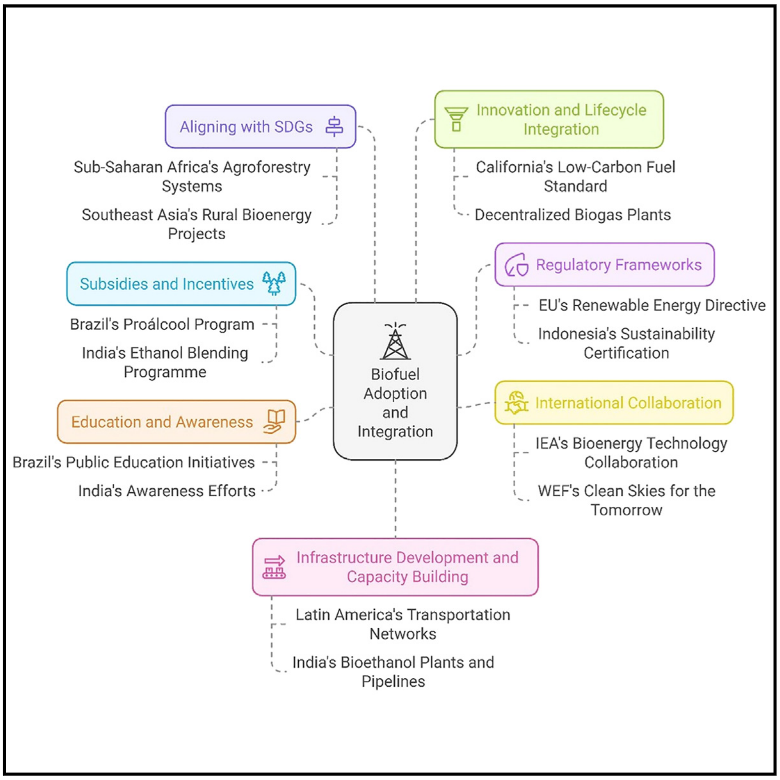
iScience

Article

Analyzing the contributions of biofuels, biomass, and bioenergy to sustainable development goals

Graphical abstract



Highlights

- Examines advancements from first-gen to fourth-gen biofuel technologies
- Highlights two key themes: sustainable energy (SDG7), climate resilience (SDG13)
- Emphasizes systemic innovation in bioeconomy, supporting SDGs 8, 9, and 12
- AI and data science enhance biofuel supply chain efficiency and sustainability

Authors

Raghu Raman, Aswathy Sreenivasan, Naveen V. Kulkarni, M. Suresh, Prema Nedungadi

Correspondence

raghu@amrita.edu

In brief

Biofuel; Biomass; Energy sustainability

Raman et al., 2025, iScience *28*, 112157
April 18, 2025
https://doi.org/10.1016/j.isci.2025.112157

CellPress

iScience

CellPress
OPEN ACCESS

Article

Analyzing the contributions of biofuels, biomass, and bioenergy to sustainable development goals

Raghu Raman,[1,6,*] Aswathy Sreenivasan,[2] Naveen V. Kulkarni,[3] M. Suresh,[4] and Prema Nedungadi[5]
[1]Amrita School of Business, Amrita Vishwa Vidyapeetham, Amritapuri, Kerala 690525, India
[2]Department of Professional Management Studies, Kristu Jayanti College, Bengaluru, Karnataka 560077, India
[3]Amrita School of Physical sciences, Amrita Vishwa Vidyapeetham, Amritapuri, Kerala 690525, India
[4]Amrita School of Business, Amrita Vishwa Vidyapeetham, Coimbatore, Tamil Nadu 641112, India
[5]Amrita School of Computing, Amrita Vishwa Vidyapeetham, Amritapuri, Kerala 690525, India
[6]Lead contact
*Correspondence: raghu@amrita.edu
https://doi.org/10.1016/j.isci.2025.112157

SUMMARY

Biofuels, biomass, and bioenergy are pivotal in transitioning to sustainable energy systems while addressing global energy demands and supporting the UN sustainable development goals (SDGs). This study synthesizes research on biofuels, from first-to fourth-generation technologies, highlighting their potential to reduce greenhouse gas emissions, enhance energy security, and foster economic growth. Using the PRISMA framework, machine learning-based SDG mapping and BERTopic modeling, the analysis identifies two thematic clusters: one focused on sustainable energy and climate resilience (SDGs 7, 12, and 13) and the other on socioeconomic development and equity (SDGs 1, 8, and 15). Topics such as bioeconomic development and supply chain optimization emphasize systemic innovation and process efficiency. The study underscores the role of policy, international collaboration, and emerging technologies like AI in advancing biofuel systems. Investments in infrastructure and capacity building are vital to aligning bioenergy development with global sustainability goals.

INTRODUCTION

Energy is pivotal to the economic growth and overall development of any nation or region.[1–3] In 2019, the U.S. Energy Information Administration (EIA) projected a nearly 50% increase in global energy consumption by 2050, which was driven primarily by regions anticipating significant economic growth, especially in Asia.[4] Currently, approximately 80% of global energy needs are met by fossil fuels—coal, oil, and natural gas.[5–9] The established technologies and economic benefits associated with fossil fuel extraction have led to their extensive exploitation.[10–12] In response to the increasing global energy demand and the imperative transition away from fossil fuels, the exploration of alternative energy sources has become increasingly critical. Renewable energy sources, including solar, hydro, bioenergy, and geothermal energy—have experienced substantial growth in production and utilization to sustainably meet these energy needs.[13,14] However, achieving complete sustainability remains a significant challenge. According to EIA projections, at the current growth rate, renewable energy sources are expected to account for only approximately 28% of the global primary energy demand by 2050, closely matching the contribution from liquid fossil fuels.[4]

On the other hand, increasing environmental concerns over the uncontrolled use of fossil fuels are also a matter of global concern.[15,16] EIA has estimated that carbon dioxide emissions will increase by approximately 34% by 2050 due to the consumption of fossil fuel-based materials, indicating a serious threat to the environment.[17] Renewable energy technologies are sustainable, and the optimal utilization of these resources could help mitigate the energy crisis and control the negative environmental impacts of fossil fuels. Furthermore, owing to the vast availability of these resources in all parts of the world, local production, and energy processing are possible, which will lead to overall social and economic growth.[3]

In this context, biofuels and bioenergy have emerged as vital components in the global energy transition, supporting climate and sustainable development goals (SDGs).[18–20] Among the various renewable energy sources, biofuels are among the best alternatives to fossil fuels, especially the liquid fuels used mainly in the transportation sector.[21,22] The ease of production and storage, high energy density, and compatibility with fossil fuel engine systems are the main advantages of biofuels that aid in their progress.[21] Sustainable bioenergy plays a crucial role in global energy transitions, supporting both climate and SDGs.[23] Through effective governance, bioenergy—as part of the broader bioeconomy—can address

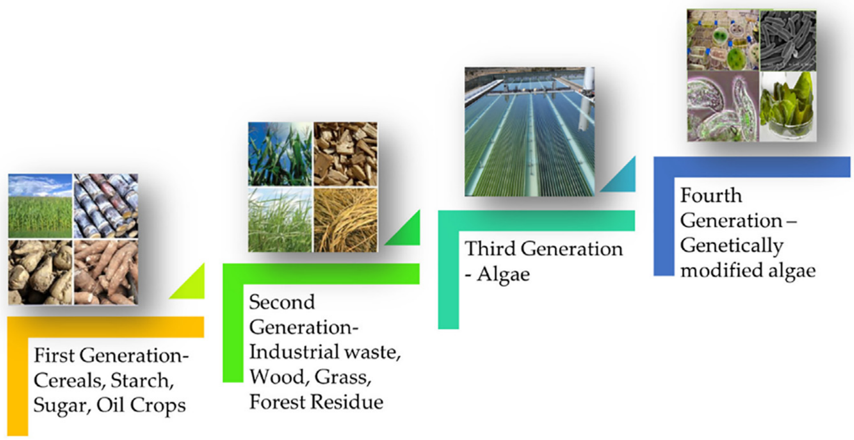


Figure 1. Generation of biofuels[22]

risks related to land and resource use, food security, natural ecosystems, and carbon stocks while promoting equity, justice, and economic competitiveness. The global biofuel demand is projected to increase by 41 billion liters or 28%, between 2021 and 2026, reaching approximately 186 billion liters by 2026.[24,25] The launch of the Global Biofuels Alliance (GBA) on September 9, 2023, during the G20 Summit in New Delhi, marked a significant step toward promoting the adoption of biofuels.[26] This India-led initiative aims to develop an alliance of governments, international organizations, and industry stakeholders to facilitate the adoption of biofuels through international cooperation. The GBA aspires to position biofuels as a key element in the energy transition, contributing to job creation and economic growth.

In recent years, there has been increased interest in analyzing the impact of biofuels and bioenergy on sustainable development[27,28]; however, there is a discernible gap in multidimensional analyses focusing specifically on the nexus of biomass, biofuels, and bioenergy with the United Nations SDGs.[29] Sustainable development encompasses a multidimensional concept that balances environmental, economic, and social goals to meet the needs of the present without compromising the ability of future generations to meet their own needs.[30] While the use of renewable energy sources plays a significant role in reducing greenhouse gas emissions and fostering resource efficiency, achieving sustainability extends beyond energy transitions. It includes promoting equitable economic growth, preserving biodiversity, ensuring social inclusion, and fostering resilient ecosystems. Renewable energy contributes to sustainability by supporting cleaner energy systems and reducing environmental degradation, but its integration must align with broader strategies addressing social equity, sustainable consumption, and responsible resource management across all sectors.[31] The decision to center our study using the SDGs stems from their globally recognized status and the urgent need to accelerate their progress,[32] reinforcing the SDGs' relevance as a unifying framework that fosters cross-sector dialogue and actionable strategies. By aligning our research with the SDGs, we aim to address these pressing challenges more directly and contribute meaningfully to international efforts that seek tangible, equitable, and sustainable outcomes.

Typically, biofuels are categorized into four types on the basis of their physicochemical properties, i.e., biogas, bioethanol, biobutanol, and biodiesel. Biofuels are produced by the fermentation of biomass products and hence offer a net zero carbon footprint.[33,34] The first-generation (1G) production of biofuels mainly involves the use of edible biomass, such as sugar, starch, and vegetable oil, as feedstock (Figure 1). The products obtained are highly efficient, but scaling up impends food security and biodiversity. Second-generation (2G) biofuels are produced from nonfood energy crops and biomass waste. This dodges the direct conflict of food vs. fuel issues; however, its negative impact on biodiversity and indirect influence on the food chain remains the same. Third-generation (3G) biofuels utilize algae and cyanobacteria biomass as feedstocks, whereas fourth-generation (4G) biofuels utilize genetically modified microorganisms to obtain higher hydrogen-to-carbon yields to minimize carbon emissions. Microalgae and bacteria have relatively high biomass growth rates, do not require arable land, and can utilize waste/saltwater. The production of biofuels via this route is cost-effective and avoids competition with typical agricultural activities.[21,22,35]

It is evident that after the evolution of second-, third- and fourth-generation biofuels, they have successfully overcome most of their limitations, such as the food vs. fuel debate and limited land and water resources, and have emerged as efficient and sustainable substitutes for fossil fuels.[21,22] Recent technological developments in the production and storage of biofuels have greatly accelerated the growth of the biofuel sector. Innovative mechanical, thermochemical, and biochemical conversion routes are being successfully used for the efficient production of biofuels as well as their further valorization. Additionally, advancements in synthetic biology, which have enabled the engineering of biomass sources with high energy efficiency, have contributed significantly to the advancement of biofuels.[36] On the other hand, the use of cutting-edge technology in the storage and transportation of biofuels has also benefited the biofuel sector. For example, the use of internet of things (IoT)-based sensors for the quality monitoring of biofuels has significantly aided in the efficient storage and transportation of biofuels.[37] Interestingly, government policies designed to reduce greenhouse gas (GHG) emissions in developed countries are found to increase the demand for biofuels further. In developing countries, the reduction in fossil fuel imports and the development of local economies also play important roles in the increased production and usage of biofuels, along with increased environmental concerns.[24]

The literature review covers a broad range of studies on biofuel, biomass, and bioenergy (Table 1). A study by Roth et al. (2020)[38] evaluated microbial cellulase production and biomass

Table 1. Review articles related to bioenergy, biofuels, and biomass

Author	Goals	Findings	Focus area	Coverage years
Roth et al. (2020)[38]	Evaluate microbial cellulase production for biofuels using lignocellulosic biomass.	Enzyme activity optimization is critical for improving biofuel production from residual biomass, especially in cellulase yield.	Microbial cellulase production, fermentation processes, lignocellulosic feedstocks.	2007 to 2017
Yang et al. (2021)[39]	Investigate the development and trends in hydrothermal liquefaction (HTL) for biomass conversion to bio-oil.	Advancements in HTL technology, particularly in feedstock flexibility and bio-oil yield efficiency, are needed.	Hydrothermal liquefaction (HTL) of biomass, bio-oil production.	1992 to 2018
Zhang et al. (2021)[40]	Analyze national research efforts on bioenergy under climate change.	Climate change influences bioenergy research priorities, with renewable energy integration being a common focus.	National bioenergy research, climate change impact, bibliometric analysis.	1999 to 2018
Papilo et al. (2022)[41]	Investigate palm oil-based bioenergy sustainability and policy in Indonesia and Malaysia.	Policy misalignment between sustainability goals and economic incentives is a significant barrier to effective palm oil bioenergy strategies.	Palm oil bioenergy, sustainability, policy review.	2000 to 2019
Wang et al. (2022)[42]	Provide a scientometric review of biomass gasification research.	Geographic disparities in biomass gasification research, with Asia and North America leading in publication and innovation.	Biomass gasification, regional research distribution, scientometric analysis.	2006 to 2020
Yuan et al. (2022)[43]	Analyze global bioenergy research trends and international collaborations from 2000 to 2020.	Developed countries dominate bioenergy research, with the USA, China, and Germany leading global output.	Global bioenergy growth, sustainability practices, international collaboration.	2000 to 2020
Hasan et al. (2023)[44]	Map the global biofuel economy, identifying key research trends and international collaborations.	Collaborations are growing, but disparities remain between developed and developing regions in research output and resources.	Global scientific production, international collaboration in biofuel research.	2001 to 2022
Habibi et al. (2023)[45]	Systematically review supply chain uncertainties and risks in biofuel networks.	Key risks identified in biofuel supply chains include disruptions from geopolitical and environmental factors.	Bioenergy supply chain resilience, risk management, uncertainty in supply networks.	Studies up to 2022.
Jahanshahi et al. (2023)[46]	Explore technological advancements and cost reduction in second-generation biofuels.	Cost-effective enzyme processes and feedstock versatility are essential for scaling second-generation biofuels.	Second-generation biofuels, lignocellulosic materials, production optimization.	2005 to 2019
Li & Xu (2023)[47]	Map cooperation and citation networks in bioenergy with carbon capture and storage (BECCS).	Cooperation gaps exist in BECCS research, with most collaborations concentrated in a few developed-country institutions.	Biomass conversion technologies, BECCS, coauthorship, and citation analysis.	1996 to 2020

CellPress
OPEN ACCESS

fermentation, identifying enzyme activity optimization as critical for improving biofuel production from lignocellulosic biomass. Research on hydrothermal liquefaction (HTL) has identified the need for advancements in feedstock flexibility and bio-oil yield efficiency in HTL technology.[39] Zhang et al. (2021)[40] analyzed national research efforts from the USA, the UK, Germany, China, India, and Brazil on bioenergy under climate change and reported that renewable energy integration is a common priority across various countries. Another study on palm oil-based bioenergy sustainability in Southeast Asia identified policy misalignment as a significant barrier to effective bioenergy strategies.[41] A scientometric review of biomass gasification research from 2006 to 2020 revealed geographic disparities, with Asia and North America leading in publications and innovation.[42] A study from 2022 highlighted global bioenergy growth and emphasized the dominance of developed countries, with the USA, China, and Germany leading in research output.[43] Additionally, a study mapping the global biofuel economy revealed not only growing collaborations but also significant disparities between developed and developing regions in terms of research output and resources.[44] A review of biofuel supply chain networks identified key risks, such as disruptions from geopolitical and environmental factors.[45] Research on second-generation biofuels highlights the necessity of cost-effective enzyme processes and versatile feedstocks for scaling biofuel production.[46] Studies on bioenergy and carbon capture and storage (BECCS) identify cooperation gaps, with most collaborations concentrated in a few institutions in developed countries.[47]

Studies that have examined biofuels in the context of sustainable development have focused primarily on individuals or a limited set of goals, neglecting the full spectrum of the 17 SDGs and other international guidelines, such as the G20 High-Level Principles.[29,48,49] Additionally, although there is increasing interest in biofuel research worldwide, comparative analyses between countries, particularly between major biofuel producers and consumers such as the United States and nations from the Global South, are scarce. Such comparative evaluations are critical for contextualizing the contributions and for identifying collaborative opportunities. Moreover, systematic analyses assessing the nature, impact, and extent of industry-academia collaboration, government initiatives, and government-private sector collaboration are limited. This work largely compartmentalizes different aspects related to bioenergy, such as scientific research, industry collaboration, and social science contributions, and aligns them with the SDGs. There is little evidence from integrated studies that cohesively map these dimensions. Furthermore, data for development (D4D) methodologies have yet to be extensively employed in this sector for more robust data aggregation and analysis, thereby missing potential insights.

Our study fills existing gaps by using a multidimensional search method to capture a broader dataset, providing a comprehensive analysis of the evolution of the biofuel sector and its alignment with the SDGs. This is the first study to map biofuel initiatives and advancements directly against the 17 SDGs, assessing their alignment with global sustainability goals.

In examining the field of biofuel, biomass, and bioenergy research that contributes to SDGs, we pose the following research questions to understand its scope and impact.

(1) RQ1: What thematic areas are mapped to the SDGs that capture the field's evolution?
(2) RQ2: Which emerging topics are poised to influence the field's trajectory significantly?

Different methodologies are utilized for RQ1 and RQ2. For RQ1, thematic analysis through cocitations is applied, providing major themes mapped to the SDGs. For RQ2, bidirectional encoder representations from transformers (BERT) topic modeling are employed, offering a detailed perspective by revealing specific, emerging discussions and their complex interconnections.

This study makes the following important contributions to the fields of biofuel, biomass and bioenergy, and sustainable development. First, it introduces a pioneering approach in which the SDG framework is used to map research publications to the SDGs explicitly. Second, it applies the scientometric technique of cocitation to map the research topic to a network of SDGs. Finally, machine learning-based BERTopic modeling is applied to the big data of 11,439 publications to explore major topics and future research directions.

RESULTS

Research focused on biofuels, biomass, and bioenergy in the context of the SDGs reveals various priorities, as shown in Table 2. SDG 7 (affordable and clean energy) leads the research, featuring 63.4% of the papers, underscoring the centrality of bioenergy in transitioning to renewable energy systems. SDG 13 (climate action) followed at 35.7%, reflecting the role of biofuels and biomass in mitigating greenhouse gas emissions. SDG 12 (responsible consumption and production) appears in 30.7% of the studies, highlighting the importance of sustainable resource use and waste reduction. SDG 9 (industry, innovation, and infrastructure) and SDG 15 (life on land) are present in 24.8% and 24.0% of the research, emphasizing industrial innovation for bioenergy systems and sustainable land management. Moderately explored areas include SDG 8 (decent work and economic growth) at 16.7% and SDG 2 (zero hunger) at 14.2%, indicating interest in the socioeconomic impacts of bioenergy. However, goals such as SDG 10 (reduced inequality) and SDG 3 (good health and well-being), which appear in less than 2% of the papers, highlight a relative lack of focus on equity and social dimensions within the bioenergy context. This distribution reflects a strong emphasis on energy transitions and climate resilience, with gaps in the exploration of the broader social impacts of bioenergy. This gap indicates the need for a broader exploration of the social and developmental aspects of bioenergy, including its role in uplifting marginalized communities and addressing inequality.

SDG thematic clusters (RQ1)

The cocitation network map visually captures how research on "biofuels, biomass, and bioenergy" aligns with various SDGs. By mapping the interconnectedness of these goals, two primary clusters emerge, each reflecting thematic connections between the SDGs and the topic of sustainable bioenergy (Figure 2).

Table 2. Mapping biofuel, biomass, and bioenergy research to SDGs

Research	SDG Name	No. of Papers	%Papers
Highly researched SDGs	SDG 7 (Affordable and Clean Energy)	7253	63.4%
	SDG 13 (Climate Action)	4085	35.7%
	SDG 12 (Responsible Consumption and Production)	3509	30.7%
	SDG 9 (Industry, Innovation and Infrastructure)	2842	24.8%
	SDG 15 (Life on Land)	2749	24.0%
Moderately researched SDGs	SDG 8 (Decent Work and Economic Growth)	1913	16.7%
	SDG 2 (Zero Hunger)	1624	14.2%
	SDG 11 (Sustainable Cities and Communities)	583	5.1%
	SDG 6 (Clean Water and Sanitation)	496	4.3%
Less researched SDGs	SDG 10 (Reduced Inequality)	207	1.8%
	SDG 3 (Good Health and Well-Being)	175	1.5%
	SDG 14 (Life Below Water)	173	1.5%
	SDG 4 (Quality Education)	112	1.0%
	SDG 16 (Peace, Justice and Strong Institutions)	100	0.9%
	SDG 1 (No Poverty)	90	0.8%
	SDG 5 (Gender Equality)	40	0.3%

Cluster 1: Sustainable energy and climate resilience

The first cluster, dominated by green rectangles, places SDG 7 (affordable and clean energy) at the forefront, highlighting the central role of biofuels as renewable energy sources. As nations pivot toward cleaner energy alternatives, biofuels and biomass have become key players in meeting energy demands sustainably. The central position of SDG 7 underscores its pivotal role in this research area. Several closely related goals surrounding SDG 7.

(1) SDG 12 (responsible consumption and production): sustainable production practices in the biofuel industry emphasize responsible resource management, aligning closely with SDG 12. The efficient use of agricultural residues and waste biomass for energy production minimizes environmental impacts, directly supporting responsible consumption and production.
(2) SDG 13 (climate action): biofuels and biomass contribute significantly to reducing greenhouse gas emissions, making SDG 13 a natural partner. The link between SDG 7 and SDG 13 is strong because of their shared objective of promoting climate-friendly energy solutions.
(3) SDG 9 (industry, innovation, and infrastructure): innovation in bioenergy production technologies and infrastructure development is crucial for scaling up renewable energy. Thus, SDG 9 is closely tied to SDG 7, emphasizing the importance of industry and infrastructure in achieving clean energy goals.
(4) SDG 6 (clean water and sanitation): sustainable biofuel production requires careful water management. The relationship between SDG 7 and SDG 6 underscores the importance of protecting water resources in biofuel cultivation.
(5) SDG 3 (good health and well-being): transitioning to clean energy reduces air pollution and improves public health, establishing a link between SDG 7 and SDG 3.
(6) SDG 11 (sustainable cities and communities): urban areas seeking to reduce their carbon footprint are increasingly integrating bioenergy into their sustainable energy plans, connecting SDG 7 with SDG 11.

This cluster reflects a cohesive narrative around sustainable energy and climate resilience, with biofuels playing a central role. The strong connections between SDG 7 and SDG 12, between SDG 7 and SDG 13, and between SDG 12 and SDG 13 emphasize the tight integration of clean energy, responsible production, and climate action.

Cluster 2: Socioeconomic development and equity

The second cluster, marked by blue rectangles, revolves around SDG 8 (decent work and economic growth) and SDG 15 (life on land). This cluster reveals a broader narrative about the socioeconomic impact of biofuels, biomass, and bioenergy.

(1) SDG 8 (decent work and economic growth): the biofuel industry creates new economic opportunities and jobs, particularly in rural areas. The emphasis on economic growth through sustainable energy solutions links SDG 8 with the bioenergy sector.
(2) SDG 15 (life on land): sustainable land management is crucial for biofuel production. SDG 15 is closely tied to SDG 8 because of the shared goal of promoting sustainable agriculture and protecting ecosystems.
(3) SDG 1 (no poverty): by creating jobs and supporting rural economies, the biofuel industry contributes to poverty reduction, establishing a link between SDG 8 and SDG 1.
(4) SDG 2 (zero hunger): sustainable biofuel cultivation must balance energy production with food security. This delicate balance connects SDG 2 with SDG 8 and SDG 15.
(5) SDG 4 (quality education): workforce development and education are critical for building capacity in the

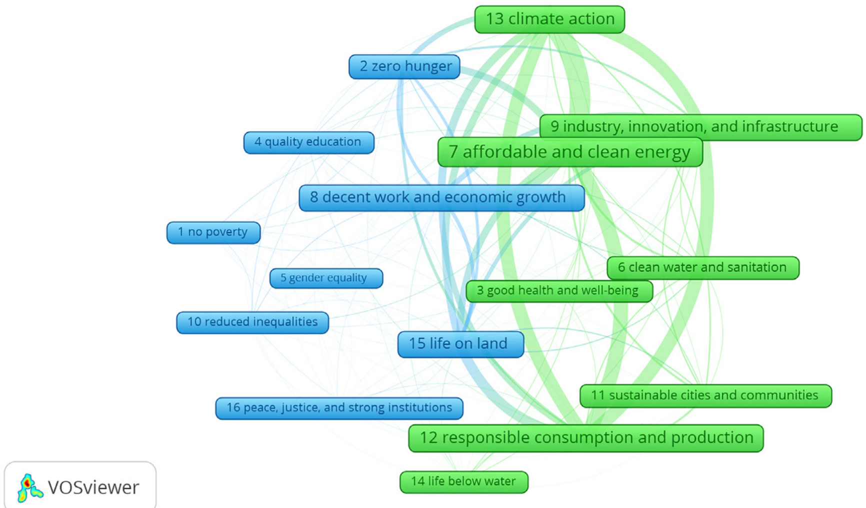


Figure 2. SDG network based on cocitations

bioenergy sector. SDG 4 aligns with SDG 8, as education empowers individuals to participate in this growing industry.

(6) SDG 5 (gender equality): inclusion and gender equality in the workforce are essential for equitable development, connecting SDG 5 to SDG 8.
(7) SDG 10 (reduced inequalities): the potential of the biofuel industry to uplift marginalized communities links SDG 10 with SDG 8.
(8) SDG 16 (peace, justice, and strong institutions): stable institutions and transparent governance are crucial for sustainable biofuel policies, connecting SDG 16 to SDG 8.

This second cluster reveals the broader socioeconomic impact of biofuels and biomass, highlighting their potential to drive inclusive economic growth while ensuring sustainable land use. In particular, the strong linkages between SDG 7 (energy) and SDG 12 (consumption), between SDG 7 (energy) and SDG 13 (climate), and between SDG 12 (consumption) and SDG 13 (climate) highlight the crucial role that biofuels and biomass play in the global sustainability agenda. Their impact on energy, climate, and responsible consumption makes them key players in advancing sustainable development across multiple domains.

Major topics (RQ2)

The BERTopic modeling identified six key topics each contributing to SDGs in unique ways (Figure 3). The most prominent theme, sustainable bioeconomic development (28%), reflects the focus on integrating ecological sustainability with economic growth through innovation and systemic changes. Biofuel and biomass sustainability (22%) emerges as a critical area, emphasizing optimized processes and supply chains to reduce environmental impacts. Biomass and bioenergy production (17%) highlights advancements in technologies to enhance energy yield while minimizing resource conflicts, closely tied to industrial scalability. Bioeconomy and biorefineries (15%) underscore the role of circular economy principles in leveraging biomass for diversified biobased products. Sector-specific innovations in aviation biofuels (10%) address the unique challenges of reducing emissions in aviation. Lastly, renewable bioenergy sources (8%) emphasize the geographic and infrastructural considerations essential for implementing decentralized and location-specific bioenergy systems. Together, these themes illustrate a multidimensional approach to advancing sustainable energy transitions.

Table 3 displays the extracted topic names, the top key terms (based on likelihood) that represent each topic, a brief description of the topic, and representative articles that reflect the topic with their SDG focus.

Sustainable bioeconomic development

The goal of sustainable bioeconomic development—which combines ecological and economic aspects for long-term viability—is the focus of this investigation and aligns with SDG 8, SDG 9, and SDG 12.

The critical role that a developed European bioeconomy plays in guiding the continent toward sustainable development is highlighted by De Besi and McCormick (2015).[50] Their meta-analytical analysis identifies key strategies, including technological innovation, regional collaboration, and the expansion of biobased product markets. A critical takeaway is the necessity of adopting a life cycle perspective to ensure the sustainability of biomass-based economies. This approach, which encourages efficient resource use and waste minimization, supports SDG 12.5, which emphasizes substantially reducing waste generation through prevention, reduction, and recycling. Additionally, fostering innovation and infrastructure development aligns with SDG 9.4, which advocates for the retrofitting and upgrading of industries to make them sustainable, with increased resource use efficiency and clean technologies. By integrating these principles, the bioeconomy contributes to fostering resilient societies equipped to address future challenges. Furthermore, the economic and employment opportunities arising from bioeconomic advancements resonate with SDG 8.2, which promotes the achievement of higher levels of economic productivity through diversification, technological upgrading, and innovation.

Focusing on the European Union's (EU) economic plan, a conceptual and analytical framework was proposed to measure and evaluate its progress.[51] The framework highlights the interconnections among biobased, green, and circular economies, defining their scope, geographic dimensions, and critical performance metrics for effective monitoring. By centering on biobased industries, the suggested indicators align with the

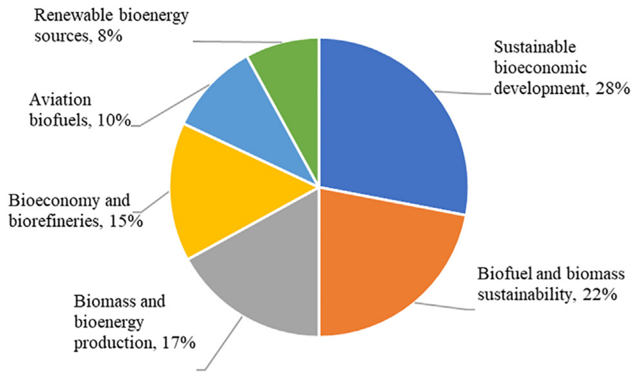


Figure 3. Major topics identified with their proportions

objectives of the EU bioeconomy strategy, particularly in promoting the sustainable management and efficient use of natural resources, which resonates with SDG 12.2. Furthermore, the framework's emphasis on integrating sustainability metrics into economic oversight supports SDG 9.4, which advocates for sustainable industrialization and upgrading industries to improve resource efficiency and environmental performance. These efforts collectively provide a structured approach to advancing sustainability in the EU's economic policies.

The German Federal Government's commitment to advancing the bioeconomy is encapsulated in its "National Research Strategy BioEconomy 2030".[52] This strategy positions the bioeconomy as a transformative concept with the potential to fundamentally reshape business paradigms akin to the impact of digitalization. The paper highlights that the success of the bioeconomy hinges on fostering dialogue within society to balance sustainability with economic growth, necessitating continuous collaboration at both the national and international levels. By emphasizing research and innovation policies, the strategy aligns with SDG 9.5, which focuses on enhancing scientific research and upgrading the technological capabilities of industrial sectors. Moreover, its promotion of sustainable industrialization resonates with SDG 9.2, which advocates for inclusive and sustainable industrial development to foster economic growth and productivity. The article also underscores the importance of inclusive and sustained economic expansion, aligning with SDG 8.4, which aims to decouple economic growth from environmental degradation through improved resource efficiency in consumption and production. The emphasis on societal dialogue to navigate sustainability challenges supports SDG 12.8, which encourages ensuring that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature. Through these interconnected efforts, the bioeconomic strategy meaningfully contributes to advancing a cohesive and sustainable development agenda.

Biofuel and biomass sustainability

This study investigated biomass production and sustainable biofuels, paying particular attention to biodiesel and its environmental effects. This particular theme focuses mainly on SDG 2, SDG 7, SDG 8, SDG 9, SDG 12, and SDG 13.

A deterministic multiobjective linear programming model by Orjuela-Castro et al. (2019)[53] analyzed Colombia's biodiesel supply chain, examining trade-offs between costs, greenhouse gas emissions, and food security across four levels. This study highlighted the potential of crop substitution with palm to enhance both environmental and economic outcomes. This approach fosters sustainable agricultural practices that improve food availability, aligning with SDG 2.4, which emphasizes resilient agricultural systems for food security and sustainable production. By prioritizing clean and renewable energy in the biodiesel supply chain, the model advances SDG 7.2, which promotes a substantial increase in the share of renewable energy in the global energy mix. Furthermore, the emphasis on reducing greenhouse gas emissions contributed to SDG 13.2, integrating climate change measures into strategies to mitigate environmental impacts. The model also aligns with SDG 12.2, focusing on the sustainable management and efficient use of natural resources and ensuring that the biodiesel supply chain adheres to sustainable consumption and production patterns.

Umar et al. (2023)[54] presented a multiobjective decision-support approach for the sustainable production and supply of third-generation biodiesel, leveraging a nonlinear optimization framework involving biomass producers, biorefineries, and retailers. By diversifying the energy mix with sustainable biofuels, this study aligns with SDG 7.2, promoting an increased share of renewable energy globally. Its focus on green job creation and economic growth in the bioenergy sector supports SDG 8.2, emphasizing higher economic productivity through technological innovation. The emphasis on infrastructure development and innovation fits within SDG 9.4, which advocates upgrading industries with sustainable and resource-efficient technologies. Additionally, the model addresses the need for efficient resource utilization and waste reduction in biodiesel production, aligning with SDG 12.5, which seeks to reduce waste generation through recycling and reuse substantially. The study's contributions to greenhouse gas emission reduction and renewable energy development support SDG 13.2, which integrates climate action into policies and planning, highlighting the essential role of biofuels in mitigating climate change. Through these interconnected elements, the research advances a sustainable framework for the bioeconomy.

A supply chain network's life cycle is optimized economically and environmentally, taking uncertainty into account when making design and operational decisions.[55] This research underscores the three pillars of sustainability—economic, environmental, and social—in biomass and biofuel production by integrating supply chain management, optimization techniques, and sustainable practices. By enhancing the efficiency and environmental performance of biofuel production, this study aligns with SDG 7.2, fostering an increased share of sustainable energy in the global mix. Its emphasis on advanced optimization techniques and robust supply chain infrastructure supports SDG 9.4, which advocates retrofitting industries with resource-efficient and environmentally sound technologies. Furthermore, by prioritizing environmentally friendly production methods and reducing the supply chain's ecological footprint, this study contributes to SDG 12.5, which seeks to minimize

Table 3. Extracted topic labels, the top ten key terms that represent each topic

Topic name	Key terms	Brief description of the topic	Representative articles	SDG focus of the topic
Sustainable bioeconomic development	(“bioeconomy”), (“bioeconomic”), (“sustainable”), (“sustainability”), (“biotechnology”), (“economy”), (“ecological”), (“strategy”), (“forest”), (“agriculture”)	Emphasizes the development of a sustainable bioeconomy, integrating ecological and economic perspectives for long-term sustainability.	De Besi and McCormick (2015),[50] Kardung and Drabik (2021),[51] Schütte (2018)[52]	SDG 8 (Decent Work and Economic Growth) SDG 9 (Industry, Innovation and Infrastructure) SDG 12 (Responsible Consumption and Production)
Biofuel and biomass sustainability	(“biofuel”), (“biodiesel”), (“biomass”), (“sustainable”), (“sustainability”), (“supply”), (“optimization”), (“Pareto”), (“logistics”), (“solutions”)	Concentrates on sustainable biofuel and biomass production approaches, focusing on biodiesel and its ecological impacts.	Orjuela-Castro et al. (2019),[53] Umar et al. (2023),[54] Gao and You (2017)[55]	SDG 2 (Zero Hunger) SDG 7 (Affordable and Clean Energy) SDG 8 (Decent Work and Economic Growth) SDG 9 (Industry, Innovation and Infrastructure) SDG 12 (Responsible Consumption and Production)
Biomass and bioenergy production	(“biomass”), (“bioenergy”), (“pellets”), (“biofuel”), (“pellet”), (“wood”), (“sustainable”), (“renewable”), (“sustainability”), (“emissions”)	Explores biomass and bioenergy production, mainly focusing on biofuels and pelletization processes for sustainable energy.	Quinteiro et al. (2020),[56] Hansson et al. (2015),[57] Buchholz et al. (2017)[58]	SDG 7 (Affordable and Clean Energy) SDG 9 (Industry, Innovation and Infrastructure) SDG 12 (Responsible Consumption and Production) SDG 13 (Climate Action) SDG 15 (Life on Land)
Bioeconomy and biorefineries	(“bioeconomy”), (“biorefineries”), (“sustainable”), (“sustainability”), (“biomass”), (“circularity”), (“bioresources”), (“recycle”), (“circular”), (“environmental”)	This theme covers the intersection of bioeconomy with biorefineries, emphasizing sustainability in using and recycling bioresources.	Stegmann et al. (2020),[59] Duque-Acevedo et al. (2022),[60] Tan and Lamers (2021)[61]	SDG 7 (Affordable and Clean Energy) SDG 9 (Industry, Innovation and Infrastructure) SDG 12 (Responsible Consumption and Production)
Aviation biofuels	(“biofuel”), (“biofuels”), (“aviation”), (“fuels”), (“fuel”), (“aircraft”), (“biomass”), (“biojet”), (“sustainable”), (“emissions”)	Centers on the development and use of biofuels in aviation, highlighting sustainable fuel alternatives for aircraft.	Batten et al. (2023),[62] Shahriar and Khanal (2022),[63] Detsios et al. (2023)[64]	SDG 7 (Affordable and Clean Energy) SDG 8 (Decent Work and Economic Growth) SDG 9 (Industry, Innovation and Infrastructure) SDG 12 (Responsible Consumption and Production) SDG 13 (Climate Action)
Renewable bioenergy sources	(“biomass”), (“bioenergy”), (“biogas”), (“renewable”), (“geographic”), (“geographical”), (“environmental”), (“sustainable”), (“spatial”), (“agricultural”)	Examines the role of biomass in renewable bioenergy production, mainly focusing on biogas and its environmental impact.	Jayarathna et al. (2020),[65] Jeong (2018),[66] Laasasenaho et al. (2019)[67]	SDG 2 (Zero Hunger) SDG 7 (Affordable and Clean Energy) SDG 9 (Industry, Innovation and Infrastructure) SDG 11 (Sustainable Cities and Communities) SDG 13 (Climate Action)

waste generation through sustainable practices. The life cycle approach also aligns with SDG 12.2, promoting sustainable management and efficient use of natural resources throughout the biofuel production process. Overall, this research advances a holistic framework for sustainable biofuel supply chain management, emphasizing long-term ecological and economic resilience.

Biomass and bioenergy production

With a focus on biofuels and the pelletization processes that support sustainable energy practices, several studies have examined the changing landscape of biomass and bioenergy production. SDG 7, SDG 9, SDG 12, SDG 13, and SDG 1 are the most mapped SDGs in this theme.

The growing importance of wood pellets as a clean, renewable fuel for household heating has been discussed by Quinteiro et al. (2020).[56] This study compares the environmental characteristics of two decentralized alternatives—wood pellet production at sawmills and wood pellet production at home—with those of the centralized industrial pellet production process via life cycle assessment (LCA). The study revealed that industrial production has the highest environmental impact, whereas home-based production is the most environmentally friendly. By emphasizing renewable fuels, this research supports SDG 7.2, which advocates increasing the global share of renewable energy. The focus on decentralized manufacturing processes contributes to SDG 9.3, enhancing access to value-added resources and sustainable industrial practices. The study's promotion of sustainable energy production aligns with SDG 12.2, ensuring the sustainable management and efficient use of natural resources. Encouraging sustainable forestry practices directly supports SDG 15.2, which emphasizes the sustainable management of forests and halting deforestation. Furthermore, by reducing the environmental impact of energy production and addressing the ecological benefits of decentralized systems, this research aligns with SDG 13.2, integrating climate action through sustainable energy solutions. Together, these findings contribute to a more environmentally sustainable and decentralized energy production framework.

The GHG emissions linked to Sweden's wood pellet value chains for the production of heat and electricity were examined by Hansson et al. (2015).[57] This study evaluated nine distinct wood pellet value chains while performing a sensitivity analysis to account for alternative assumptions. The findings reveal that wood pellet value chains have significant potential to serve as a sustainable energy source, achieving substantial GHG reductions compared with those of fossil fuels. By promoting renewable energy for heat and power, this research aligns with SDG 7.2, which seeks to increase the share of renewable energy in the global mix. Additionally, the focus on low-carbon alternatives contributed to SDG 13.2, integrating climate action through strategies that mitigate GHG emissions and enhance sustainability in energy production. These efforts support the transition to a resilient and low-emission energy future.

The effects of locally manufactured and supplied wood pellets on GHG emissions from household heating in the US Northern Forest region were examined by Buchholz et al. (2017).[58] This study used a LCA technique to examine the greenhouse gas balances related to the manufacturing, processing, and consumption of wood pellets. This study highlights the importance of the feedstock mix, market assumptions, and biogenic carbon fluxes in shaping the GHG profiles of pellet heating systems and their impact on forest carbon pools. By promoting efficient and sustainable wood pellet production and consumption, this research aligns with SDG 12.2, which advocates for sustainable management and efficient use of natural resources, and SDG 12.5, which emphasizes waste reduction through sustainable practices. The study also supports SDG 9.4, which focuses on innovation and upgrading technologies to enhance the sustainability of industrial practices in the wood pellet sector. By promoting low-carbon energy alternatives, this research contributes to SDG 13.2, integrating climate change measures through renewable energy adoption. Additionally, the emphasis on renewable energy for household heating aligns with SDG 7.2, increasing the share of renewables in the energy mix, and SDG 7.1, ensuring access to affordable, reliable, and sustainable energy. Together, these findings provide a comprehensive framework for understanding and mitigating the environmental impacts of wood pellet production and use.

Bioeconomy and biorefineries

The convergence of the bioeconomy and biorefineries is the focus of this subject inquiry, highlighting the significance of sustainability in the use and recycling of bioresources. Three important pieces of research add to this thorough comprehension. This particular theme focuses mainly on SDG 7, SDG 9, and SDG 12.

Stegmann et al. (2020)[59] explored the role of biomass in achieving global climate targets and examined the concept of a circular bioeconomy (CBE) within northwestern European bioeconomy clusters. Through literature reviews and interviews, the study defined the CBE, analyzed its role in regional clusters, and identified strategies focusing on feedstock use, product priorities, and biorefinery integration. This research highlights challenges and opportunities for advancing sustainability, emphasizing the importance of utilizing residues, developing integrated biorefineries, and prioritizing material applications. By advocating for a circular approach, this study aligns with SDG 12.2, which promotes sustainable management and efficient use of natural resources, and SDG 12.5, which focuses on reducing environmental impact through waste minimization and reuse. The shift toward sustainable consumption and production patterns, as discussed, reinforces the broader objectives of building resource-efficient and environmentally sustainable bioeconomic systems. This work provides valuable insights into the transition to a circular and sustainable bioeconomy.

The management of agricultural waste biomass (AWB) by fruit and vegetable producer organizations (FVPOs) in southeastern Spain was examined by Duque-Acevedo et al. (2022)[60] through a case study involving FVPO surveys. The study outlines techniques for AWB reduction and valorization, offering insights into environmental practices and providing a foundation for governments to refine legal frameworks supporting AWB valorization. By emphasizing efficient waste management and value-adding practices, this research aligns with SDG 12.3, which seeks to halve global food waste and reduce postharvest losses, and SDG 12.5, which promotes substantial reductions in waste generation through reuse and recycling. The findings underscore the role of FVPOs in advancing sustainable agricultural practices and fostering a circular approach to agricultural waste management.

The conceptual definitions of the circular economy, bioeconomy, and circular bioeconomy are provided by Tan et al. (2021),[61] emphasizing the importance of the carbon cycle in creating a unified understanding of these frameworks. The study advocates low-carbon energy inputs, sustainable supply networks, and innovative technologies for converting renewable bioresources while also stressing the circular economy's goal of closing material loops. The introduction of the biobased circular carbon economy highlights the importance of closing the carbon cycle as a cornerstone for transitioning to a sustainable and circular bioeconomy. This approach aligns with SDG 7.2, which promotes an increased share of renewable energy by advocating low-carbon inputs. This supports SDG 9.4, which emphasizes upgrading infrastructure and industries to adopt sustainable technologies and enhance resource efficiency. Additionally, the focus on reducing waste and improving resource utilization aligns with SDG 12.2, which promotes sustainable management and efficient use of natural resources, and SDG 12.5, which targets waste reduction through circular practices. Together, these elements provide a robust framework for advancing a sustainable bioeconomy.

Aviation biofuels

This in-depth investigation explores the most recent advancements and difficulties in aviation biofuels and provides a multifaceted evaluation of environmentally friendly fuel options for aircraft. Three landmark studies offer varied perspectives on the effects on the environment, the feasibility of the economy, and international efforts aimed at achieving low-carbon aviation solutions aligning with SDG 7, SDG 8, SDG 9, SDG 12, and SDG 13.

In a groundbreaking study, Batten et al. (2023)[62] examined the potential of repurposing commercial first-generation biorefineries to produce low-carbon renewable aviation fuel, focusing on the production of 1,4-dimethylcyclooctane (DMCO) from maize feedstocks in dry grind biorefineries. The findings underscore the feasibility of corn-to-DMCO as a near-term renewable aviation fuel, with significant potential to reduce greenhouse gas (GHG) emissions and displace fossil fuels in aviation. This research aligns with SDG 7.2 by contributing to the expansion of renewable energy sources and supporting the transition to modern and sustainable energy systems. It also advances SDG 9.4, encouraging innovation and retrofitting in the biorefinery sector to enhance industrial sustainability and resource efficiency, thereby fostering economic growth. By promoting the development of sustainable aviation fuel, this study supports SDG 12.2 through efficient resource utilization and SDG 12.5 by reducing the environmental impact of conventional fuels. Finally, the focus on significant GHG emission reductions aligns with SDG 13.2, integrating climate action through sustainable solutions in the aviation sector, which is critical for addressing the urgent challenges posed by climate change.

A thorough analysis of the global technoeconomic state of sustainable aviation fuel (SAF) technology was provided by Shahriar and Khanal (2022),[63] highlighting its potential to reduce CO2 emissions and the challenges to its economic viability. The study evaluates organizational efforts, government incentives, and policy measures to promote SAF adoption, providing a detailed overview of the current state and future applications of renewable aviation fuels. This research aligns with SDG 7.2, emphasizing the role of renewable energy in enhancing the sustainability of air travel. An examination of the economic impacts and potential for job creation within the SAF industry contributes to SDG 8.2, which advocates for productivity growth through technological innovation. The focus on advanced SAF technology and the need for industrial development support SDG 9.4, fostering sustainable industry practices through resource-efficient technologies. Efforts to minimize aviation fuel's environmental impact align with SDG 12.2 by promoting sustainable resource management and SDG 12.5 by reducing waste through cleaner production processes. Finally, the emphasis on reducing aviation's carbon footprint directly supports SDG 13.2, integrating climate action into sectoral strategies to mitigate the effects of climate change.

Detsios et al. (2023)[64] explored the transition to alternative aviation fuels in alignment with the goals of the Paris Agreement, conducting a comparative analysis of prominent drop-in sustainable liquid fuels (SAFs) through technoeconomic assessments, environmental evaluations, and future projections. The study also examined the impact of the "ReFuelEU Aviation" initiative, emphasizing its role in creating a supportive regulatory environment and scaling up SAF production to establish a sustainable aviation sector. This research supports SDG 7.2 by promoting the integration of renewable energy sources into the aviation sector, thereby enhancing its sustainability. The potential for job creation and economic development in the sustainable aviation sector aligns with SDG 8.2, which emphasizes economic productivity through technological innovation. By advancing innovation and industrial capacity in SAF production, this study contributes to SDG 9.4, fostering sustainable and resource-efficient industry practices. Furthermore, its focus on reducing greenhouse gas emissions through low-carbon fuel alternatives supports SDG 13.2, integrating climate action into the aviation sector's strategies to mitigate its environmental impact. Together, these insights provide a roadmap for sustainable growth and climate-resilient development in aviation.

Renewable bioenergy sources

With a focus on biogas and its environmental effects, this analysis of sustainable bioenergy sources closely examines the role of biomass in generating bioenergy. Three relevant studies offer critical new perspectives on the use of biomass for the production of sustainable energy, focusing on SDG 2, SDG 7, SDG 9, SDG 11, SDG 13, and SDG 15.

Jayarathna et al. (2020)[65] introduced an innovative approach that combines geographic information systems (GISs), suitability analysis, spatial biomass evaluation, and optimality analysis to address the challenges posed by the distributed nature of biomass sources and the need to minimize delivery costs. Using a location-allocation model and fuzzy multicriteria analysis, the

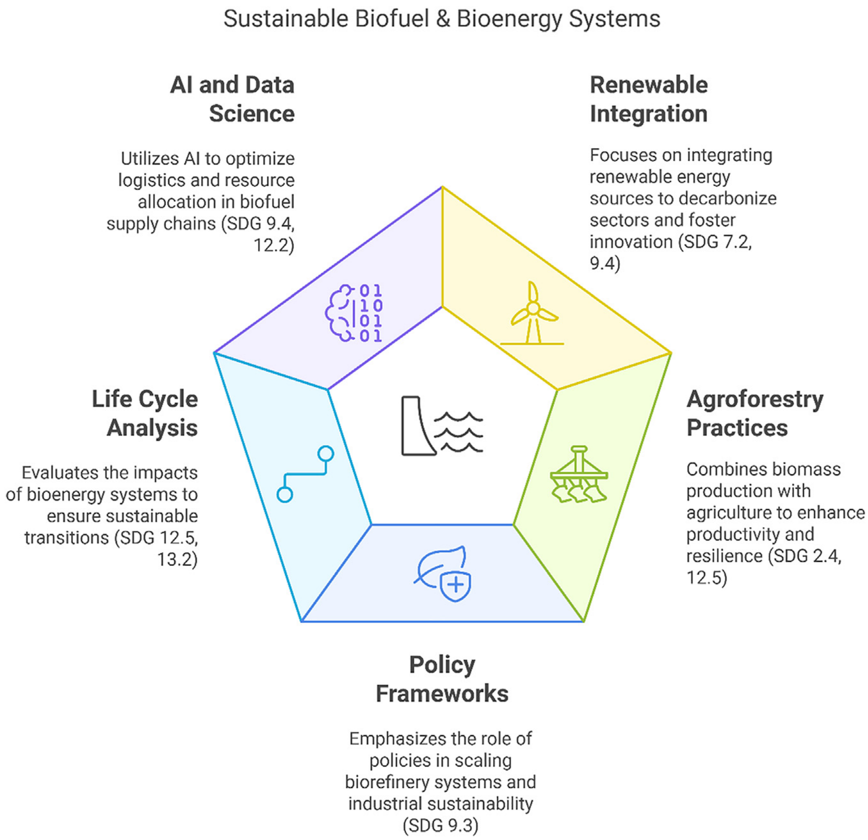


Figure 4. Sustainable biofuel and bioenergy systems

study considers road networks and spatially scattered biomass availability to identify optimal sites for biomass energy plants. A case study from Queensland demonstrated the methodology, emphasizing its potential to integrate various biomass types efficiently. This research underscores the role of agroforestry systems in enhancing sustainable agricultural practices and food security, supporting SDG 2.4 by promoting resilient agricultural practices that increase productivity and adapt to climate variability. By integrating biomass production into agroforestry landscapes, it also diversifies farmers' income sources, contributing to economic stability. The study's focus on infrastructure development for renewable energy directly aligns with SDG 7.2, fostering an increased share of renewable energy in the global mix. Its emphasis on climate considerations aligns with SDG 13.2, integrating climate change measures into planning to reduce greenhouse gas emissions and build resilience. Additionally, by analyzing the regional distribution of biomass sources and their effects on land use, this research supports SDG 15.3, which advocates for the sustainable management of land and ecosystems to combat degradation and promote restoration.

An innovative method combining scenario analysis and GIS-based location analysis to evaluate the impact of climate change and biomass feedstocks in agroforestry systems was proposed by Jeong (2018).[66] Using a participatory operational framework, the study integrated sensitivity analysis, simple additive weighting (SAW), and fuzzy decision-making trial and evaluation laboratory (F-DEMATEL) techniques to create a robust decision-making tool for the sustainable design and placement of biomass power facilities. A case study from Spain demonstrated the practical application of this approach. This study underscores the role of agroforestry systems in promoting sustainable agricultural practices and enhancing food security, aligning with SDG 2.4, which focuses on resilient agricultural practices that improve productivity and adapt to climate variability. Advocating for the development of renewable energy infrastructure supports SDG 7.2, emphasizing the integration of renewable energy into sustainable and modern energy systems. Furthermore, by strategically placing biomass power facilities, research has advanced efforts to transition to affordable, reliable, and sustainable energy solutions, reinforcing global climate goals. The inclusion of climate considerations in the methodology aligns with SDG 13.2, which calls for integrating climate action into policy and planning to reduce greenhouse gas emissions and improve adaptive capacity.

A GIS-based model was developed to identify optimal locations for wood terminals, farms, and centralized biogas plants in rural areas, highlighting the effectiveness of GIS tools in bioenergy decision-making.[67] By integrating kernel density tools in ArcGIS and location optimization tools in R, this study enables optimized biomass transportation and supports strategic decisions regarding power plant sizing and placement. The findings highlight the potential for improving the efficiency of bioenergy systems by reducing transportation costs and ensuring that biomass availability aligns with power plant capacity. This research supports SDG 2.4 by emphasizing the integration of agroforestry systems that contribute to sustainable agricultural practices and enhance food security. It directly advances SDG 7.2 by promoting the efficient use of renewable energy sources and reducing logistical inefficiencies, fostering broader access to sustainable, modern, and reliable energy. Additionally, by optimizing energy infrastructure, this study addresses the need for innovative approaches that enhance both energy efficiency and resource management, contributing to a more sustainable energy landscape.

DISCUSSION

The reviewed studies emphasize the significant role of sustainable practices, renewable energy integration, and innovative technologies in addressing interconnected environmental, economic, and social challenges across sectors (Figure 4). Many investigations highlight the importance of cross-sector approaches, where biomass energy systems are coupled with agricultural, industrial, and environmental objectives to create synergistic benefits. For example, GISs and optimization models are employed to identify optimal biomass facility locations and improve logistics,[68,69] contributing to the sustainable management and efficient use of natural resources, aligning with subtarget 12.2. By reducing transportation distances and enhancing infrastructure efficiency, these approaches also address resource efficiency goals under subtarget 9.4. The transition to renewable energy sources, particularly SAFs, reflects efforts to decarbonize the aviation sector while fostering economic growth and technological innovation.[70,71] Studies evaluating SAFs emphasize their potential to reduce greenhouse gas emissions and diversify the global energy mix, directly supporting subtarget 7.2, which promotes renewable energy, and subtarget 13.2, which integrates climate considerations into policy and planning.[72] These efforts also highlight job creation and increased productivity within the SAF industry, contributing to subtarget 8.2 by encouraging technological innovation for economic growth.

Agroforestry systems play a crucial role in integrating energy production with sustainable agricultural practices. By coupling biomass production with agriculture, these systems increase land productivity, increase resilience to climate variability, and diversify farmers' income streams.[73] This supports subtarget 2.4, which emphasizes resilient agricultural practices to improve food security and adapt to climate change.[74] Additionally, integrating agroforestry into biomass systems supports more sustainable resource use and environmental stewardship, aligning with subtarget 15.3, which addresses land degradation and promotes sustainable land use. Policy frameworks and incentives are critical for scaling innovations in biorefinery systems and biofuel supply chains.[75] Studies underscore the importance of fostering access to value-added processes, supporting subtarget 9.3, and leveraging regulatory support to achieve industrial sustainability. Circular economy principles, such as reducing waste and closing material loops, align with subtarget 12.5, which advocates waste reduction through recycling and reuse. These efforts promote the efficient use of resources while reducing environmental impacts.

Life cycle analysis has emerged as a key tool for understanding the environmental, economic, and social impacts of renewable bioenergy systems.[76] By evaluating emissions, resource efficiency, and socioeconomic trade-offs, life cycle approaches align with subtarget 12.5, which focuses on waste reduction, and subtarget 13.2, which integrates climate actions into broader strategies. These analyses inform decisions that balance environmental benefits with socioeconomic considerations, ensuring that renewable energy transitions contribute meaningfully to sustainability. As the global landscape shifts toward sustainable energy, the implications for practice and policy surrounding biofuels are critical. These recommendations aim to guide stakeholders in optimizing biofuel supply chains through artificial intelligence (AI) and data science,[77] improving biomass production practices, and developing supportive policies for sustainable growth. The transition of biofuels from pilot projects to large-scale production is fraught with technical, economic, and logistical challenges. Addressing these issues requires a multifaceted approach involving research into more efficient production processes, investment in infrastructure, and public-private partnerships to support scale-up initiatives.

The incorporation of AI and data science into biofuel supply chains enhances logistic optimization, maintenance strategies, and resource allocation, dovetailing with the broader goals of sustainable bioeconomic development.[78] This integration not only aligns with but also amplifies our analyses on optimizing the utilization of renewable resources. Effective logistics are critical for sustainable bioenergy. AI can develop predictive models to optimize biomass sourcing and fuel distribution, minimizing costs and environmental impacts. By analyzing data on weather conditions, traffic patterns, and biomass availability, AI algorithms can increase logistical efficiency, ensuring that biofuel production aligns with sustainability goals by reducing the carbon footprint throughout the supply chain.[79] AI and ML algorithms can be used to predict equipment failure and schedule maintenance, thereby preventing unscheduled downtime. These predictive maintenance strategies ensure continuous production and are integral to the sustainability and economic efficiency of biofuel operations.[80] Data analytics can enhance decision-making regarding the allocation of resources such as manpower, biomass, and capital. Through the analysis of productivity patterns across various production scenarios, biofuel plants can optimize outputs and reduce waste,[81,82] contributing directly to the goals of SDG 12. By applying advanced analytics and machine learning, we can significantly advance our ability to manage the complex dynamics of biofuel supply chains, thus enhancing the scalability and sustainability of bioenergy globally. However, while the potential of biofuels to significantly impact energy systems is clear, their development and implementation are not without challenges.

Implications for practice

Advancing biofuel systems requires innovative agricultural practices for nonfood biomass, continued research on high-efficiency biofuel technologies, integration with broader renewable energy networks, efficient and sustainable supply chains, and AI-driven data tools—all converging to support resilience, resource efficiency, and alignment with the SDGs (Figure 5).

Innovation in crop production

To mitigate impacts on food security and biodiversity, innovative agricultural practices and crop choices are essential. The development of nonfood biomass crops, such as switchgrass or jatropha, that require less water and can grow on marginal lands reduces competition with food crops and minimizes environmental trade-offs. Agroforestry systems that integrate biomass production into diverse landscapes increase land productivity and resilience to climate variability, supporting SDG 2.4, which emphasizes resilient agricultural practices that improve productivity and address climate challenges.

Advancing biofuel technologies

Investment in research and development is critical for improving the efficiency and sustainability of biofuel technologies. Second- and third-generation biofuels, derived from lignocellulosic biomass or algae, offer higher yields with fewer environmental

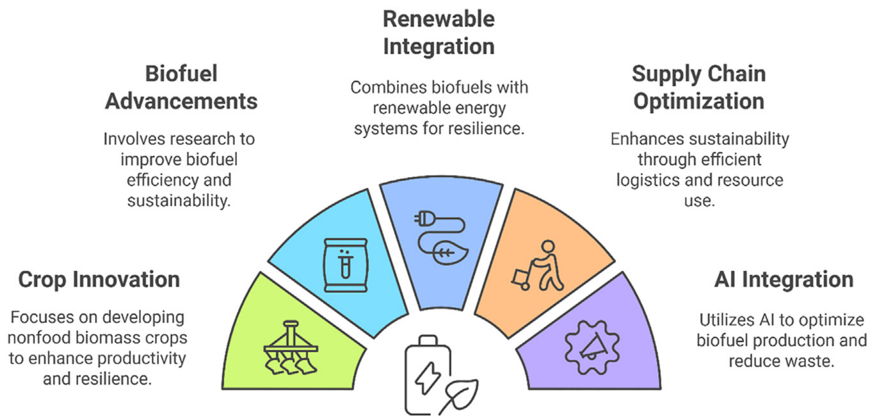


Figure 5. Implications for practice

impacts. Advancements in bioconversion processes, such as enzymatic hydrolysis, align with SDG 7.2, which promotes an increased share of renewable energy in the global energy mix. These technologies also contribute to SDG 13.2 by supporting low-carbon energy systems that integrate climate actions into policy and development strategies.

Integration with renewable energy systems

Biofuels should be integrated into broader renewable energy strategies to improve energy resilience and access. For example, combining decentralized biomass power plants with solar microgrids ensures a consistent and reliable energy supply in remote areas. These systems contribute to SDG 7.1, which focuses on ensuring universal access to affordable, reliable, and sustainable energy. Integrating biofuels with other renewable energy sources also supports SDG 9.4 goals by upgrading energy infrastructure to adopt sustainable and resource-efficient technologies.

Supply chain optimization

Efficient supply chains are critical to the economic and environmental sustainability of biofuels. GIS tools and location-allocation models optimize plant locations and transportation routes, reducing costs and emissions. This approach aligns with SDG 12.2, which advocates sustainable management and efficient use of natural resources. Decentralized bioenergy systems further contribute to SDG 7.2 by enhancing local energy production and distribution while reducing dependency on centralized systems.

AI and data science integration

The integration of AI and data science technologies can revolutionize biofuel supply chains. Predictive maintenance for biorefineries, real-time logistics optimization, and AI-driven life cycle analyses ensure that production processes remain efficient and sustainable. These tools align with SDG 9.4, which emphasizes the adoption of clean and environmentally sound technologies to improve industrial sustainability. Additionally, the use of AI in life cycle analysis supports SDG 12.5, which focuses on reducing waste generation through sustainable production practices.

Implications for policy

Biofuels offer a promising path toward sustainable energy transitions, requiring coordinated policies that provide incentives, ensure robust regulation, foster international collaboration, educate stakeholders, align with SDGs, drive innovation, and support infrastructure and capacity development (Figure 6).

Subsidies and incentives

Economic policies that lower barriers to biofuel adoption are essential for fostering their competitiveness with fossil fuels. By addressing fluctuations in agricultural prices and the high costs of new technologies, subsidies and financial incentives can enable biofuels to scale effectively. For example, Brazil's Proálcool program demonstrates how ethanol subsidies help establish bioethanol as a viable fuel alternative. In India, the Ethanol Blending Program incentivizes sugar mills to produce ethanol, helping reduce oil imports and promoting energy self-reliance. In Africa, regional initiatives such as the African Union's efforts to promote bioenergy are exploring farmer support mechanisms for cultivating biofuel crops, emphasizing localized solutions to energy access challenges.

Regulatory frameworks

Robust regulatory frameworks are crucial for minimizing the environmental risks associated with biofuel production, such as deforestation and biodiversity loss. These frameworks ensure that biofuel systems align with sustainability objectives while balancing economic and environmental considerations. For instance, the European Union's Renewable Energy Directive mandates emission reduction thresholds and restricts land-use changes that threaten ecosystems. In Southeast Asia, Indonesia has introduced sustainability certification for palm oil producers to mitigate the environmental impacts of biodiesel feedstock production. These regulations provide a blueprint for ensuring that biofuel expansion does not compromise critical environmental resources.

International collaboration

The global nature of energy transitions necessitates international partnerships to harmonize standards, share knowledge, and support emerging markets in adopting biofuel technologies. Initiatives such as the International Energy Agency's Bioenergy Technology Collaboration Program facilitate cross-border research and development efforts. The World Economic Forum's Clean Skies for the Tomorrow coalition focuses on scaling SAFs, bringing together governments, businesses, and researchers to address challenges collectively. In the Global South, regional collaboration among countries in Latin America and Africa is fostering the development of biofuels through technology transfer and shared investments in infrastructure.

Education and awareness

Public understanding of biofuels is critical for increasing adoption and acceptance, particularly in regions transitioning to renewable energy systems. Educational campaigns that explain the environmental and economic benefits of biofuels can engage

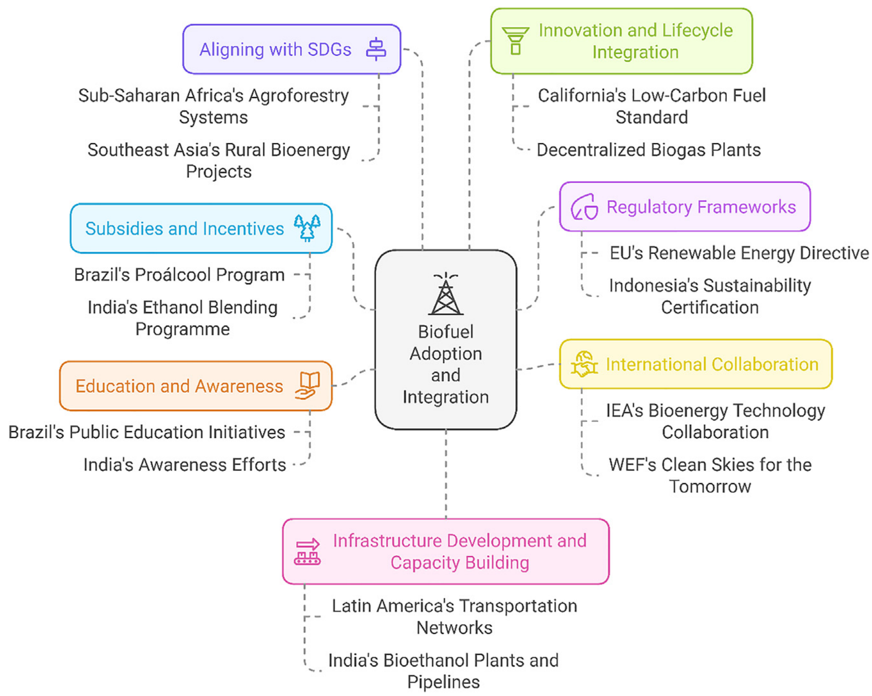


Figure 6. Implications for policy with examples

stakeholders at all levels, from policymakers to local communities. For example, Brazil's education initiatives on flex-fuel vehicles and ethanol use contributed to widespread public acceptance. In India, awareness efforts as part of the Ethanol Blending Program highlight the importance of ethanol-blended fuels in reducing emissions and increasing energy security. Regional programs in Africa also focus on engaging communities in discussions about the benefits of bioenergy, creating a foundation for long-term support.

Aligning biofuel development with SDGs

Biofuel policies must align with broader development objectives to maximize their impact. Integrating biofuel strategies with the SDGs can ensure that bioenergy contributes to energy access, economic growth, and environmental stewardship. For example, in sub-Saharan Africa, integrating biofuel crops into agroforestry systems enhances land productivity and food security, addressing SDG 2.4. Similarly, rural bioenergy projects in Southeast Asia create employment opportunities and foster inclusive growth, contributing to SDG 8.2. The promotion of biofuels in aviation, as seen through global efforts to develop SAFs, addresses SDG 13 by reducing greenhouse gas emissions and advancing climate action.

Innovation and life cycle integration

Research and development are central to driving the biofuel sector forward, particularly for advanced biofuels that address sustainability challenges. Policies supporting life cycle analysis ensure that environmental, social, and economic impacts are evaluated comprehensively. For example, California's low-carbon fuel standard applies life cycle assessments to prioritize low-carbon fuels, a practice that has inspired similar initiatives globally. In developing regions, innovations such as decentralized biogas plants in rural India and community-led bioenergy systems in East Africa demonstrate how localized solutions can align with global sustainability goals while addressing unique regional needs.

Infrastructure development and capacity building

The development of infrastructure and the enhancement of institutional capacity are critical for supporting biofuel production and distribution, especially in regions where existing energy systems are underdeveloped or fragmented. Adequate infrastructure ensures the efficient collection, processing, storage, and transportation of biomass, whereas capacity-building initiatives help equip stakeholders with the skills and knowledge needed to manage biofuel systems effectively. For example, in Latin America, countries such as Brazil and Argentina have invested heavily in transportation networks and biorefineries to facilitate ethanol and biodiesel production. Similarly, India has developed dedicated bioethanol plants and pipelines to expand the ethanol blending program, enabling efficient distribution across regions. In sub-Saharan Africa, capacity-building programs supported by international organizations have helped smallholder farmers adopt bioenergy crops and optimize supply chains. Infrastructure development also includes the integration of advanced technologies, such as decentralized bioenergy systems, which can provide localized energy solutions in rural areas. Capacity-building efforts targeting policymakers, industry leaders, and community stakeholders can ensure informed decision-making and foster collaboration across sectors.

Conclusions

The discussion surrounding biofuels, biomass, and bioenergy has evolved significantly over recent years, driven by the increasing need for sustainable energy solutions and their critical role in advancing the SDGs.[19,28] As explored throughout this paper, biofuels present a viable alternative to fossil fuels, contributing to SDG 7 by providing renewable energy options that reduce reliance on finite fossil reserves. By mitigating greenhouse gas emissions, they also support SDG 13, which helps to combat climate change and its impacts. The progression from first-generation biofuels, which rely on food crops, to fourth-generation technologies, which employ advanced biotechnologies and nonfood biomass, reflects significant technological and ecological advancements, furthering SDG 9 by fostering innovation in sustainable energy systems. Additionally, the expanded adoption of biofuels aligns with global energy consumption trends and addresses environmental concerns associated with traditional fossil fuels, supporting the broader agenda for sustainable and equitable development.

The two thematic clusters (RQ1) identified in the analysis highlight the interconnected contributions of bioenergy to sustainable development across multiple SDGs.

(1) The first cluster emphasizes sustainable energy and climate resilience, where biofuels align with SDG 7 by offering renewable energy alternatives supported by sustainable production practices (SDG 12) and contributions to greenhouse gas reduction (SDG 13). Innovation and infrastructure development (SDG 9) are essential for scaling bioenergy systems, with further benefits for urban sustainability (SDG 11) and water resource management (SDG 6).
(2) The second cluster focuses on socioeconomic development and equity, with bioenergy fostering inclusive economic growth (SDG 8) by creating jobs and reducing poverty (SDG 1). Sustainable land management supports ecosystems (SDG 15), while energy production is balanced with food security (SDG 2). Workforce education (SDG 4), inclusivity (SDGs 5 and 10), and stable governance (SDG 16) ensure equitable growth and effective policy implementation, underscoring the role of bioenergy in advancing sustainability and socioeconomic progress.

The six topics examined present unique approaches to advancing sustainability while also sharing common challenges and opportunities (RQ2). Each topic aligns with multiple SDGs, contributing to global energy, environmental, and economic objectives.

(1) Sustainable bioeconomic development and the bioeconomy: focus on integrating economic and ecological goals through innovation and systemic economic changes. These efforts align with SDG 8.2, which emphasizes achieving greater economic productivity through diversification and technological upgrading, and SDG 9.4, which promotes the upgrading of infrastructure and industries to improve sustainability and resource efficiency. Additionally, this theme supports SDG 12.2, which advocates sustainable management and efficient use of natural resources.
(2) Biofuel and biomass sustainability, and biomass and bioenergy production: prioritize optimizing supply chains and reducing environmental impacts within existing frameworks. This aligns with SDG 7.2, which focuses on increasing the share of renewable energy in the global energy mix, and SDG 13.2, which integrates climate action into policies and strategies to reduce greenhouse gas emissions.
(3) Aviation biofuels: address sector-specific emissions challenges in aviation by balancing economic feasibility with environmental imperatives. This aligns with SDG 7.2, which promotes renewable energy adoption, and SDG 9.4, which encourages resource-efficient and sustainable industrial development. The focus on reducing emissions also supports SDG 13.2, contributing to global climate action through the development of low-carbon fuel substitutes for aviation.
(4) Renewable bioenergy sources: emphasize spatial and geographic considerations essential for optimizing bioenergy infrastructure. This aligns with SDG 7.1, which ensures access to affordable and sustainable energy in remote and rural areas, and SDG 15.2, which promotes sustainable management of forests and other land ecosystems to halt degradation and foster restoration.

In the future, developing biofuels, biomass, and bioenergy with innovative solutions and sustainable practices can help achieve multiple SDGs, creating a cleaner and more resilient future.

Limitations of the study

This study is not without its limitations. One key consideration within the PRISMA framework is the potential bias introduced by relying on literature from a single database. With respect to the application of BERT topic modeling, while it effectively processes extensive datasets and identifies critical themes, its reliance on semantic relationships between words and phrases introduces an element of objectivity by reducing human intervention in topic categorization.[83] Nevertheless, the performance of topic modeling algorithms can be affected by the quality of the input data and inherent design assumptions. Additionally, mapping publications to specific sustainable SDGs presents challenges because of the inherent complexity of aligning diverse research outputs with specific SDG targets.[84] Exploring alternative SDG mapping approaches, such as those utilized by the Aurora Network or the University of Auckland, in future studies could provide complementary insights and improve the robustness of comparative analyses. However, integrating these frameworks falls beyond the scope of this review.

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Raghu Raman, (raghu@amrita.edu).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- Data: data reported in this paper will be shared by the lead contact upon request.
- Code: This paper does not report original code.
- All other items: Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

ACKNOWLEDGMENTS

Authors are very thankful to the Associate editor and anonymous reviewers for their valuable time for reviews. Authors offer their gratitude to Mata Amritanandamayi Devi, a world-renowned humanitarian leader and the Chancellor of Amrita Vishwa Vidyapeetham, for guidance and the research vision. This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

AUTHOR CONTRIBUTIONS

Conceptualization: R.R.; methodology: R.R.; investigation: R.R. and P.N.; validation: R.R. and P.N.; writing – R.R., A.S., N.V.K., S.M., and P.N.; writing—review and editing: R.R., A.S., N.V.K., S.M., and P.N.; supervision: R.R.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this work, the author(s) used ChatGPT 4o for English editing and grammar checks. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- METHOD DETAILS
  - PRISMA protocol
  - SDG framework
  - BERTopic modeling
- QUANTIFICATION AND STATISTICAL ANALYSIS

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2025.112157.

Received: August 28, 2024
Revised: December 24, 2024
Accepted: February 28, 2025
Published: March 4, 2025

REFERENCES

1. Osman, Y. (2024). Implications of energy consumption by sector on carbon emissions in Saudi Arabia. Int. J. Energy Econ. Pol. *14*, 311–318.
2. Usman, M., Rasheed, K., Mahmood, F., Riaz, A., and Bashir, M. (2023). Impact of Financial Development and Economic Growth on Energy Consumption in Developing Countries of Asia. Int. J. Energy Econ. Pol. *13*, 512–523.
3. Bhuiyan, M.A., Zhang, Q., Khare, V., Mikhaylov, A., Pinter, G., and Huang, X. (2022). Renewable energy consumption and economic growth nexus—a systematic literature review. Front. Environ. Sci. *10*, 878394.
4. EIA, E. (2019). Projects Nearly 50% Increase in World Energy Usage by 2050, Led by Growth in Asia. https://www.eia.gov/todayinenergy/detail.php?id=42342.
5. Dutta, I., Parsapur, R.K., Chatterjee, S., Hengne, A.M., Tan, D., Peramaiah, K., Solling, T.I., Nielsen, O.J., and Huang, K.W. (2023). The role of fugitive hydrogen emissions in selecting hydrogen carriers. ACS Energy Lett. *8*, 3251–3257.
6. Holechek, J.L., Geli, H.M.E., Sawalhah, M.N., and Valdez, R. (2022). A global assessment: can renewable energy replace fossil fuels by 2050? Sustainability *14*, 4792.
7. Megía, P.J., Vizcaíno, A.J., Calles, J.A., and Carrero, A. (2021). Hydrogen production technologies: from fossil fuels toward renewable sources. A mini review. Energy Fuels *35*, 16403–16415.
8. Halkos, G.E., and Gkampoura, E.C. (2020). Reviewing usage, potentials, and limitations of renewable energy sources. Energies *13*, 2906.
9. Ahmad, T., and Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. Energy Rep. *6*, 1973–1991.
10. Mayer, A. (2022). Fossil fuel dependence and energy insecurity. Energy Sustain. Soc. *12*, 27.
11. Lu, T., Xiao, X., Yu, H., and Ren, D. (2023). The integration of technological advancements in fossil fuels towards environmental sustainability: Insights from big data analytics. Resour. Policy *86*, 104196.
12. Månberger, A. (2021). Reduced use of fossil fuels can reduce supply of critical resources. Biophys. Econ. Sust. *6*, 6.
13. Stančin, H., Mikulčić, H., Wang, X., and Duić, N. (2020). A review on alternative fuels in future energy system. Renew. Sustain. Energy Rev. *128*, 109927.
14. Moriarty, P., and Honnery, D. (2022). Renewable energy in an increasingly uncertain future. Appl. Sci. *13*, 388.
15. Azni, M.A., Md Khalid, R., Hasran, U.A., and Kamarudin, S.K. (2023). Review of the Effects of Fossil Fuels and the Need for a Hydrogen Fuel Cell Policy in Malaysia. Sustainability *15*, 4033.
16. Perera, F. (2017). Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. Int. J. Environ. Res. Public Health *15*, 16.
17. Martins, F., Felgueiras, C., Smitkova, M., and Caetano, N. (2019). Analysis of Fossil Fuel Energy Consumption and Environmental Impacts in European Countries. Energies *12*, 964.
18. Hanssen, S.V., Daioglou, V., Steinmann, Z.J.N., Doelman, J.C., Van Vuuren, D.P., and Huijbregts, M.A.J. (2020). The climate change mitigation potential of bioenergy with carbon capture and storage. Nat. Clim. Chang. *10*, 1023–1029.
19. Mensah, T.N.O., Oyewo, A.S., Bogdanov, D., Aghahosseini, A., and Breyer, C. (2024). Pathway for a fully renewable power sector of Africa by 2050: Emphasising on flexible generation from biomass. Renew. Energy *234*, 121198.
20. Woolf, D., Lehmann, J., and Lee, D.R. (2016). Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. Nat. Commun. *7*, 13160.
21. Liu, T., Miao, P., Shi, Y., Tang, K.H.D., and Yap, P.S. (2022). Recent advances, current issues and future prospects of bioenergy production: a review. Sci. Total Environ. *810*, 152181.
22. Khan, N., Sudhakar, K., and Mamat, R. (2021). Role of biofuels in energy transition, green economy and carbon neutrality. Sustainability *13*, 12374.
23. Xu, Y., Smith, P., and Qin, Z. (2024). Sustainable bioenergy contributes to cost-effective climate change mitigation in China. iScience *27*, 110232.
24. IEA (2022). Renewables 2022 (IEA). https://www.iea.org/reports/renewables-2022.
25. Sathish Kumar, R., Sasikumar, R., and Dhilipkumar, T. (2024). Exploiting agro-waste for cleaner production: A review focusing on biofuel generation, bio-composite production, and environmental considerations. J. Clean. Prod. *435*, 140536.
26. Tiburcio, R.S., Macêdo, T.R.d., and Neto, A.M.P. (2023). Brazilian Biofuels Policy (RenovaBio): Overview and generation of decarbonization credits by biodiesel production facilities. Energy Sustain. Dev. *77*, 101334.
27. Prasad, S., Yadav, K.K., Kumar, S., Pandita, P., Bhutto, J.K., Alreshidi, M.A., Ravindran, B., Yaseen, Z.M., Osman, S.M., and Cabral-Pinto, M.M. (2024). Review on biofuel production: Sustainable development scenario, environment, and climate change perspectives– A sustainable approach. J. Environ. Chem. Eng. *12*, 111996.
28. Patro, A., Dwivedi, S., Thakur, A., Sahoo, P.K., and Biswas, J.K. (2024). Recent approaches and advancement in biochar-based environmental

sustainability: Is biochar fulfilling the sustainable development goals? iScience *27*, 110812.

29. Acheampong, M., Ertem, F.C., Kappler, B., and Neubauer, P. (2017). In pursuit of Sustainable Development Goal (SDG) number 7: Will biofuels be reliable? Renew. Sustain. Energy Rev. *75*, 927–937.
30. Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Öhman, M.C., Shyamsundar, P., Steffen, W., Glaser, G., Kanie, N., and Noble, I. (2013). Sustainable development goals for people and planet. Nature *495*, 305–307.
31. Algarni, S., Tirth, V., Alqahtani, T., Alshehery, S., and Kshirsagar, P. (2023). Contribution of renewable energy sources to the environmental impacts and economic benefits for sustainable development. Sustain. Energy Technol. Assessments *56*, 103098.
32. Fuso Nerini, F., Mazzucato, M., Rockström, J., van Asselt, H., Hall, J.W., Matos, S., Persson, Å., Sovacool, B., Vinuesa, R., and Sachs, J. (2024). Extending the Sustainable Development Goals to 2050—a road map. Nature *630*, 555–558.
33. Yusuf, M., and Ibrahim, H. (2024). Introduction to Biofuel Production: A Step Towards Sustainable Energy. In Emerging Sustainable Technologies for Biofuel Production (Springer Nature Switzerland), pp. 1–14.
34. King, R., and Tingas, E.A. (2021). Potential for carbon-neutral advanced biofuels in UK road transport. J. Energy Eng. *147*, 04021025.
35. Liska, A.J., Yang, H., Milner, M., Goddard, S., Blanco-Canqui, H., Pelton, M.P., Fang, X.X., Zhu, H., and Suyker, A.E. (2014). Biofuels from crop residue can reduce soil carbon and increase CO 2 emissions. Nat. Clim. Chang. *4*, 398–401.
36. Aro, E.M. (2016). From first generation biofuels to advanced solar biofuels. Ambio *45*, 24–31.
37. Ntambara, B., Nyambo, D.G., and Solsbach, A. (2023). Internet of things (IoT)-based on real-time and remote boiler fuel monitoring system: a case of Raha Beverages Company Limited, Arusha-Tanzania. Discov. Internet Things *3*, 19.
38. Roth, J.C.G., Hoeltz, M., and Benitez, L.B. (2020). Current approaches and trends in the production of microbial cellulases using residual lignocellulosic biomass: a bibliometric analysis of the last 10 years. Arch. Microbiol. *202*, 935–951.
39. Yang, J., Hong, C., Xing, Y., Zheng, Z., Li, Z., Zhao, X., and Qi, C. (2021). Research progress and hot spots of hydrothermal liquefaction for bio-oil production based on bibliometric analysis. Environ. Sci. Pollut. Res. Int. *28*, 7621–7635.
40. Zhang, Y., Yu, Q., and Li, J. (2021). Bioenergy research under climate change: a bibliometric analysis from a country perspective. Environ. Sci. Pollut. Res. Int. *28*, 26427–26440.
41. Papilo, P., Marimin, M., Hambali, E., Machfud, M., Yani, M., Asrol, M., Evanila, E., Prasetya, H., and Mahmud, J. (2022). Palm oil-based bioenergy sustainability and policy in Indonesia and Malaysia: A systematic review and future agendas. Heliyon *8*, e10919.
42. Wang, L., Wang, S., Zhou, J., Xie, L., Qin, H., and Ma, H. (2022). A Scientometric Review: Biomass Gasification Study from 2006 to 2020. ACS Omega *7*, 38246–38253.
43. Yuan, R., Pu, J., Wu, D., Wu, Q., Huhe, T., Lei, T., and Chen, Y. (2022). Research Priorities and Trends on Bioenergy: Insights from Bibliometric Analysis. Int. J. Environ. Res. Public Health *19*, 15881.
44. Hasan, M., Abedin, M.Z., Amin, M.B., Nekmahmud, M., and Oláh, J. (2023). Sustainable biofuel economy: A mapping through bibliometric research. J. Environ. Manage. *336*, 117644.
45. Habibi, F., Chakrabortty, R.K., and Abbasi, A. (2023). Towards facing uncertainties in biofuel supply chain networks: a systematic literature review. Environ. Sci. Pollut. Res. Int. *30*, 100360–100390.
46. Jahanshahi, A., Lopes, M., Brandão, M., and De Castro, E.A. (2023). Development of bioenergy technologies: A scientometric analysis. Heliyon *9*, e20000.
47. Li, M., and Xu, X. (2023). Mapping the field of bioenergy with carbon capture and storage (BECCS): scientific cooperation and co-citation analyses. Environ. Sci. Pollut. Res. Int. *30*, 3402–3415.
48. Pramanik, A., Sinha, A., Chaubey, K.K., Hariharan, S., Dayal, D., Bachheti, R.K., Bachheti, A., and Chandel, A.K. (2023). Second-generation bio-fuels: Strategies for employing degraded land for climate change mitigation meeting United Nation-sustainable development goals. Sustainability *15*, 7578.
49. Nazari, M.T., Mazutti, J., Basso, L.G., Colla, L.M., and Brandli, L. (2021). Biofuels and their connections with the sustainable development goals: a bibliometric and systematic review. Environ. Dev. Sustain. *23*, 11139–11156.
50. De Besi, M., and McCormick, K. (2015). Towards a bioeconomy in Europe: National, regional and industrial strategies. Sustainability *7*, 10461–10478.
51. Kardung, M., and Drabik, D. (2021). Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe. Ecol. Econ. *188*, 107146.
52. Schütte, G. (2018). What kind of innovation policy does the bioeconomy need? N. Biotechnol. *40*, 82–86.
53. Orjuela-Castro, J.A., Aranda-Pinilla, J.A., and Moreno-Mantilla, C.E. (2019). Identifying trade-offs between sustainability dimensions in the supply chain of biodiesel in Colombia. Comput. Electron. Agric. *161*, 162–169.
54. Umar, M., Tayyab, M., Chaudhry, H.R., and Su, C.W. (2023). Navigating epistemic uncertainty in third-generation biodiesel supply chain management through robust optimization for economic and environmental performance. Ann. Oper. Res., 1–40.
55. Gao, J., and You, F. (2017). Modeling framework and computational algorithm for hedging against uncertainty in sustainable supply chain design using functional-unit-based life cycle optimization. Comput. Chem. Eng. *107*, 221–236.
56. Quinteiro, P., Greco, F., da Cruz Tarelho, L.A., Righi, S., Arroja, L., and Dias, A.C. (2020). A comparative life cycle assessment of centralised and decentralised wood pellets production for residential heating. Sci. Total Environ. *730*, 139162.
57. Hansson, J., Martinsson, F., and Gustavsson, M. (2015). Greenhouse gas performance of heat and electricity from wood pellet value chains–based on pellets for the Swedish market. Biofuel. Bioprod. Biorefin. *9*, 378–396.
58. Buchholz, T., Gunn, J.S., and Saah, D.S. (2017). Greenhouse gas emissions of local wood pellet heat from northeastern US forests. Energy *141*, 483–491.
59. Stegmann, P., Londo, M., and Junginger, M. (2020). The circular bioeconomy: Its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. *6*, 100029.
60. Duque-Acevedo, M., Belmonte-Ureña, L.J., Batlles-delaFuente, A., and Camacho-Ferre, F. (2022). Management of agricultural waste biomass: a case study of fruit and vegetable producer organizations in southeast Spain. J. Clean. Prod. *359*, 131972.
61. Tan, E.C.D., and Lamers, P. (2021). Circular bioeconomy concepts—a perspective. Front. Sustain. *2*, 701509.
62. Batten, R., Galant, O., Karanjikar, M., and Spatari, S. (2023). Meeting sustainable aviation fuel policy targets through first generation corn biorefineries. Fuel *333*, 126294.
63. Shahriar, M.F., and Khanal, A. (2022). The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel *325*, 124905.
64. Detsios, N., Theodoraki, S., Maragoudaki, L., Atsonios, K., Grammelis, P., and Orfanoudakis, N.G. (2023). Recent advances on alternative aviation fuels/pathways: A critical review. Energies *16*, 1904.
65. Jayarathna, L., Kent, G., O'Hara, I., and Hobson, P. (2020). A Geographical Information System based framework to identify optimal location and

size of biomass energy plants using single or multiple biomass types. Appl. Energy *275*, 115398.

66. Jeong, J.S. (2018). Biomass feedstock and climate change in agroforestry systems: Participatory location and integration scenario analysis of biomass power facilities. Energies *11*, 1404.
67. Laasasenaho, K., Lensu, A., Lauhanen, R., and Rintala, J. (2019). GIS-data related route optimization, hierarchical clustering, location optimization, and kernel density methods are useful for promoting distributed bioenergy plant planning in rural areas. Sustain. Energy Technol. Assessments *32*, 47–57.
68. Akca, M.S., Sarikaya, O.V., Doker, M.F., Ocak, F., Kirlangicoglu, C., Karaaslan, Y., Satoglu, S.I., and Altinbas, M. (2023). A detailed GIS based assessment of bioenergy plant locations using location-allocation algorithm. Appl. Energy *352*, 121932.
69. Delivand, M.K., Cammerino, A.R.B., Garofalo, P., and Monteleone, M. (2015). Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: a case study on electricity productions in South Italy. J. Clean. Prod. *99*, 129–139.
70. Raman, R., Hughes, L., Mandal, S., Das, P., and Nedungadi, P. (2024). Mapping metaverse research to the sustainable development goal of good health and well-being. IEEE Access, 1–11.
71. Dubey, P., Schulte, L.A., and Mba Wright, M. (2024). The Economic and Environmental Case for Cattle Manure and Prairie Grass-Derived Sustainable Aviation Fuel. Energy Fuels *38*, 20721–20731.
72. Khujamberdiev, R., and Cho, H.M. (2024). Biofuels in Aviation: Exploring the Impact of Sustainable Aviation Fuels in Aircraft Engines. Energies *17*, 2650.
73. Barman, A., Dutta, S., Bera, A., Saha, P., Roy, J., Roy Choudhury, M., Bera, M., and Das, S. (2024). Synergizing sustainability: a critical review on harnessing agroforestry for biomass, carbon sequestration, and water-food-energy nexus. Energy Ecol. Environ. *9*, 579–613.
74. Sharma, N., Bohra, B., Pragya, N., Ciannella, R., Dobie, P., and Lehmann, S. (2016). Bioenergy from agroforestry can lead to improved food security, climate change, soil quality, and rural development. Food Energy Secur. *5*, 165–183.
75. Yılmaz Balaman, Ş., Scott, J., Matopoulos, A., and Wright, D.G. (2019). Incentivising bioenergy production: Economic and environmental insights from a regional optimization methodology. Renew. Energy *130*, 867–880.
76. Aghbashlo, M., Khounani, Z., Hosseinzadeh-Bandbafha, H., Gupta, V.K., Amiri, H., Lam, S.S., Morosuk, T., and Tabatabaei, M. (2021). Exergoenvironmental analysis of bioenergy systems: A comprehensive review. Renew. Sustain. Energy Rev. *149*, 111399.
77. Lim, H., and Kim, S. (2024). Applications of Machine Learning Technologies for Feedstock Yield Estimation of Ethanol Production. Energies *17*, 5191.
78. Liao, M., and Yao, Y. (2021). Applications of artificial intelligence-based modeling for bioenergy systems: A review. GCB Bioenergy *13*, 774–802.
79. Okolie, J.A. (2024). Introduction of Machine Learning and artificial intelligence in biofuel technology. Curr. Opin. Green Sustain. Chem. *47*, 100928.
80. Kou, N., and Zhao, F. (2013). Operational flexibility: a key factor in the development of biofuel technologies. Sustain. Energy Technol. Assessments *1*, 28–33.
81. Solis, C.M.A., San Juan, J.L.G., Mayol, A.P., Sy, C.L., Ubando, A.T., and Culaba, A.B. (2021). A multi-objective life cycle optimization model of an integrated algal biorefinery toward a sustainable circular bioeconomy considering resource recirculation. Energies *14*, 1416.
82. Guerreiro, E.M.A., Silva, M., Guerreiro, M., Carvalho, T., Converti, A., Siqueira, H.V., and Piekarski, C.M. (2022). Framework for Optimized Analysis of Waste Bioenergy Projects. Energies *15*, 6136.
83. Kimura, T. (2024). Virtual Teams: A Smart Literature Review of Four Decades of Research. Hum. Behav. Emerg. Technol. *2024*, 8373370.
84. Raman, R., Nair, V.K., and Nedungadi, P. (2023). Discrepancies in Mapping Sustainable Development Goal 3 (Good Health and Well-Being) Research: A Comparative Analysis of Scopus and Dimensions Databases. Sustainability *15*, 16413.
85. Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., et al. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ *372*, n71.
86. van Eck, N.J., and Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics *84*, 523–538.
87. Raman, R., Sreenivasan, A., Ma, S., Patwardhan, A., and Nedungadi, P. (2023). Green Supply Chain Management Research Trends and Linkages to UN Sustainable Development Goals. Sustainability *15*, 15848.
88. Donthu, N., Kumar, S., and Pattnaik, D. (2020). Forty-five years of Journal of Business Research: A bibliometric analysis. J. Bus. Res. *109*, 1–14.
89. Raman, R., Nair, V.K., Nedungadi, P., Sahu, A.K., Kowalski, R., Ramanathan, S., and Achuthan, K. (2024). Fake news research trends, linkages to generative artificial intelligence and sustainable development goals. Heliyon *10*, e24727.
90. Le Blanc, D. (2015). Toward Integration at Last? The Sustainable Development Goals as a Network of Targets. Sustain. Dev. *23*, 176–187.
91. Nilsson, M., Griggs, D., and Visbeck, M. (2016). Policy: map the interactions between Sustainable Development Goals. Nature *534*, 320–322.
92. Raman, R., Gunasekar, S., Dávid, L.D., Rahmat, A.F., and Nedungadi, P. (2024). Aligning sustainable aviation fuel research with sustainable development goals: Trends and thematic analysis. Energy Rep. *12*, 2642–2652.
93. Hofmann, T. (2001). Unsupervised learning by probabilistic latent semantic analysis. Mach. Learn. *42*, 177–196.
94. Asmussen, C.B., and Møller, C. (2019). Smart literature review: a practical topic modelling approach to exploratory literature review. J. Big Data *6*, 1–18.
95. Egger, R., and Yu, J. (2022). A topic modeling comparison between lda, nmf, top2vec, and bertopic to demystify twitter posts. Front. Sociol. *7*, 886498.
96. Grootendorst, M. (2022). BERTopic: Neural topic modeling with a class-based TF-IDF procedure. Preprint at arXiv. https://doi.org/10.48550/arXiv.2203.05794.
97. Raman, R., Gunasekar, S., Kaliyaperumal, D., and Nedungadi, P. (2024). Navigating the Nexus of Artificial Intelligence and Renewable Energy for the Advancement of Sustainable Development Goals. Sustainability *16*, 9144.
98. Yi, J., Oh, Y.K., and Kim, J.M. (2025). Unveiling the drivers of satisfaction in mobile trading: Contextual mining of retail investor experience through BERTopic and generative AI. J. Retailing Consum. Serv. *82*, 104066.
99. Oh, Y.K., Yi, J., and Kim, J. (2024). What enhances or worsens the user-generated metaverse experience? An application of BERTopic to Roblox user eWOM. Internet Res. *34*, 1800–1817.
100. Kim, K., Kogler, D.F., and Maliphol, S. (2024). Identifying interdisciplinary emergence in the science of science: combination of network analysis and BERTopic. Humanit. Soc. Sci. Commun. *11*, 603.
101. Khodeir, N., and Elghannam, F. (2024). Efficient topic identification for urgent MOOC Forum posts using BERTopic and traditional topic modeling techniques. Educ. Inf. Technol., 1–27.

STAR★METHODS

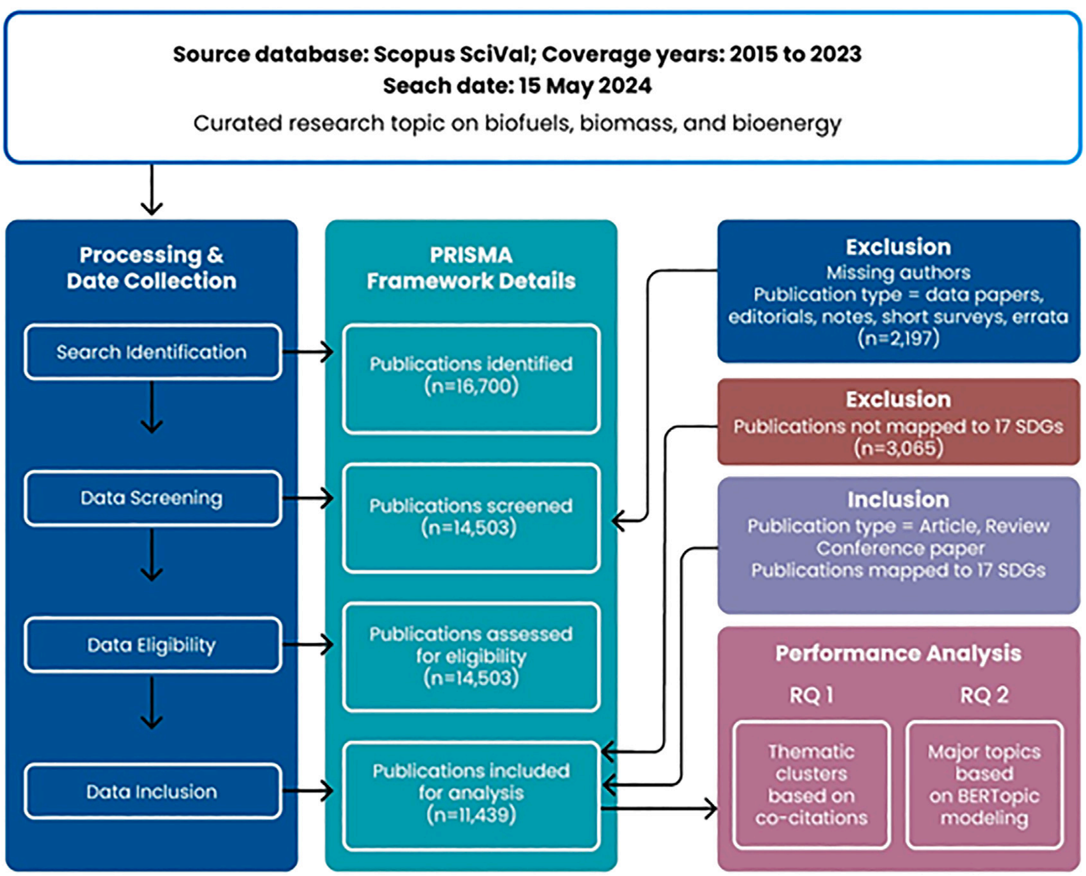
KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
PRISMA model	Page et al.[85]	https://doi.org/10.1136/bmj.n71
VOSviewer	Van Eck, N., & Waltman, L.[86]	www.vosviewer.com
Other		
Data S1	This paper	Biofuel dataset.xlsx

METHOD DETAILS

PRISMA protocol

This study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework as outlined by Page et al. (2021).[85] PRISMA provides a structured approach for conducting systematic reviews, including the formulation of research questions, development of a search strategy, literature search execution, screening, and analysis (Below Figure). Its effectiveness across various research domains is well-established.[87]



Research framework based on PRISMA and BERTopic modeling

We chose Scopus, a robust database of peer-reviewed literature, for its suitability for conducting quantitative studies.[88] During the identification phase conducted on 15 May 2024, the research utilized Scopus's curated topic on biofuels, biomass, and bioenergy, resulting in 16,700 publications from 2015-2023. The year 2015 was significant because it marked the formal adoption of the UN SDGs. During the screening phase, 2,197 publications lacking complete author details, publications of the type of book, book chapters, data papers, editorials, errata, notes, letters, and short surveys were excluded, leaving 14,503 publications of the type of article, reviews, and conference papers. Next, during the eligibility phase, publications aligned with the SDGs were identified via proprietary algorithms within the Scopus database, informed by initiatives such as the Aurora Network Global's SDG Queries and the University of Auckland's SDG Mapping Initiative. Elsevier's SDG Mapping Initiatives, integrated directly within Scopus, provided preset search queries for each SDG and utilized a machine-learning model refined through expert review. This precision of SDG mapping facilitates detailed analyses of research trends, as demonstrated in studies by Fake News and Metaverse.[70,89] For the final dataset, publications directly mapped to SDGs were included, resulting in 11,439 publications.

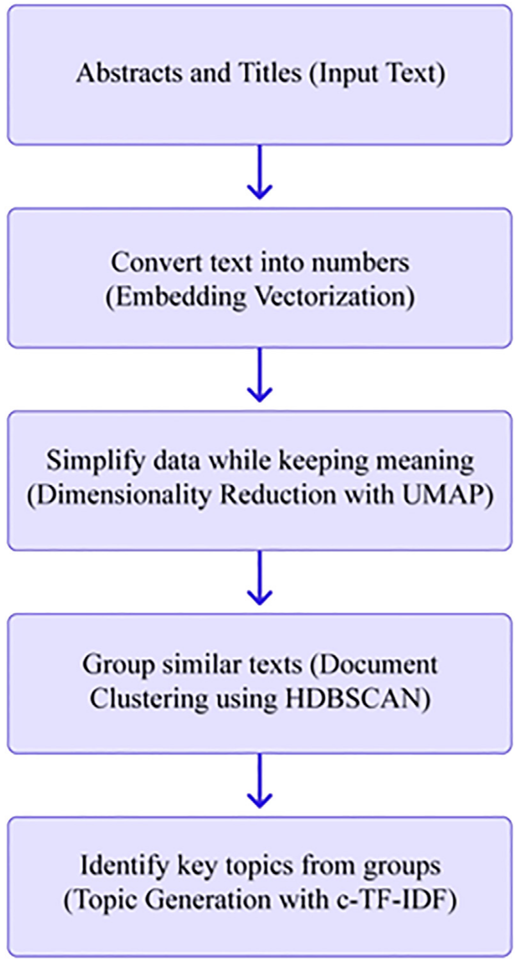
SDG framework

Network analyses by Le Blanc (2015)[90] and Nilsson et al. (2016)[91] reveal varying degrees of interconnections among the SDGs. Some goals demonstrate strong links across numerous targets, whereas others show weaker connections. Using a cocitation mapping technique and VOSviewer,[86] a widely recognized tool in scientometrics—for its ability to both import data directly from Scopus and create intuitive scientific networks, we visualized the semantic proximity between SDGs on the basis of joint citation frequency. VOSviewer offers a clear, data-driven visualization of how these goals interconnect.[92] Its robust capabilities, including user-friendly interfaces and advanced layout algorithms, facilitate deeper insights into emerging research clusters. The resulting map portrays each SDG as a node whose size indicates its prevalence in research, whereas the thickness of connecting lines represents cocitation frequency, highlighting the interconnected network of SDGs.

BERTopic modeling

Topic modeling greatly enhances exploratory analysis and literature review processes, as proposed by Hofmann (2001).[93] Asmussen and Møller (2019)[94] advanced the methodology by integrating machine learning techniques. A range of methods exist for topic modeling—among them Non-negative Matrix Factorization (NMF), Latent Dirichlet Allocation (LDA), Probabilistic Latent Semantic Analysis (PLSA), and To2Vec. However, these methods often fail to capture the deeper semantic links between words and face challenges when dealing with short-text data.[95] Unlike traditional topic modeling methods that rely on Bag-of-Words (BoW) approaches, which focus on term frequency, Grootendorst's machine learning-based BERTopic (2022)[96] leverages pretrained BERT embeddings and significantly improved topic modeling performance. Egger and Yu (2022)[95] confirmed BERTopic's ability to capture semantic meanings and contextual relationships effectively. BERTopic modeling has been successfully used to map research topics to SDGs.[97] In our study, we employed BERTopic within a Python environment via transformers and the Class-Tf-idf-Transformer to generate concise topic clusters. This streamlined the creation of comprehensible topics while preserving essential descriptive words. Preprocessing included text cleaning, natural language processing (NLP), and tokenization. We used the "all-mpnet-base-v2" model from the sentence transformer for sentence embeddings and applied uniform manifold approximation and projection (UMAP) for dimensionality reduction. For the main topic modeling task, the "all-MiniLM-L6-v2" model was used to fit the BERTopic model to the preprocessed text. This process extracted distinct topics and provided probability calculations for topic assignments. We then analyzed the generated topics for coherence and examined the distribution of publications across topics to gain insights into the associations between publications and identified topics.

The modeling process starts with converting input text into numerical representations, known as embedding vectorization (Below Figure). These embeddings are then refined through Unified Manifold Approximation and Projection (UMAP), a technique that reduces dimensionality to group similar data points and enhances the interpretability of topic clusters.[98] To form clusters, Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) is applied, which identifies dense areas of data while filtering out noise. Subsequently, key terms for each cluster are extracted using class-based Term Frequency-Inverse Document Frequency (c-TF-IDF), a method that emphasizes words based on their distribution across documents.[99] For this study, we utilized the "all-MiniLM-L6-v2" model, tailored for tasks such as clustering and semantic analysis.[100] Topics are assigned to documents using these representative terms, with probabilities indicating the strength of each document's association with specific topics.[101]



BERTopic modeling steps

During BERTopic model training, we configured key parameters: a minimum topic size of 20 (min_topic_size = 20) and 20 keywords per topic (top_n_words = 20). The min_topic_size parameter sets the smallest number of publications that can form a topic, with higher values yield fewer but more focused topics. The top_n_words parameter specifies the number of keywords that represent each topic. Following training, we generated a list of topics and their associated publications. Topic labels were derived from the keywords and the twenty most cited publications within each topic. For clarity in our analysis, we concentrated on the five most prominent topics identified by BERTopic. Within these selected topics, we further examined the three most highly cited publications.

QUANTIFICATION AND STATISTICAL ANALYSIS

There are no quantification or statistical analyses to include in this study.