended negative social, economic, and environmental consequences of the intended interventions in the system (Sterman, 2000; Head, 2019; Mueller, 2020; Bali, 2021). On the other hand, systems thinking focuses on a holistic understanding of the problem to develop strategic and longer-lasting solutions.

Systems thinking could assist policymaking by offering tools to disaggregate, understand, and act on connected systemic issues while accounting for their critical linkages (Sterman, 2000, 2012; Meadows, 2008; Hynes et al., 2020). It is part of the complexity science-informed approaches such as systems theory, cybernetics, and complexity theory (Sterman, 2000; Nel and Taeihagh, 2024). It focuses on the system rather than its parts to approach complex problems (Sweeney and Meadows, 2010) to understand their interrelationships and underlying dynamics. Thus, it is concerned with understanding the system's behavior, dynamics, and critical patterns to minimize or eliminate the unintended negative consequences of intended interventions (Sterman, 2000; Sweeney and Meadows, 2010).

Major global economies have introduced several measures to enhance the production, trade, and consumption of bioenergy. For example, the United States (Jeffers et al., 2013; Dumortier et al., 2021; Lark et al., 2022; Newes et al., 2022), the European Union member states (Timilsina, 2014; Debnath and Whistance, 2023), India (Sinha et al., 2019) and China (Zhang and Feng, 2021). Nonetheless, these regimes have an isolated focus on problems related to energy security, climate change, socioeconomic development, and geopolitics rather than a holistic approach to achieving sustainability. This is why, apart from the anticipated positive benefits of bioenergy production and consumption to society, it has also caused unintended negative socioeconomic (Vandergeten et al., 2016) and ecological consequences for certain global regions and communities (Butchart et al., 2010; Tudge et al., 2021; Merfort et al., 2023). This study adopts a systems thinking approach to conceptualize the sustainability challenges to the current bioenergy production and consumption and propose places for policy intervention to address these challenges.

1.3 Transition toward a sustainable and just bioeconomy

The concept of "bioeconomy" has no common definition despite its global adoption in policy strategies (IACGB - International Advisory Council on Global Bioeconomy, 2020). The term "bioeconomy" or "bioeconomics" was first coined by Nicholas Georgescu-Roegen to describe a new economy with a purpose (Georgescu-Roegen, 1971). It was "*to conserve resources and to obtain a rational control over the development and use of technologies in order for it to serve the true human wants—and not rising profits, warfare, or national prestige. . . . a worldwide economy that is predicated on justice and that allows for the wealth of the earth to be shared equally among its inhabitants now and in the future* (translation by Vogelpohl and Töller, 2021, p. 143). This description of bioeconomy points to the normative principles of resource conservation, sustainable (de)growth, and inter- and intra-generational justice.

In the past 115 years, the global societal metabolism of materials, energy, and water has increased eight to 12-fold due to rapid population increase, urbanization, and industrialization (Haberl et al., 2019). This has contributed to human-driven climate change (Haberl et al., 2019; Ciobanu and Onofrei, 2021), planetary boundaries' violation (Steffen et al., 2015), and societal injustice (Martinez Alier, 1995; Terwilliger, 2023). Globally, over 3,300 ecological distribution conflicts are recorded on The EJAtlas (Martinez-Alier, 2021) (https://ejatlas.org/). There are no signs of global societal metabolism stabilizing soon, new acceleration is expected due to growth in the developing economies (Haberl et al., 2019; Ciobanu and Onofrei, 2021). The current predominant narratives of bioeconomy are centered around anthropocentric values of economic growth and technological innovation, ignoring the dimensions of social equity and justice (Giuntoli et al., 2023). The transition toward sustainable bioenergy requires acknowledging and operationalizing the underlying normative principles of Georgescu-Roegen's bioeconomy. Such a bioeconomy does not seek sub-optimized solutions focusing on a single product or value chain (e.g., biofuels), and expansion of production or consumption. Based on sufficiency, it rather operates within the ecological limits of production and addresses the socioeconomic externalities throughout the value chain. It avoids shifting socioeconomic externalities of production and consumption to other spatial or temporal scales by establishing regional and global governance mechanisms. There is a research gap in mapping the current system and assessing the challenges that need to be overcome in order to approach this "ideal bioeconomy."

1.4 Aim and objectives of the study

This study aims *to analyze the global sustainability challenges to the current system of bioenergy production and consumption and explore the system leverages to address these challenges*. To achieve this aim, the key objectives are to:

1. Identify and highlight the significant challenges in the broader system of bioenergy production and consumption in a global sustainability perspective.
2. Integrate the main systems variables and cause-effect relationships in a causal loop diagram.
3. Explore and integrate key causal relationships and feedback loops to examine the main synergies and conflicts in the current system.
4. Discuss the places for policy interventions to address the sustainability impacts of bioenergy production and consumption.

To achieve this, we adopt a stepwise methodology (Section 2) to present qualitative system models of the major societal drivers behind the global bioenergy economy, its socio-economic and ecological consequences (Section 3), and discuss the need for a sustainable and just bioeconomy (Section 4).

2 Methodology

This research approaches the complex issue of sustainable production and consumption of bioenergy, a post-normal problem with uncertain facts, disputed values across different stakeholders, and high stakes needing urgent decisions (Funtowicz and Ravetz, 1993). To explore the challenges to sustainable bioenergy development and identify policy interventions for leveraging the bioenergy production and consumption system in the context of climate mitigation, we expand the system boundaries of the bioenergy production and consumption system. We utilize a driver-pressure-impact-state-impact-response (DPSIR) framework (Ness et al., 2010) and group model building (Vennix, 1996, 1999) to map the diverse socio-economic interactions between the human activity system and the natural systems (see Figure 1). By human activity system, we mean the socio-technical, political, and economic system associated with the production and consumption of bioenergy. The natural systems consist of ecosystems and environmental systems. The overall drivers of natural resource consumption in society are rapid urbanization, population growth, and socioeconomic development. These drivers lead to pressures in the human systems, such as energy demand and land use (change). These pressures then change the state of the natural systems, e.g., carbon, water and nutrient cycles, atmospheric emissions, and wastes. This altered state of the natural systems has impacts on both the natural (e.g., climate impacts, biodiversity loss, soil depletion, etc.) and human systems (e.g., human development, ecosystem services, etc.). The DPSIR framework was used to conceptualize the cause-and-effect relationships among variables in the system.

2.1 Research methods

The methodology employed includes several steps (Figure 2). In the first step, we used Critical interpretive synthesis (Dixon-Woods et al., 2006) to synthesize multi-disciplinary data from the literature on the social, economic, and ecological impacts of bioenergy production and consumption. In the second step, we conducted semi-structured interviews with experts to explore the more pragmatic stance on the current system of bioenergy production and consumption. In the third step, the quantitative and qualitative inferences from the prior two steps are discussed in (Step 3) group brainstorming sessions. This led to the fourth step, the development of a causal loop diagram (CLD) representing the key causal relationships and feedback loops in the system (Step 4) to examine the main synergies and conflicts for a sustainable bioeconomy. We adopt a life cycle thinking approach to address the broad research questions by including the direct and indirect impacts (i.e., the scope 1, 2, and 3 emissions and other social and economic

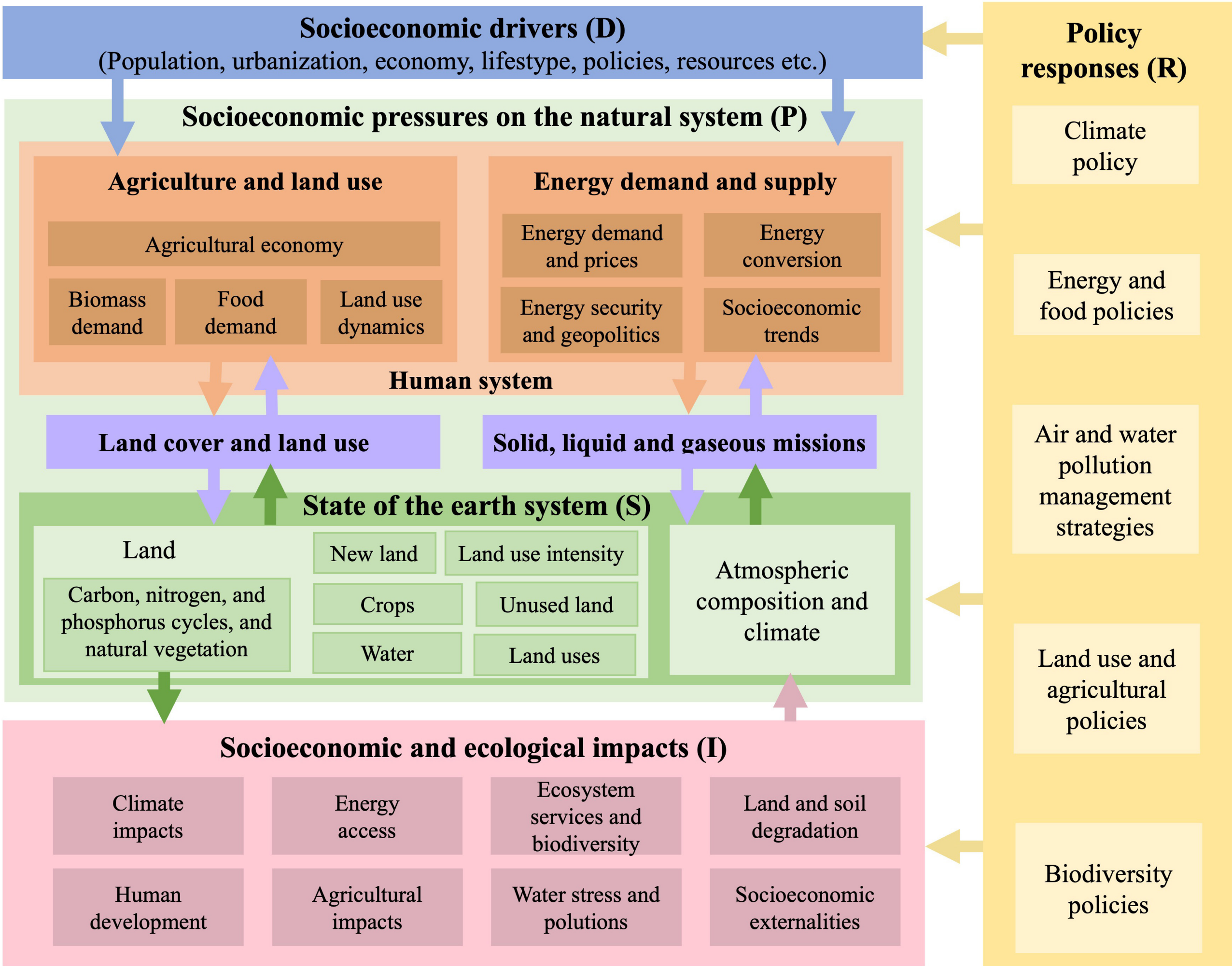

FIGURE 1
D-P-S-I-R framework to structure the cause-and-effect interrelationships among the key variables in biofuel production and consumption system. Adapted from the IMAGE 3.0 (Integrated Model to Assess the Global Environment) developed by PBL Netherlands Environmental Assessment Agency (https://models.pbl.nl/image/index.php/IMAGE_framework).

externalities) of bioenergy production and consumption from a global perspective.

2.1.1 Critical interpretive synthesis (Step 1)

Critical interpretive synthesis (Dixon-Woods et al., 2006) is an approach to synthesizing multidisciplinary and multi-method evidence. In contrast to a traditional literature review, in critical interpretive synthesis, the review questions are not precisely specified at the outset of the review but are iteratively revised during the review and analysis process (Dixon-Woods et al., 2006). It explicitly allows the integration of qualitative and quantitative inferences or evidence. In this research, we utilized critical interpretive synthesis to identify and support key cause-and-effect interactions in the systems of bioenergy production and consumption. Appendix 1 provides an overview of the key research themes synthesized and the cause-and-effect interactions identified during this synthesis.

2.1.2 Semi-structured interviews with experts (Step 2)

Semi-structured interviews are conducted with experts from academia, research institutions, and industry working on bioenergy-related issues in Sweden. It included eight academic and two industrial experts (further details are provided in Appendix 2). The academic experts had backgrounds in social sciences, landscape ecology, energy policy, agricultural science, industrial ecology, environmental science, and biology. The industrial expert worked in managerial roles in organizations with bioenergy refining, storage, and distribution operations in Sweden. These interviews were conducted to get an overview of the socioeconomic drivers and environmental impacts of the bioenergy economy in society (see Appendix 3 for a list of interview questions). The interviews were transcribed and coded using NVivo software (https://lumivero.com/products/nvivo/) to identify the key cause-and-effect variables related to bioenergy production, trade, consumption, and subsequent socioeconomic and ecological impacts. These interviews complemented the

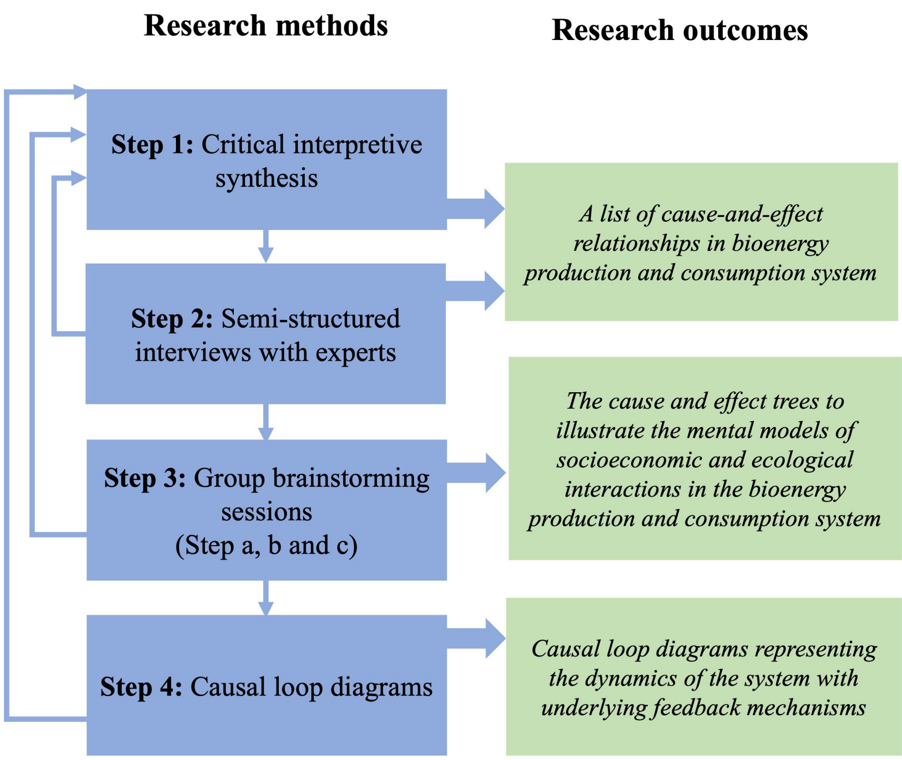

FIGURE 2
An overview of the application of research methods in this study.

cause-and-effect interactions identified in Step 1 and informed the critical interpretive synthesis.

2.1.3 Group brainstorming sessions (Step 3)

The qualitative and quantitative inferences obtained during Steps 1 and 2 were employed to further refine the identified system variables and their causes and consequences (as illustrated in Figure 3, also see Appendix 4). These were represented in individual cause-and-effect tree diagrams to illustrate mental models of socio-economic and environmental interactions in bioenergy production and consumption. A series of group brainstorming sessions were conducted with the researchers at the Center for Environmental and Climate Science, Lund University, to further discuss and validate these cause-and-effect models (not the same experts who were interviewed during Step 2). At this step, these models were complemented with the mental models of the participants of brainstorming sessions. Appendix 4 provides an overview of the process of developing typical cause and effect trees in this research. Nonetheless, in most cases, the model representation and analysis were kept at an abstract level.

At this step, the participants were asked to provide their subjective judgment on the validity of the interrelationships represented in the cause-and-effect trees. The potential observer bias arising from such subjecting judgment was low because the cause-and-effect trees were developed based on theoretical inferences (i.e., step 1) and expert interviews (i.e., step 2). Further, the participants joined the sessions voluntarily and were not part of the research project.

The directionality of cause-and-effect chains was not always straightforward to establish (i.e., similar to the dilemma of "*whi chcame first, the eggs or the chicken*"). This was especially the case for system variables related to socioeconomic impacts and policy interventions. To solve such conflicting situations, inferences from literature and the DPSIR framework were used.

2.1.4 Causal loop diagrams (Step 4)

The systemic relationships between individual cause-and-effect trees are then represented in a causal loop diagram (CLD; see Appendix 4). This validated system dynamics model represents "*a theory about how a system works in some respect*" (Barlas, 1996, p. 186). The aim behind developing CLD was to provide insights into the feedback mechanisms behind the socioeconomic and ecological impacts that are often displaced in time and space. This is done to highlight the places where policies are lacking and should focus on to avoid problem shifting and/or impact displacement in time and space. To identify the system structures and/or interactions that need to be disrupted or mitigated and areas of leverage in the system with a large impact, we used a similar process developed by The Omydiar Group (2017).

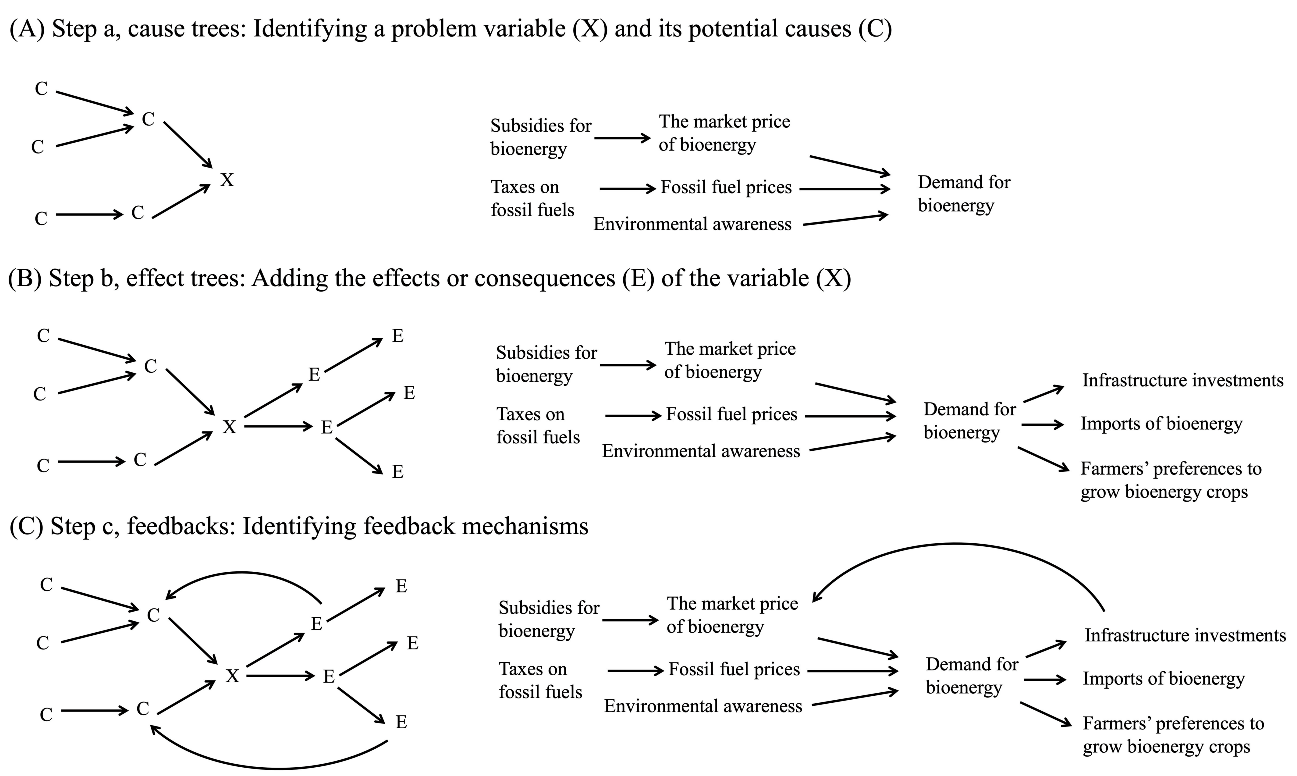

FIGURE 3
Stepwise process of developing cause and effect trees (Steps a–c). Adapted from Vennix (1996) and Singh et al. (2019). **(A)** Identifying a problem variable and its causes. **(B)** Adding effects or consequences. **(C)** Identifying feedback mechanisms.

3 Results

We identified the cause-and-effect interactions in the globalized bioenergy production and consumption system (Table 1). Based on these, we explain the socioeconomic drivers behind the global bioenergy economy (Section 3.1), the global implications of large-scale biomass cultivation for energy purposes (Section 3.2), its ecological challenges (Section 3.3), and socioeconomic negative externalities (Section 3.4).

3.1 Socioeconomic drivers of the global bioenergy economy

The major drivers of the global bioenergy economy are multifaceted and interconnected, encompassing social, economic, environmental, and geopolitical factors. These are linked to the aims to address climate change, the pursuit of energy security, and socioeconomic development.

3.1.1 Climate change

After the oil crises of the 1970s, biofuels were considered as an alternative fuel and a supplement to fossil fuels for the transportation sector (Timilsina, 2014). In the early 2000s, biofuels were recognized as an essential means of addressing the ongoing climate change and decarbonizing the transportation sector (Ladanai and Vinterbäck, 2009; Fulton et al., 2015). Thus, despite a lack of consensus on whether biofuels could sustainably meet future large-scale energy demand (Fulton et al., 2015), governments worldwide have introduced targets for bioenergy use (Oliveira et al., 2017; Das, 2021). To achieve this, biofuel blending mandates and financial subsidies have been implemented by more than 40 governments worldwide (Timilsina and Shrestha, 2011; Timilsina, 2014; Debnath and Whistance, 2023). These include the European Union (Franco et al., 2010; Schleifer, 2013; Bórawski et al., 2019; Musiał et al., 2021), the United States (Jeffers et al., 2013; Dumortier et al., 2021; Lark et al., 2022; Newes et al., 2022), the United Kingdom (Cross et al., 2021), India (Sinha et al., 2019; Shukla and Mallick, 2023), and China (Weng et al., 2019; Zhang and Feng, 2021).

Fossil fuels supply 96.3% of all transportation fuel needs (International Energy Agency, 2019), accounting for 8 Gt CO_2 emissions (International Energy Agency, 2023c). To achieve reductions in greenhouse gas emissions in the transportation sector, biofuels have been proposed as a short- to medium-term solution. In developed countries, climate change issues dominate the energy policy discourses. These countries have implemented financial mechanisms to encourage biofuel use, such as fuel subsidies, tax incentives, and infrastructure-related investments. However, the climate change mitigation potential of biofuels, extensively researched and debated, is contingent upon the type of feedstock, production process, and scale of production (Fargione et al., 2008; Food and Agriculture Organization, 2013).

TABLE 1 Cause-and-effect interactions identified during the critical interpretive synthesis and semi-structured interviews.

System domains	Cause variables		Effect variables	
	Main causes	Further causes	Main effects	Further effects
Policies promoting the production and consumption of bioenergy	- Energy security - Climate change - Socioeconomic development (especially, rural areas)	- Fossil fuel prices - Geopolitical tensions - Rural development agendas - Climate change mitigation ambitions	- Direct taxes (e.g., carbon and energy tax) - Subsidies for bioenergy use - Environmental awareness - Bioenergy profitability/ productivity	- Market prices of bioenergy - Fossil fuel prices - Infrastructural development (production capacity, end-use technology incentives) - Prices and availability of food on global market
Demand for bioenergy	- Fossil fuel prices - Cost of bioenergy - Consumers' attitudes	- Bioenergy policies - Infrastructural investments - Blending mandates	- Demand for biomass - Infrastructural investments - Bioenergy consumption - Import of bioenergy/biomass	- Biomass production - Cost effectiveness of bioenergy production - Biomass productivity - Sustainability impacts - Food security
Biomass production	- Biomass demand for bioenergy - Biomass demand for food	- Demand for bioenergy - Demand for local food - Local food supply capacity	- Environmental pressures on land resources - Changes in land uses	- Sustainability impacts
Demand for agricultural land	- Local bioenergy/food production - Farmers willingness to cultivate energy and/or food crops	- Consumer demand for local food - Market prices of food/ bioenergy/animal feed - Policies to promote local food/bioenergy production	- Land use change - Marginal land uses - Biomass residues utilization - Intensified land uses	- Biomass/bioenergy yield - Prices of bioenergy/food - High value habitat loss - Soil carbon storage - Water depletion
Negative socioeconomic externalities	- Global demand for bioenergy and food products - Instances of land grabbing - Water depletion - Access to food	- Global demand for bioresources (food, feed, bioenergy) - Export of bioproducts from resource-deprived and/or ecological-sensitive global regions - Indirect land use changes	- Undervalued natural and social capital - Unfair land tenures - Access to local resources for local communities - Unequal share of profits and impacts	- Economic inequalities - Social impacts - Resource-deprived local communities - Conflicts and social unrest
Environmental implications of bioenergy production and consumption	- Intensive land use practices - Globalized supply chains	- Food prices - Fossil energy prices - Demand for bioresources	- Soil carbon storage - Biodiversity loss - Food scarcity - High value habitat loss	- Local environmental change - Soil depletion - Socioeconomic externalities

3.1.2 Energy security

Biofuels can be produced from existing renewable biomass resources. Therefore, they have the potential to enhance energy security by reducing reliance on (fossil)energy imports. Biofuels can help build a sustainable energy system by improving energy flexibility and reliability (Bose and Kumar, 2021; Akhtar, 2023). Biofuels' role in creating a sustainable energy regime and a positive long-term impact on the ecosystem has been recognized globally (Demirbas, 2009; Viju and Kerr, 2013; Gunatilake et al., 2014; Bose and Kumar, 2021). Developing countries have been investing in bioenergy production and consumption infrastructure to reduce (fossil) energy imports, enhance energy security, and lower energy prices. Indeed, biofuel demand is growing in several emerging economies, such as Indonesia, Brazil, and India (International Energy Agency, 2023b). These countries possess significant biomass feedstock, production capacity, and low product costs, e.g., palm oil in Indonesia, soybean in Brazil, and biodiesel in India. They aim to increase bioenergy demand through a mixture of policies focusing on shifting consumers' and producers' preferences for adopting biofuels.

3.1.3 Socio-economic development

Biofuels can help alleviate energy poverty, generate income, and develop local and regional economies (Bose and Kumar, 2021; Sahoo et al., 2022). They can be a low-cost alternative to expensive imported energy, thereby creating more revenues for the governments. Biofuels can help develop agriculture and farming and create more jobs, especially in rural areas (Demirbas, 2009; Sahoo et al., 2022). For instance, the oil palm industry in Indonesia employs more than 6 million people (Purnomo et al., 2020).

These drivers have contributed to developing favorable market conditions for biofuels by increasing the demand for biofuels and reducing the market price of biofuels (represented with reinforcing loop R1 in Figure 4). This was achieved by a range of approaches, including agricultural policies, blending mandates, subsidy support for technologies, import tariffs, tax incentives or penalties, and research and development. The concrete aims to support biofuel development and influencing the financial attractiveness of their production, trade, and use (reinforcing loop R1). For instance, by influencing consumers' preferences toward biofuel use (reinforcing sub-loop R1a), making bioenergy

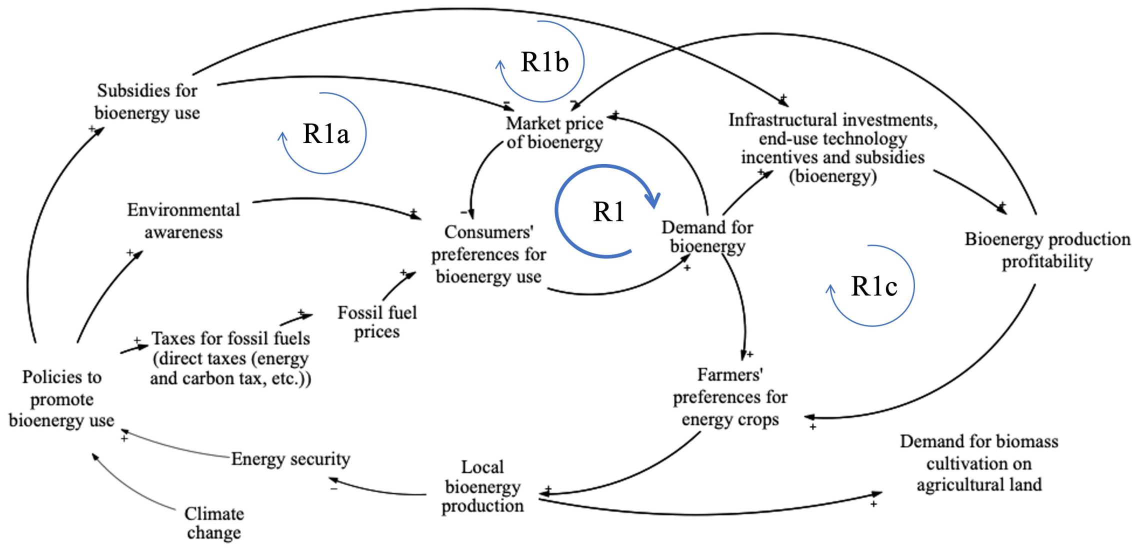

FIGURE 4
A CLD representing key socioeconomic drivers for the global biofuel demand (reinforcing loop R1). This loop is supported by reinforcing sub-loop R1a (consumers' preferences toward biofuel use), reinforcing sub-loop R1b (bioenergy price-competitiveness), and reinforcing sub-loop R1c (motivating farmers to produce energy crops).

more price-competitive by supporting infrastructure for bioenergy growth (reinforcing sub-loop R1b), motivating farmers to produce energy crops (reinforcing sub-loop R1c). These policies are well-received in society due to their orientation toward addressing climate change and energy security issues and contributing to local or regional socio-economic development. Thus, the global biofuel economy is greatly influenced by geopolitics regimes and international trade dynamics. For instance, an expectation of profitable biofuel exports to the European Union has led certain regions to invest in bioenergy production infrastructure, such as Southern Africa (Henley and Fundira, 2019). The BRICS (Brazil, Russia, India, China, and South Africa) nations have successfully implemented policies to promote biofuel in their respective energy markets (Saravanan et al., 2020). Global biofuel production has rapidly grown in the United States, the European Union, and Brazil. Market factors and policies dictate biofuel trade volumes (Lamers et al., 2012) and influence the prices of other commodities (e.g., fuel, food, and feed) in the global markets. Nonetheless, none of the above-mentioned aims of climate mitigation, energy security, or socioeconomic development have been fully achieved (Debnath and Whistance, 2023).

Thus, the global biofuel economy has followed the typical logic of economic growth by addressing the technological, market, financial, and behavioral barriers (creating the reinforcing loop R1). This logic had an implicit assumption that renewable resources are automatically better than fossil fuels. And it has not addressed social and justice issues. This is why the changing (bio)energy policy regimes have created unintended negative socioeconomic and ecological externalities. These are elaborated on in the remainder of this Section.

3.2 Global implications of bioenergy production

In the past decades, significant research has highlighted the socioeconomic and ecological impacts of biofuel production. Biofuel production has been scrutinized for ecological impacts linked to land-use change, increased resource use (e.g., fertilizers), water depletion and soil erosion, and biodiversity loss. The globalization of the biofuel economy has been criticized for its negative socioeconomic externalities, such as food insecurity, land grabbing, unethical contract conditions, social disparity, and gender discrimination.

The CLD in Figure 5 represents some of the major socioeconomic and ecological implications of biofuel production and consumption. This study identified several underlying feedback mechanisms behind these implications (see Table 2). While these implications are spread, spatially and temporally, in the globalized supply chains of biofuels, no such distinction is made in the representation. The following subsystems are represented in this CLD: *demand for biomass* driving *demand for agricultural land* (R1 and R2) leading to increased *biomass/biofuel yield* using *marginal lands (or uncultivated farmland, abandoned land, etc.)*, changes in *direct and indirect land use*, and *intensive farming practices* (locally as well as regionally and globally; e.g., R3); and these changes subsequently impacting *soil carbon storage*, *biodiversity*, and *climate change* (R4 and R5). This section outlines the sustainability challenges to biofuel production and consumption from a global perspective.

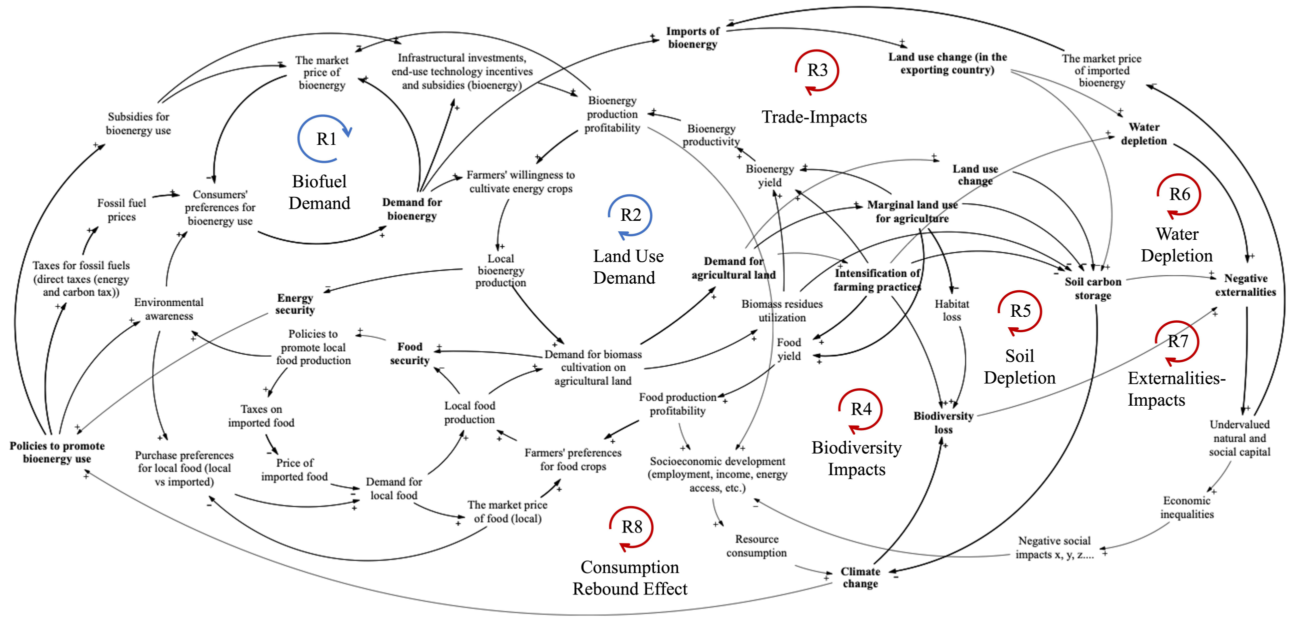

FIGURE 5
Illustration of the ecological impacts of increased biofuel demand due to environmental policies focusing on climate mitigation by promoting bioenergy production and consumption, leading to reinforcing feedback loops R2: Land Use Demand, R3: Trade-Impacts, R4: Biodiversity Impacts, R5: Soil Depletion, and R6: Water Depletion. The negative social consequences resulting from under-valued natural resources and human capital (R7: Externalities-Impacts) and consumption rebound effects due to overconsumption of (energy or other natural resources) achieved by productivity gains (R8: Consumption Rebound Effects).

3.2.1 Implications of rapid expansion of biofuel production

In the last few decades, global biofuel production has significantly grown due to the above-described drivers. The major biofuel production occurs in the United States, Brazil, the European Union, China, and India due to their agricultural production capacities (Cai et al., 2011). Countries like Argentina, South Africa, Indonesia, Malaysia, Mexico, and Thailand have favorable conditions for biofuel production potential and the requisite technology capabilities (Köhler et al., 2014). Globally, between 2004 and 2010, existing policies and increased oil prices have resulted in a threefold increase in ethanol production and an eightfold increase in biodiesel production (Timilsina and Shrestha, 2011). In 2018, their global production reached a volume of 167.9 billion liters (from 49.9 billion liters in 2005) (Kurowska et al., 2020).

The rapid and large-scale expansion of biomass cultivation for biofuels in some global regions has significant socioeconomic and ecological implications. For instance, in some cases, this expansion has come at the expense of converting forests into cropland and replacing food crops (Achten and Verchot, 2011; Taheripour and Tyner, 2013; Yu and Lu, 2018; Rudke et al., 2022), leading to deforestation, greenhouse gas emissions from land-use change (Timilsina and Shrestha, 2011), water resource depletion (Harto et al., 2010), nitrogen losses, and food prices (Humpenöder et al., 2018). Thus, large-scale bioenergy expansion directly conflicts with the Sustainable Development Goals (SDG) agenda due to negative sustainability impacts and trade-offs (Humpenöder et al., 2018).

3.2.2 Ecological constraints to net primary production of biomass

As compared to stock-limited fossil fuels, biomass-derived biofuels are renewable resources for energy. However, the renewable biomass feedstocks needed to produce biofuels depend on the biosphere's capacity to supply the feedstock flows over time. A useful measure of human intervention in the biosphere is conceptualized by an integrated socioecological indicator—the human appropriation of net primary production (HANPP) (Krausmann et al., 2013). HANPP is the difference between the net primary production (NPP) of the potential vegetation in an ecosystem without humans (NPP_0) and the fraction of NPP of actual vegetation left in the ecosystem after human use (Haberl et al., 2007, 2014). HANPP, therefore, quantifies the human-induced effects of changes in productivity and harvest on ecological biomass flows (Haberl et al., 2007, 2014; Krausmann et al., 2013; Mayer et al., 2021). HANPP is the lowest (0%) for a wilderness area and highest (100%) for sealed soils (Haberl et al., 2007; Krausmann et al., 2013). Studies confirm (Chen et al., 2019; Liu et al., 2019) increasing leaf area of vegetation (or NPP) in recent years by human-driven (i.e., human land-use management) and climate-driven factors (e.g., climate change, CO_2 fertilization, nitrogen deposition, etc.). However, these increases are partially offset by urbanization (Liu et al., 2019), and at least in some regions and land-use types by warming (Das et al., 2023). Further, globally, NPP has been on the decline due to drivers such as urbanization, human population, and socioeconomic development (Krausmann et al., 2013; Haberl et al., 2014; Liu et al., 2019). To limit global warming to 2°C, an estimated daily biofuel production increase from 9.7 ×

TABLE 2 A summary of the main loops of the "current" system.

Feedback mechanisms	The contributing feedback loops in the current sytem
Bioenergy demand	*Loop Number 1 of length 2:* Demand for bioenergy—The market price of bioenergy—Consumers' preferences for bioenergy use
	Loop Number 2 of length 4: Demand for bioenergy—Infrastructural investments, end-use technology incentives and subsidies (bioenergy)—Bioenergy production profitability—The market price of bioenergy—Consumers' preferences for bioenergy use
	Loop Number 3 of length 6: Demand for bioenergy—Farmers' willingness to cultivate energy crops—Local bioenergy production—Energy security—Policies to promote bioenergy use—Environmental awareness—Consumers' preferences for bioenergy use
Land use	*Loop Number 1 of length 7:* Demand for agricultural land—Intensification of farming practices—Bioenergy yield—Bioenergy productivity—Bioenergy production profitability—Farmers' willingness to cultivate energy crops—Local bioenergy production—Demand for biomass cultivation on agricultural land
	Loop Number 2 of length 10: Demand for agricultural land—Marginal land use for agriculture—Soil carbon storage—Climate change—Policies to promote bioenergy use—Environmental awareness—Consumers' preferences for bioenergy use—Demand for bioenergy—Farmers' willingness to cultivate energy crops—Local bioenergy production—Demand for biomass cultivation on agricultural land
	Loop Number 3 of length 11: Demand for agricultural land—Land use change—Soil carbon storage—Climate change—Policies to promote bioenergy use—Subsidies for bioenergy use—The market price of bioenergy—Consumers' preferences for bioenergy use—Demand for bioenergy—Farmers' willingness to cultivate energy crops—Local bioenergy production—Demand for biomass cultivation on agricultural land
Soil carbon storage	*Loop Number 1 of length 5:* Soil carbon storage—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)
	Loop Number 2 of length 8: Soil carbon storage—Climate change—Policies to promote bioenergy use—Taxes for fossil fuels (direct taxes (energy and carbon tax))—Fossil fuel prices—Consumers' preferences for bioenergy use—Demand for bioenergy—Imports of bioenergy—Land use change (in the exporting country)
	Loop Number 3 of length 9: Soil carbon storage—Climate change—Policies to promote bioenergy use—Environmental awareness—Purchase preferences for local food (local vs. imported)—Demand for local food—Local food production—Demand for biomass cultivation on agricultural land—Demand for agricultural land—Intensification of farming practices
Biodiversity loss	*Loop Number 1 of length 7:* Biodiversity loss—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change
	Loop Number 2 of length 7: Biodiversity loss—Negative externalities—Undervalued natural and social capital—Economic inequalities—Negative social impacts x, y, z....—Socioeconomic development (employment, income, energy access, etc.)—Resource consumption—Climate change
	Loop Number 3 of length 15: Biodiversity loss—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change—Policies to promote bioenergy use—Environmental awareness—Consumers' preferences for bioenergy use—Demand for bioenergy—Farmers' willingness to cultivate energy crops—Local bioenergy production—Demand for biomass cultivation on agricultural land—Demand for agricultural land—Intensification of farming practices
Water depletion	*Loop Number 1 of length 5:* Water depletion—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)
	Loop Number 2 of length 14: Water depletion—Negative externalities—Undervalued natural and social capital—Economic inequalities—Negative social impacts x, y, z....—Socioeconomic development (employment, income, energy access, etc.)—Resource consumption—Climate change—Policies to promote bioenergy use—Taxes for fossil fuels [direct taxes (energy and carbon tax)]—Fossil fuel prices—Consumers' preferences for bioenergy use—Demand for bioenergy—Imports of bioenergy—Land use change (in the exporting country)
	Loop Number 3 of length 15: Water depletion—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change—Policies to promote bioenergy use—Environmental awareness—Purchase preferences for local food (local vs. imported)—Demand for local food—Local food production—Demand for biomass cultivation on agricultural land—Demand for agricultural land—Intensification of farming practices
Bioenergy import impacts	*Loop Number 1 of length 5:* Imports of bioenergy—Land use change (in the exporting country)—Water depletion—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy
	Loop Number 2 of length 5: Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy
	Loop Number 3 of length 7: Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change—Biodiversity loss—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy
Consumption rebounds effects	*Loop Number 1 of length 6:* Resource consumption—Climate change—Policies to promote bioenergy use—Subsidies for bioenergy use—Infrastructural investments, end-use technology incentives and subsidies (bioenergy)—Bioenergy production profitability—Socioeconomic development (employment, income, energy access, etc.)

(Continued)

TABLE 2 (Continued)

Feedback mechanisms	The contributing feedback loops in the current sytem
	Loop Number 2 of length 7: Resource consumption—Climate change—Biodiversity loss—Negative externalities—Undervalued natural and social capital—Economic inequalities—Negative social impacts x, y, z....—Socioeconomic development (employment, income, energy access, etc.)
	Loop Number 3 of length 9: Resource consumption—Climate change—Policies to promote bioenergy use—Subsidies for bioenergy use—The market price of bioenergy—Consumers' preferences for bioenergy use—Demand for bioenergy—Infrastructural investments, end-use technology incentives and subsidies (bioenergy)—Bioenergy production profitability—Socioeconomic development (employment, income, energy access, etc.)
Negative socioeconomic externalites	*Loop Number 1 of length 5:* Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Water depletion
	Loop Number 2 of length 5: Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage
	Loop Number 3 of length 7: Negative externalities—Undervalued natural and social capital—Economic inequalities—Negative social impacts x, y, z....—Socioeconomic development (employment, income, energy access, etc.)—Resource consumption—Climate change—Biodiversity loss

There are many other feedback loops, however, the loops with the highest strength are emphasized (also with minimum length).

10^6 GJ to 4.6×10^7 GJ—a 20-fold increase - between 2016 and 2040 would be needed (16% of transportation fuels) (International Energy Agency, 2017; Correa et al., 2019). This puts ecological limitations on the use of biomass for human needs, including energy purposes. Therefore, in the future, it will be difficult to raise NPP for longer periods.

3.2.3 Global impacts of rapidly changing trade roles

The production, use, and trade of biofuels are highly globalized. Historically, the major driving factors behind the global biofuel demand and supply depended on (energy) policy regimes in countries that are their major producers as well as consumers, such as the United States, the European Union, and Brazil (Debnath and Whistance, 2023). The other factors that dictate which biofuel's demand grows and where it will be sourced are transport fuel demand, costs, and specific policy design (International Energy Agency, 2022). These factors influence the volume and direction of global biofuel trade (Debnath and Whistance, 2023). For example, in the past, the EU's Renewable Energy Directive (RED) drove the member countries to be the major importers of biodiesel. This (and their national policy agendas) has resulted in unbalanced biofuel production and consumption in these countries. Indeed, Sweden, being one of the biggest consumers of biofuels in the EU (25 TWh of biofuels), produced only 30% of their consumption in 2022 (7.5 TWh) (Lundberg et al., 2023). Sweden has imported low-lifecycle emission biofuels from both within the EU and outside due to their national blending mandates that have created a higher willingness to pay for these fuels (Swedish Energy Agency, 2021; Lundberg et al., 2022, 2023). At the same time, The Netherlands produced twice its domestic consumption due to large investments in the bioenergy production sector and logistical advantages of ports in the country (Lundberg et al., 2023).

In contrast, the USA's Renewable Fuel Standard (RFS) made them the ethanol exporter (Debnath and Whistance, 2023). However, as more and more countries are adopting sustainability criteria, the biofuel trade is declining (Debnath and Whistance, 2023). Indeed, the recent biofuel-related trade restrictions by the EU (after it implemented RED II to reduce the import of fuels with high indirect land use change (iLUC) risk) reduced Indonesia's biodiesel export from 1.1 billion MT in 2019 to 34 thousand MT in 2020. Overall, in 2021, the global trade of biodiesel decreased from 21% of the total production in 2012 to 14% in 2021. Some countries have even changed their trade roles amid these changing energy and sustainability regimes. For example, at the beginning of the biofuel trade, the United States was the largest importer of ethanol, and Brazil was its major exporter. However, as of 2024, the United States has become a major exporter of ethanol, and Brazil is an importer. This globalization of the biofuel economy has caused structural changes in agricultural and food systems across the world that have negative macroeconomic implications, locally or regionally. For instance, Newfarmer and Sztajerowska (2012) described how trade-induced growth may also negatively impact economic growth, employment, income distribution, productivity, and working conditions.

3.2.4 Impact of globalized biofuel economy on energy return on investment

Energy return on investment (EROI) is the ratio of energy returned to society and energy required to get that energy. It is a useful approach for examining the disadvantages and advantages of different fuels (Hall et al., 2009). A low EROI is a limiting factor for the sustainable use of biofuels for mitigating global climate change (Staples et al., 2017). EROI is lower for liquid and gaseous biofuels (German National Academy of Sciences Leopoldina, 2012). The transportation and shipping of biofuels over long distances in the globalized markets negatively impact the overall EROI. Therefore, in principle, a low EROI should promote more local or regional production and consumption of bioenergy. However, this issue may not act as a strong drive because, in the current global bioenergy value chain, the negative (economic) impacts of a low EROI are either disproportionately shared by different actors across the value chain or mitigated by subsidies, or not properly acknowledged.

3.3 Ecological challenges to large-scale bioenergy cultivation

3.3.1 Land-use change

The policies to promote bioenergy have resulted in favorable market conditions for both the producers (farmers, energy suppliers, etc.) and the consumers (households, businesses, and governments; represented by reinforcing loops R1a, R1b, and R1c in Figure 4). This has created a globalized market for high-value bioenergy products, e.g., biofuels (reinforcing loop R3 in Figure 5). Indeed, in recent decades, the bioenergy markets in the European Union, USA, Brazil, the Philippines, and Canada have been one of the major drivers for direct and indirect land use change globally (Merfort et al., 2023). For instance, while the EU's Common Agricultural Policy has reduced the farmed area in their borders, their crops and meat imports have been found to impact deforestation and biodiversity loss in ecologically sensitive areas in Brazil and Indonesia (Merfort et al., 2023). Reducing bioenergy-driven land use change emissions has been recognized as a key factor in deploying bioenergy for climate mitigation (Merfort et al., 2023).

3.3.2 Impacts of intensive farming practices

The increasing demand for agricultural biomass is a major driver for intensive farming practices and the use of marginal lands. Indeed, continuous increases in crop yield over the past 50 years were only possible due to fertilizer application and irrigation. However, this has also contributed to significant climate and ecological risks.

Intensive farming practices have been causing loss of soil carbon, impoverishment of soil structure, biodiversity, and organic matter, including carbon content due to plowing, eutrophication due to excessive fertilizer use (Elobeid et al., 2013; Lark et al., 2022), ecosystem damage, and biodiversity loss (Scheper et al., 2023) due to pesticide use (Fairley, 2022; Sahoo et al., 2022). Indeed, human activities have already exceeded some of the planetary boundaries, for example, biogeochemical flows of nitrogen and phosphorus, freshwater change, functional and genetic biosphere integrity, climate change, and land use change (Rockstrom et al., 2009; Steffen et al., 2015; Richardson et al., 2023). Thus, the option of intensive biomass cultivation to meet future human needs not only becomes a necessity but also a major constraint from an ecological perspective.

Further, intensive harvesting of biomass feedstocks leads to decreased carbon gains or increased carbon losses (from soils), thereby, reducing the potential greenhouse gas benefits (Anderson-Teixeira et al., 2009; Kochsiek and Knops, 2012). Furthermore, the greenhouse gas emissions from biofuel production depend on the type of feedstock and conversion process. A lower density, higher moisture content, and hydrophilic nature of biomass make biofuels more expansive and less efficient than fossil-based energy (Rana et al., 2020). Second-generation biofuels have greater potential for reducing these emissions than first-generation. The emissions from third-generation biofuels are found to be higher than those from conventional fuels (ranging from 10.2 to 1,910 g Co_2 eq./MJ) (Patel and Singh, 2023).

Furthermore, biofuel production negatively impacts wild and agricultural biodiversity. A global synthesis by Tudge et al. (2021) shows that local species richness and total abundance were 37% and 49% lower at sites with first-generation, and 19% and 25% lower at sites with second-generation biofuel crops, respectively. However, Winberg et al. (2023) highlight that bioenergy-related effects on ecosystems depend on the original land use, bioenergy crop type, and the scale of production. Nonetheless, they emphasized the need for research and policy to explicitly consider trade-offs between bioenergy production and biodiversity and ecosystem services, and how to avoid them.

3.3.3 The inter-resource dependencies of biofuel production on other inputs

Agricultural biomass cultivation, harvesting, and processing require significant resource inputs such as energy, fertilizers, pesticides, and other chemicals. This puts pressure on other fossil resources, such as phosphorus and water. Further, the water footprints of biofuels are estimated to be 50—240 times higher than those of fossil fuels (Patel and Singh, 2023) and other fossil-free energy technologies, such as solar photovoltaic (Harto et al., 2010). Any trade-offs in such inter-resource interactions will become more critical in the future.

3.4 Socio-economic externalities of the globalized bioenergy economy

CLD in Figure 5 represents these broad negative socioeconomic and ecological externalities of biofuel production and consumption. These negative externalities lead to undervalued natural resources and human capital since the true costs of resource extraction, production, and consumption are not accounted for and reflected in the market prices (loop R7: Externalities Impacts in Figure 5). The undervaluation of natural and human capital has further resulted in rapid and unequal wealth accumulation (and consumption-rebound effects which are not explicitly represented in the CLD).

Firstly, the globalized biofuel value chains produce multiple negative socio-economic and ecological externalities and displace them across geographical boundaries. For instance, as highlighted earlier, biofuel cultivation driven by export demands has resulted in illegal land grabbing [e.g., in some African countries (Robertson and Pinstrup-Andersen, 2010; Palmer, 2014; Vandergeten et al., 2016; Aha and Ayitey, 2017; Conigliani et al., 2018; Cudlínová et al., 2020; Bae, 2023)], corporate lobbying (Pilgrim and Harvey, 2010; Tosun and Schulze, 2015; Deppermann et al., 2016; Cloteau, 2020), large-scale land acquisition by foreign investors in the African continent (Nyantakyi-Frimpong, 2013; Onoja, 2015), soil infertility and erosion (Chatskikh et al., 2013; Khanal et al., 2013; Thomaz et al., 2022), and biodiversity loss (Butchart et al., 2010; Vijay et al., 2016; Essl et al., 2018; Tudge et al., 2021) in producing regions.

Secondly, in the globalized economy, the distributional effects (Martinez Alier, 1995) extend beyond the country implementing the policy (Johnstone and Serret, 2006). Existing research (Ariza-Montobbio et al., 2010; McCarthy, 2010; Obidzinski et al., 2012;

Duvenage et al., 2013; Hodbod and Tomei, 2013; Nyantakyi-Frimpong, 2013; Onoja, 2015; Mwale and Mirzabaev, 2016; Schultz and van Riet, 2018) identifies both the positive and negative distributional effects of the biofuel economy. The positive effects include local energy access, labor opportunities, biofuel production-related new economic activity, and improved wages. The marginalization of some local stakeholders, food insecurity, loss of land access for poorer people in rural areas, social disparity, gender discrimination, and adverse labor conditions are some of the significant negative effects (Hodbod and Tomei, 2013).

These socio-economic benefits and/or costs of producing biofuels are not equally shared in society. As per the wide-held perception among policymakers, poor households pay more for the financial costs and receive fewer environmental benefits from environmental policies (Johnstone and Serret, 2006). Globally, biofuel production and consumption in developed countries have been linked to increased global food prices (Fairley, 2022; Lark et al., 2022) due to interactions between agricultural systems and other economic sectors both within and across countries (The Organisation for Economic Co-operation and Development, 2019). Global biofuel production is blamed for the significant consumption of maize, wheat, and vegetable oil due to the increased food prices of these crops, globally (Kurowska et al., 2020; Lark et al., 2022).

OECD countries' agricultural support and protection policies have complex impacts on producers and consumers in other countries. For instance, the EU's Common Agricultural Policy (CAP) setting subsidies based on area rather than on production results in reduced farmland in the region but increased agricultural imports. Indeed, European forests have expanded by 9% [13 million hectares (Mha)], but around 11 Mha was deforested elsewhere to grow crops that were consumed within the EU (Fuchs et al., 2020). Three-quarters of this deforestation was due to oilseed production in Brazil and Indonesia—the regions with global significance for biodiversity conservation, climate mitigation, and carbon storage (Fuchs et al., 2020). Malik et al. (2023) report some of the significant negative externalities of the EU's food trade—5% of the EU's total CO2 consumption-based footprint, 9% of NO_X footprint, 16% of the particulate matter footprint, 6% of the total SO_2, and 46% of the land-use footprint. The local populations are more likely to be exposed to these negative environmental externalities.

4 Discussion

This study explores and integrates key causal relationships and feedback loops to examine the main synergies and conflicts in the current global bioenergy economy, highlighting the points that our analysis suggests need to be addressed to achieve a globally sustainable and just bioeconomy. We go beyond existing research in eliciting and integrating knowledge from multiple disciplines, such as environmental economics, energy economics, industrial ecology, systems dynamics, environmental justice, and sustainability transitions, utilizing CLDs to visualize the cause-and-effect interactions that are often obscured from different actors in the system, and often distant in time and space.

The study highlights some of the major drivers of the global bioenergy economy are societal concerns related to climate change, energy security, and socio-economic development. These drivers have resulted in a rapid (and unsustainable) global expansion of production, trade, and consumption of bioenergy. This in turn has caused unintended negative ecological and socioeconomic consequences. This research draws from expert interviews, literature synthesis, and discussions with researchers to bring together some of the significant cause-and-effect interactions linking these drivers and consequences, from a systems perspective. For this purpose, we have utilized CLDs to represent and highlight the system structure behind biofuel demand (R1), land use demand (R2), bioenergy trade impacts (R3), biodiversity loss (R4), soil depletion (R5), water depletion (R6) socioeconomic externalities due to undervalued natural and human capital (R7), and consumption rebound effects (R8; see Figure 5). In this complex system, societal policy agendas focusing on the profitability of production, consumption, and trade of bioenergy represent the core of this complex system driving the (unintended) negative ecological and socioeconomic consequences. To address these consequences, systemic transitions are needed in society.

4.1 Need for transition toward a sustainable and just bioeconomy

The CLD model represented a reinforcing loop of climate change and bioenergy development. This implies that the current system of biofuel production and consumption requires balancing modes of system behaviors to fully utilize the climate mitigation potential of bioenergy (or biofuels) and sustainable development. There is a need for a green, just, and sufficient bioeconomy (Giuntoli et al., 2023). Some examples of such balancing modes of system behaviors include sustainable intensification of land use, local or regional production and consumption of bioenergy resources, protection of ecologically sensitive areas from the unintended negative effects of bioenergy-induced demand for land or biomass, and promotion of socio-ecological justice and equity to mitigate the negative social and economic externalities in the globalized bioenergy value chains. In this section, we highlight the need for establishing the following three modes of system behaviors for a sustainable global bioenergy economy:

1. *A sustainable bioeconomy* to address the ecological crisis.
2. *Just transitions* for solving the socioeconomic externalities.
3. *Coherent governance* mechanisms to guide the societal transitions.

CLD in Figure 6 represents the development of a sustainable and just bioeconomy. In this CLD, the system interactions that need balancing effects (the green arrows) through deliberate changes in practices and policies in the bioenergy production and consumption system (in blue text) are shown. Appendix 5 shows these balancing effects. These balancing effects introduce new balancing feedback loops in the system addressing the negative socioeconomic and ecological consequences (see Table 3).

Societal transformations toward a sustainable bioeconomy recognize aspects that go beyond anthropocentric or utilitarian views of nature (Giuntoli et al., 2023). This implies the societal demands for biomass (for energy, material, feed, or food purposes)

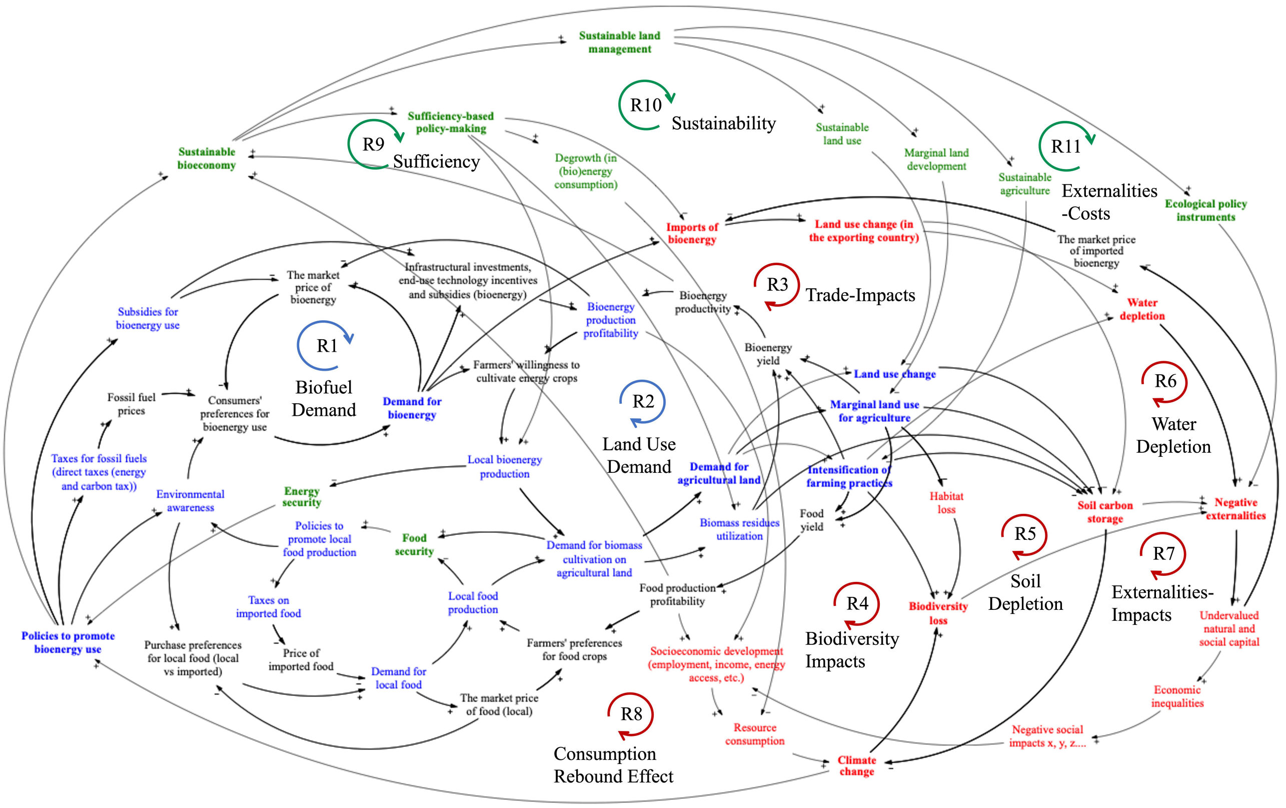

FIGURE 6
New reinforcing feedback loops R9: Sufficiency, R10: Sustainability, and R11: Externalities-Costs focusing on sustainable and just bioeconomy promoting degrowth and sustainable farming practices and internalizing socioeconomic externalities in biofuel costs (green text). These feedback loops introduce the balancing effects to reduce the negative socioeconomic and ecological impacts of biofuel development (red text) and inform the current production and consumption practices and policies (blue and black text).

are met within the local or regional ecological limits even at the expense of growth. In this new system, productivity gains (i.e., economic or material—represented by reinforcing sub-loop R1c in Figure 4) are achieved with a sustainable intensification of farming practices, marginal land uses (or under-utilized or abandoned cropland) and utilizing biomass residues but within the ecological limits of the biosphere. These ecological limits serve as the balancing mechanisms to address soil depletion, biodiversity loss, externalities costs, and consumption rebound effects (see Figure 5 representing these loops). Agricultural intensification with improved water resources management and enhanced fertilization efficiency could reduce the negative impacts of bioenergy production (Humpenöder et al., 2018). Utilizing abandoned cropland and biomass residues to enhance bioenergy production could minimize the ecological risks (Gvein et al., 2023).

Until recently, biofuel utilization in society has focused on the substitution of fossil fuels with renewable fuels with added socioeconomic and environmental benefits. This substitution has been led by growth-oriented and market-based approaches rather than sufficiency. Consequently, this resulted in a rapid expansion of biomass resources and the establishment of globalized value chains of renewable fuels. This has further caused significant environmental impacts (as described in Section 3.3) at the cost of reduced biofuel prices. Thus, in this bioeconomy, through suitable policy measures, the reliance on imports of bioresources is discouraged, operationalizing sufficiency and addressing the negative socioeconomic and ecological consequences of expanding the supply sources beyond regions. However, the emphasis is put on approaches to sustainable (bio)energy production and consumption in society. This requires a comprehensive view of bioenergy resources and their potential utilization for meeting societal needs rather than focusing on a single end-use sector or a specific (bio)fuel type. Indeed, a mix of bioenergy end-uses maximizes bioenergy life cycle emission reduction and, thus, its global climate change mitigation potential (Staples et al., 2017).

In the context of the EU Bioeconomy, Giuntoli et al. (2023) highlight how its narratives have predominantly centered around economic growth, technological innovation, and anthropocentric values and have ignored the social and justice dimensions. They have questioned society's roles, relations, and responsibilities since it has failed to produce the desired social and ecological outcomes. They call for a "*green, just, and sufficient bioeconomy*" (Giuntoli et al., 2023, p. 39) with a focus on societal transformation (i.e., values, norms, and institutions), socio-metabolic limits (i.e., sufficiency and planetary boundaries), and societal responsibility and reciprocity (i.e., justice and equity).

Since the current economic system does not account for the economic costs of socioeconomic and ecological externalities, they are often reflected as disproportionate economic gains. This drives the economic growth engine and causes negative rebound effects

TABLE 3 A summary of the main loops of a "sustainable and just" bioeconomy system.

Feedback mechanisms	New feedback loops in a sustainable and just bioeconomy
Sufficiency	*Loop Number 1 of length 4:* Sufficiency-based policy-making—Biomass residues utilization—Bioenergy yield—Bioenergy productivity—Sustainable bioeconomy
	Loop Number 2 of length 5: Sufficiency-based policy-making—Degrowth (in (bio)energy consumption)—Resource consumption—Climate Change—Policies to porote bioenergy use—Sustainable bioeconomy
	Loop Number 2 of length 9: Sufficiency-based policy-making—Biomass residues utilization—Bioenergy yield—Bioenergy productivity—Bioenergy production profitability—Farmers' willingness to cultivate energy crops—Local bioenergy production—Energy security—Policies to promote bioenergy use—Sustainable bioeconomy
Sustainability	Loop Number 1 of length 5: Sustainable land management—Sustainable agriculture—Intensification of farming practices—Bioenergy yield—Bioenergy productivity—Sustainable bioeconomy
	Loop Number 2 of length 10: Sustainable land management—Marginal land development—Marginal land use for agriculture—Bioenergy yield—Bioenergy productivity—Bioenergy production profitability—Farmers' willingness to cultivate energy crops—Local bioenergy production—Energy security—Policies to promote bioenergy use—Sustainable bioeconomy
	Loop Number 3 of length 6: Sustainable land management—Sustainable land use—Land use change—Soil carbon storage—Climate change—Policies to promote bioenergy use—Sustainable bioeconomy
Externalities-costs	*Loop Number 1 of length 9:* Ecological policy instruments—Negative externalities—Undervalued natural and social capital—Economic inequalities—Negative social impacts x, y, z....—Socioeconomic development (employment, income, energy access, etc.)—Resource consumption—Climate change—Policies to promote bioenergy use—Sustainable bioeconomy
	Loop Number 2 of length 9: Ecological policy instruments—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change—Policies to promote bioenergy use—Sustainable bioeconomy
	Loop Number 3 of length 18: Ecological policy instruments—Negative externalities—Undervalued natural and social capital—The market price of imported bioenergy—Imports of bioenergy—Land use change (in the exporting country)—Soil carbon storage—Climate change—Policies to promote bioenergy use—Environmental awareness—Consumers' preferences for bioenergy use—Demand for bioenergy—Farmers' willingness to cultivate energy crops—Local bioenergy production—Demand for biomass cultivation on agricultural land—Biomass residues utilization—Bioenergy yield—Bioenergy productivity—Sustainable bioeconomy

There are many other feedback loops, however, the loops with the highest strength are emphasized (also with minimum length).

(i.e., social, economic, and environmental, as described in Section 3). For instance, low profitability can hamper the adoption of biodiversity-based farming practices (Clough et al., 2016; Scheper et al., 2023; Thomson Ek et al., 2024). This growth engine could be countered if these externalities are fully accounted for through ecological policy instruments. This may result in higher consumer prices and slowed economic growth, but a more just bioeconomy. These ecological and socioeconomic externalities are time- and space-dependent and are often not straightforward (Brose et al., 2010), but need to be accounted for in policy making. This calls for more inclusive environmental policymaking that includes analysis of environmental effectiveness and economic efficiency for different parts of society. The current paradigm of innovation, dominated by private-sector actors and interests, is exclusive and unequal, leading to disruptive technological impacts and uneven spatial development (Schrock and Lowe, 2021). To foster equality and justice, policymakers must enable inclusive innovation (Schrock and Lowe, 2021).

Societal transitions toward a sustainable bioeconomy require coherent governance mechanisms. This must (1) identify the cause-and-effect interactions of all the primary sectors of biomass or bioenergy production (i.e., agricultural, forestry, marine, etc.) with other sectors of the economy and beyond national boundaries (Iriarte et al., 2021); (2) acknowledge and address the synergies and conflicts in interests, roles, and values be enhancing the stakeholders' collaboration and feedback (McLoughlin and Thoms, 2015); and (3) govern the societal transitions by implementing adaptive resource management based on incremental, experiential learning (McLoughlin and Thoms, 2015). The importance of governance of the bioeconomy across sectors and boundaries has increasingly been recognized. However, despite the negative social, economic, and environmental externalities of bioenergy production and consumption, such governance frameworks for the bioeconomy are absent (Lago et al., 2018; Iriarte et al., 2021).

4.2 Limitations of the study and future research opportunities

This paper presents a conceptual systemic model of key drivers of the global biofuel economy and its socioeconomic and environmental impacts. It contains several significant interactions in this system, it is, however, still incomplete like any other model. We do not consider all the beneficial effects of bioenergy use due to the substitution of fossil fuels that are key in promoting the use of biofuels and land-use intensification. Several other causal links and feedback loops could be added. For example, an increased environmental awareness in society can lead to reduced demand for both fossil fuels and biofuels and result in other environmentally conscious behaviors that can have overall positive benefits for the environment. The model also does not fully explore the positive benefits of the globalization of the biofuel economy. For instance, bioenergy could enable energy access to marginalized populations in certain regions and significantly improve the livelihood of farmers and local actors in this economy. The use of bioenergy could also increase fuel costs in some contexts that may lead to reduced energy consumption, such as in Sweden, where regulation of including a higher percentage of biofuels in diesel has increased fuel costs. Certain types of marginal or abandoned land use can have a positive impact on biodiversity and soil quality.

The causality and polarity relationships shown in the CLD are based on the dominant discourse about the issue based on literature. However, some of these causal interactions may have alternative causality and polarity. For example,

- Environmental awareness may not always alter consumers' preferences for bioenergy use or reduced energy demand.
- Reduced prices of bioenergy may cancel out the environmental benefits of using bioenergy due to over-consumption (consumption rebound effects).
- Intensified farming practices may not always lead to increased biomass yield.
- Intensive farming practices may improve the soil quality for some types of lands (e.g., abandoned land).
- An increased biomass demand may not always increase the utilization of agricultural residues
- Bioenergy production profitability may not always result in the farmers' preference for cultivating energy crops, and so on.

The purpose of the model determines its system representation and complexity level (Laurenti et al., 2016). Therefore, we have selected only the relevant variable as per the purpose of this model. This has resulted in an abstract representation of some of the interactions between the natural and social systems (e.g., social externalities). While it was also difficult to represent all of them in a meaningful and reliable way, we intended to represent macroeconomic effects with larger system boundaries. Further, some simplifications are done by representing the behavior of the studied system rather than the detailed interactions between the system variables. Furthermore, there may be "unknown unknowns" that are not captured by the bounded rationality of the authors.

Local, regional, and global interactions are linked not only through the biogeological cycles of carbon, nitrogen, and oxygen but also through imports and exports of resources [see, e.g., the umbrella concept of telecoupling (Liu et al., 2013) that refers to environmental and socioeconomic interaction in today's globalized world]. CLDs have represented these complex and complicated interactions more simply to keep a broad view of the system.

Huge gaps in wealth and wellbeing exist in high-income and medium/low-income countries, as well as rich and poor in these countries. Thus, the benefits of global growth are distributed unevenly, creating significant economic inequalities. Several negative social impacts are associated with economic inequalities, such as adverse effects on social cohesion, physical and mental health, life satisfaction, social trust, wellbeing, and malnutrition. The far-and-wide impacts of these externalities on society are way too complicated and complex to be meaningfully represented in a CLD. Therefore, we have chosen to represent them abstractly (R7 Externalities—Impacts).

To meet the broad objectives of this research, a purposive choice was made to be general, qualitative, and interdisciplinary. This choice led to a few trade-offs, such as a limited analysis of identified issues rather than their in-depth analysis. We may have overlooked specific ecological and socioeconomic consequences regarded as important in an expert field. Further, we have not based our findings on a detailed quantitative or qualitative analysis. CLDs are often developed as a first step to fully understanding a complex problem and exploring potential solution strategies. An in-depth quantitative analysis of the various causal interactions described above can further reveal their relative strength, feedback loops, and dynamics over time.

The developed model of the global bioenergy economy can be used to assess the policy packages at different levels (regional, national, or international). The model can be used to understand critical linkages between the planned policy instruments and their potential negative socioeconomic and ecological consequences. Understanding these linkages can help policymakers identify strategies to proactively address these consequences. The new feedback loops identified in a sustainable and just bioeconomy can guide the development of appropriate economic instruments, institutional structures and governance mechanisms.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans because this study does not collect, store, or generate any sensitive data about the interviewed experts for which ethical approval was needed. A verbal consent was obtained from all of the experts' before the start of the interview process. They were also informed about the purpose of the research and the anonymity of their views. No direct quotations are made from the experts' shared information in the manuscript. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. YC: Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsuep.2024.1460370/full#supplementary-material

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