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EDITED BY
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University of Debrecen, Hungary

*CORRESPONDENCE
Susy Harjanti
✉ susy.harjanti@binus.ac.id

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Unlocking circular economy and green innovation pathways for sustainable biofuel: a global bibliometric analysis with insights from Indonesia's B40 transition

Susy Harjanti*, Harjanto Prabowo and Rano Kartono Rahim

Management Department, BINUS Business School Doctor of Research in Management, Bina Nusantara University, Jakarta, Indonesia

The global transition toward sustainable energy systems requires biofuel production pathways that embrace circular economy principles and green innovation strategies. While circular economy and green innovation are widely referenced in the biofuel literature, research remains fragmented, lacking a comprehensive mapping of their intersection and practical insights for policy and industry. This study conducts a global bibliometric analysis to systematically map research trends, thematic structures, and collaboration networks at the intersection of circular economy and green innovation within the biofuel sector. Using data from Scopus and Web of Science (2020–2025), the analysis employs VOSviewer and Biblioshiny to examine publication growth, thematic clusters, temporal evolution, influential authors, and country-level collaborations. The findings reveal distinct thematic clusters linking circular economy strategies, waste management, green technology adoption, and sustainability policy. Despite this growing body of research, significant knowledge gaps remain, including limited integration of circular economy practices, fragmented technological innovation pathways, and underdeveloped policy frameworks. Collaboration network analysis highlights uneven global research connectivity, underscoring opportunities for stronger thematic integration and international cooperation. By offering a global mapping of these trends and gaps, this study provides strategic insights to guide the development of more circular and innovative biofuel systems. With specific reference to Indonesia's B40 transition policy as an illustrative context, the analysis highlights actionable pathways to support sustainability, decarbonization, and market access goals. The results offer a critical evidence base for policymakers, industry leaders, and researchers to prioritize investments, strengthen collaboration networks, and design coherent strategies for advancing sustainable biofuel production.

KEYWORDS

circular economy, green innovation, biofuel industry, bibliometric analysis, sustainable production, B40 transition, collaboration networks

1 Introduction

This paper introduces the growing urgency of renewable energy and biofuels, underscoring their role in addressing sustainability and energy security challenges. It then explores the theoretical underpinnings of Green Innovation (GI) and Circular Economy (CE), highlighting their convergence in shaping sustainable practices within the biofuel sector. Finally, the focus turns to Indonesia's biodiesel industry as the research context, where the integration of CE and

GI provides valuable insights for advancing resilient and sustainable energy pathways.

1.1 The urgency of renewable energy and biofuel

The global energy landscape is undergoing a transformative transition driven by the dual imperatives of climate change mitigation and energy security. This transition favors renewable energy integration to replace traditional fossil fuel dependence, aligning with international commitments such as the Paris Agreement and Sustainable Development Goals (SDGs) aimed at limiting global temperature rises and fostering clean energy access universally. To facilitate this shift, policy frameworks have become indispensable, serving as the scaffolding for incentivizing renewable energy technologies and guiding coherent national and international strategies. Global trends indicate an accelerating deployment of renewables, supported by technological innovation, cost reductions, and regulatory instruments. Policy mechanisms such as subsidies, mandates, carbon pricing, and green financing effectively stimulate market adoption and innovation in renewable energy, including biofuels (Rahman et al., 2022). Specific to bioenergy, policies that mandate blending percentages for biodiesel within fuel markets, known as blending mandates, have been critical to promoting uptake and scaling production. Indonesia exemplifies this policy-driven transition, particularly with its ambitious biodiesel blending policies, such as the B30 mandate, which requires a 30% biodiesel blend in diesel fuel in 2020 and B40 mandate launched in January 2025. These strategic policies serve multiple objectives: reducing fossil fuel imports, promoting rural development, increasing national energy self-reliance, and contributing to global climate commitments (Khan et al., 2021). At the European level, the Green Deal underscores the role of integrated policy and technological innovation to forge sustainable, circular, and competitive energy systems, where biofuels are a vital component of renewable energy transformation (Stefanis et al., 2024; Umar et al., 2021). Such convergence of policy imperatives affirms that achieving sustainable energy transitions is dependent on robust, multi-scalar policy frameworks that foster innovation, sustainable resource management, and inclusive growth.

Biofuels, as renewable fuels derived from biological sources, offer a pragmatic energy solution bridging the nexus among energy security, environmental sustainability, and socio economic development. They encompass various types, predominantly biodiesel derived from vegetable oils and animal fats, and bioethanol from sugar or starch-rich biomass. Biodiesel production often utilizes feedstocks such as crude palm oil (CPO), soybean oil, and in certain contexts, coconut oil, leveraging domestically abundant agricultural resources. Importantly, biofuels contribute to energy diversification by providing alternatives to petroleum-based fuels, enhancing national energy security especially for countries heavily reliant on fuel imports. Indonesia, as the world's largest palm oil producer and exporter, strategically emphasizes palm oil-based biodiesel as a domestic renewable energy source while simultaneously striving to balance food provision and export objectives (Puspitawati et al., 2024; Sharma et al., 2020a, 2020b). Lifecycle assessments further reveal that while biodiesel production can offer substantial carbon reductions, primary environmental impacts are frequently associated with plantation phases, necessitating sustainable cultivation practices (Wahyono et al., 2020; Palansooriya et al., 2022). Thus, biofuels emerge as pivotal renewable energy resources, requiring integrated sustainability assessments and informed policy approaches to reconcile energy, environmental, and socio economic goals (Aron et al., 2020).

1.2 Green innovation and circular economy: theoretical foundations in the biofuel industry

Green innovation in the biofuel sector involves the development and application of novel technologies, processes, and systems that reduce environmental impacts, enhance resource efficiency, and foster sustainable production within the energy value chain (Awasthi et al., 2020). It encompasses innovations ranging from feedstock development and microbial engineering to process intensification and waste valorization, driving the transition towards sustainable bioenergy. Green innovation in this context is not limited to technological improvements but also includes advancements in business models and regulatory frameworks that incentivize sustainable practices. This holistic perspective is essential to overcome systemic challenges such as feedstock variability, scaling bottlenecks, and financing constraints that have historically impeded the biofuel industry's growth. The circular economy (CE) paradigm offers a systemic model aimed at decoupling economic growth from environmental degradation by prioritizing resource efficiency, waste minimization, and value retention within production and consumption cycles (Yuan et al., 2021). By focusing on the principles of reduce, reuse, and recycle, CE frameworks enable the redesign of industrial processes to foster sustainability and resilience. In the biofuel industry, circular economy principles are particularly pertinent as they promote the comprehensive utilization of biomass resources, valorization of waste streams, and integration of bioenergy within broader biorefinery platforms (D'Amato et al., 2017; Friant et al., 2020). Such platforms optimize conversion processes to simultaneously produce fuels, chemicals, and energy, thereby enhancing economic viability and environmental performance (Clauser et al., 2021; Bag et al., 2022). However, real-world application of CE in biofuels is nuanced, contending with issues often described as "value uncaptured" within circular business models. This refers to negative outcomes such as excess or insufficient value creation during product lifecycles, leading to environmental, social, or economic burdens (Gennari and Bocchi, 2023; Jain et al., 2022). Addressing these challenges requires identifying the forms of value absence, destruction, surplus, or missed opportunities, and developing strategies to turn these into value creation prospects. Moreover, biofuel production from waste biomass, including fishery and agricultural residues, exemplifies CE by converting otherwise discarded materials into valuable fuels and by-products (Tan et al., 2024a, 2024b). The sustainable management of these resources not only reduces environmental pollution but also strengthens local economies through innovative value chains (Banu et al., 2021). CE implementation in biofuels necessitates cross-sector collaboration, supportive policy frameworks, technological integration, and stakeholder engagement to establish regenerative systems that maintain material flows and foster sustainable industrial symbiosis (Kurniawan et al., 2022).

The integration of green innovation and circular economy concepts propels the biofuel industry toward more sustainable and resilient systems. Green innovation acts as a catalyst by introducing technologies and processes that enable circularity, while the circular economy framework provides an overarching strategic structure for systemic resource management and value optimization. For example, green technologies facilitating efficient conversion of organic waste to biofuels embody circularity by reducing raw material inputs and minimizing waste generation (Ciliberto et al., 2021). Such synergistic approaches enable the design of circular business models focused on sustainability and continuous value creation, addressing challenges related to resource scarcity and environmental externalities (Gennari and Bocchi, 2023). Nevertheless, the biofuel sector's transition to a circular economy is not without obstacles. The presence of "value uncaptured" aspects, where circular strategies underperform or generate unintended negative consequences, indicates the need for refined models that address ecological, social, and economic trade offs effectively (Shah et al., 2023). Additionally, emerging digital technologies, such as Industry 4.0 tools, offer promising avenues to enhance transparency, efficiency, and integration in sustainable supply chains, reinforcing circularity (Hettiarachchi et al., 2022; Cheng et al., 2022). By leveraging these synergies, the biofuel industry can advance beyond linear resource use models toward regenerative systems that deliver environmental benefits, foster innovation-driven competitiveness, and create shared value for stakeholders (Velvizhi et al., 2022a, 2022b).

1.3 Indonesia's biodiesel industry as research context

Indonesia occupies a pivotal position in the global biodiesel landscape, primarily through its vast palm oil production sector. As the largest producer and exporter of palm oil worldwide, Indonesia not only sustains a significant portion of global supply but also strategically channels this commodity into the biodiesel industry, positioning palm oil-based biodiesel as a cornerstone of its renewable energy strategy (Puspitawati et al., 2024; van Langen et al., 2021). This biofuel contributes substantially to national energy portfolios by serving as a domestic renewable energy source and by fulfilling export demands, leveraging Indonesia's agricultural comparative advantage. The government has institutionalized this leadership through policies mandating biofuel blending ratios, exemplified by the B30 mandate requiring 30% biodiesel blending in diesel fuel (Zhang et al., 2020). This blending mandate exemplifies policy-driven efforts to stimulate biofuel consumption and production, which, coupled with Indonesia's strong export capabilities, underlines its significant influence on regional and global bioenergy markets (Djatmika et al., 2023; Barros et al., 2020). Indonesia's biodiesel sector thus operates at the confluence of energy security, economic development, and environmental stewardship. Its governance architecture both reflects and shapes global discourse on biofuel sustainability, providing a pertinent context for examining the operationalization of green innovation and circular economy paradigms within a large scale, commodity-driven biofuel industry. Indonesia's biodiesel policies yield multifaceted economic outcomes, encompassing macroeconomic growth, sectoral shifts, and regional development impacts. Computable general equilibrium analyses suggest that downstream biodiesel policies enhance economic growth, increase investment inflows, and stimulate national exports over the long term (Puspitawati et al., 2024). Moreover, the B30 blending mandate specifically contributes to regional economic stimulation by integrating biofuel production within local economies, fostering energy security, and reducing dependence on imported fossil fuels (Sahara et al., 2022; ESDM, 2019). However, these policies also generate nuanced challenges, such as inflationary pressures in the short term and unintended agricultural inter-sectoral competition that can lead to reduced production of certain food commodities like sugarcane and soybeans, potentially escalating food prices (Sahara et al., 2022; Kang et al., 2020). Environmental assessments complement this understanding by highlighting that while biodiesel production offers sustainable energy pathways, key environmental impacts, particularly in the oil palm plantation stage, necessitate integrated management to mitigate carbon footprint and ecosystem damage (Wahyono et al., 2020; Kardung et al., 2021). Within Indonesia's biodiesel industry, nascent but growing initiatives embody the integration of circular economy principles and green innovation. Efforts to valorize waste and diversify feedstocks, including incorporation of advanced biological resources like black soldier fly larvae, reflect progressive strides toward sustainable biofuel production aligned with circularity goals (Odoi-Yorke et al., 2025; Ranjbari et al., 2021). Simultaneously, government and industry stakeholders acknowledge the critical need for improved regulatory coordination and dedicated institutional frameworks to oversee circular biofuel initiatives efficiently and inclusively (Djatmika et al., 2023; Garlapati et al., 2020). Therefore, Indonesia presents an illustrative case for studying the operationalization of circular economy and green innovation in a large-scale, agro industrial biofuel context. Insights from this case can inform broader discourse on achieving sustainability transitions in bioenergy sectors globally.

The novelty of this study lies in a dual approach: a theory aware bibliometric diagnosis paired with an applied country anchor, Indonesia's biodiesel transition (B30 → B40), as triangulation, which together makes the underdeveloped CE–GI nexus visible and actionable. Our cross-domain maps show that Circular Economy (CE) and Green Innovation (GI) streams remain underdeveloped, with a GI-heavy, CE-light pattern over time. Indonesia's biodiesel trajectory from B2.5 to B40 (among the world's highest mandated blends) mirrors this global pattern, in this case policy and engineering advances scale blends and national distribution, while CE practices remain largely regulation-led. This matters strategically, as countries pursue higher blends, feedstock demand, especially palm rises and, without CE-guided GI (waste/residue routing, closed loop logistics, symbiosis), land pressure and cost/volatility risks escalate. We therefore introduce a simple CE–GI convergence lens to interpret the evidence and organize actionable pathways toward a sustainable biofuel business model in Indonesia and other biofuel producing countries.

Accordingly, this study is guided by two central research questions:

1. How have global research trends and thematic areas evolved in supporting sustainable circular economy and green innovation solutions for the biofuel industry?
2. What collaboration networks, knowledge gaps, and strategic pathways can enable Indonesia's B40 transition toward a more circular and innovative biofuel system?

Employing bibliometric tools, the study extracts data from comprehensive databases such as Scopus and Web of Science. It systematically maps research clusters, co-authorship networks, and keyword co-occurrences, enabling a rigorous survey of research landscapes, gaps, and collaboration patterns (Odoi-Yorke et al., 2025; Shah et al., 2023; Kanda et al., 2021).

2 Methodology

This research employs a comprehensive bibliometric approach combined with science mapping techniques to examine the intersection of circular economy (CE) principles and green innovation (GI) strategies in the sustainable biofuel industry. Bibliometric analysis is used as a quantitative method to process large-scale scholarly metadata (titles, abstracts, keywords, references, etc.), allowing identification of patterns and trends in the literature (van Eck and Waltman, 2010; Haustein and Larivière, 2015; Amofa et al., 2023). The study utilizes tools like VOSviewer and Biblioshiny for data processing and visualization (van Eck and Waltman, 2010; Aria and Cuccurullo, 2017), integrating performance indicators (publication and citation counts) with science mapping techniques such as co-authorship networks, citation analysis, and keyword co-occurrence to uncover intellectual structures and emerging thematic clusters (Afzal et al., 2025; Umar et al., 2021). To ensure contextual relevance, the bibliometric findings are triangulated with Indonesia's recent biodiesel policy trajectory, notably the transition from a B30 mandate to the B40 program officially launched in January 2025 (Christina, 2025; Dewi, 2024; ESDM, 2025). This approach provides a real world implementation lens for interpreting the academic landscape, which is crucial for linking traditionally separate research streams of CE and GI within an industry context (Sharma et al., 2020a, 2020b). Furthermore, the systematic combination of bibliometric mapping and empirical policy context enhances the interdisciplinarity and replicability of the analysis, as it enables efficient screening of a broad corpus and transparent documentation of search strategies, inclusion criteria, and analytical procedures (Haustein and Larivière, 2015; Szomszor et al., 2020). Science mapping visualizations complement the quantitative analysis by illustrating the conceptual and collaborative networks in the field, thereby highlighting how circular economy initiatives and green innovations co-evolve and which actors or knowledge domains lead the discourse (Smyrnova-Trybulska et al., 2018; Alkhammash, 2023).

This study draws on two major bibliographic databases, Scopus (Elsevier) and Web of Science (Clarivate Analytics), to ensure comprehensive and high quality coverage of the interdisciplinary biofuel literature. These databases were selected for their strong indexing in environmental sciences, engineering, energy, business, and policy research (van Eck and Waltman, 2010; Haustein and Larivière, 2015). Scopus provides extensive coverage of peer-reviewed journal articles with rich author, affiliation, and citation data, enabling detailed co-authorship and organizational network analyses (Costa et al., 2018; Si et al., 2019). Web of Science complements this by offering robust longitudinal depth and consistent indexing practices, particularly valuable for tracing thematic and citation trends over time (Abramo and D'Angelo, 2011; Orduña-Malea and Costas, 2021). Combining both databases reduces disciplinary bias, ensuring that interdisciplinary research on circular economy (CE), green innovation (GI), and biofuel policy is comprehensively captured (Smyrnova-Trybulska et al., 2018; Alkhammash, 2023). Only peer-reviewed English-language journal articles were included to guarantee quality and global comparability. The final dataset, retrieved on July 11, 2025, was analyzed using VOSviewer and Biblioshiny for mapping citation patterns, co-occurrence networks, and intellectual structures.

The search strategy was developed to systematically capture literature linking CE, GI, and the biofuel sector through a structured Boolean approach. Thematic dimensions were identified: (i) circular economy and sustainability concepts, (ii) green innovation and technology development, (iii) biofuel and renewable fuel frameworks. For Scopus, the TITLE-ABS-KEY fields were used to search titles, abstracts, and author keywords with logical operators combining synonyms and related terms (van Eck and Waltman, 2010; Haustein and Larivière, 2015). Web of Science searches were performed in the Topic (TS) fields using equivalent Boolean structures to ensure comparable coverage (Abramo and D'Angelo, 2011). Filters were applied to restrict results to English-language, peer-reviewed journal articles published between 2020 and 2025, aligning with Indonesia B30 to B40 biodiesel transition and focusing on final stage publications in Environmental Science, Energy, Business, Economics, and Multidisciplinary subject areas (Costa et al., 2018; Si et al., 2019). The focus on 2020–2025 is to capture the B30–B40 policy window in which CE and GI shift from concepts to implementation. The overlay shows CE/LCA as recent hubs (after 2022) linking policy and supply chain topics, whereas GI for higher blends dominates and CE streams (UCO, POME) are still emerging. Adding pre 2020 literature would mostly increase the weight of legacy discussions without changing the core cluster architecture of this transition period. While the limitation on the metric-based corpus to peer-reviewed, English language journals indexed in Scopus and Web of Science to preserve uniform metadata, enable reliable cross database deduplication, and apply field normalized citation measures. Including non-English outlets would require language-specific tokenization and keyword cross walks that risk fragmenting terms and biasing co-occurrence, centrality, and clustering estimates. Accordingly, all network results should be interpreted as reflecting the English indexed literature. The complete search string in Scopus that was used to construct the dataset is the following:

TITLE-ABS-KEY ("circular economy" OR "closed loop" OR "resource efficiency" OR "sustainable production") AND ("green innovation" OR "eco-innovation" OR "environmental innovation" OR "sustainable technology") AND ("biofuel" OR "bioenergy" OR "renewable fuel" OR "biomass") AND ("sustainability" OR "sustainable development" OR "environmental sustainability" OR "green practices") AND ("waste management" OR "recycling" OR "resource recovery" OR "life cycle assessment") AND PUBYEAR > 2020 AND PUBYEAR < 2026 AND (LIMIT-TO (PUBSTAGE,"final")) AND (LIMIT-TO (SUBJAREA,"ENVI") OR LIMIT-TO (SUBJAREA,"ENER") OR LIMIT-TO (SUBJAREA,"BUSI") OR LIMIT-TO (SUBJAREA,"SOCI") OR LIMIT-TO (SUBJAREA,"ECON") OR LIMIT-TO (SUBJAREA,"MULT")) AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")).

While for Web of Science, the following query has been used:

TS = (("circular economy" OR "closed loop" OR "resource efficiency" OR "sustainable production").

AND ("biofuel" OR "bio-energy" OR "bio fuel" OR "renewable fuel" OR "biomass" OR "bio-based fuel")).

OR TS = (("green innovation" OR "eco-innovation" OR "environmental innovation" OR "sustainable technology").

AND ("biofuel" OR "bio-energy" OR "bio fuel" OR "renewable fuel" OR "biomass" OR "bio-based fuel")).

OR TS = (("waste management" OR "recycling" OR "resource recovery" OR "life cycle assessment").

AND ("biofuel" OR "bio-energy" OR "bio fuel" OR "renewable fuel" OR "biomass" OR "bio-based fuel")).

Included in the datasets are: (i) publications from 2020 to 2025, (ii) peer-reviewed journal articles (excluding editorials, proceedings, books, reports), and (iii) English-language articles. The search produced 7,181 records: 626 from Scopus and 6,555 from Web of Science. Scopus records (.csv) and WoS records (.bib) were integrated for cleaning (Costa et al., 2018; Abramo and D'Angelo, 2011) (see Figure 1 for the data cleaning workflow). The combined dataset (7,181 records) was processed using RStudio (2024.12.1 Build 563) with the Bibliometrix R package (Haustein and Larivière, 2015; Szomszor et al., 2020), yielding 7,117 unique articles after cleaning. Key steps included: (i) metadata harmonization across title, authors, journal, DOI (van Eck and Waltman, 2010; Si et al., 2019); (ii) deduplication using fuzzy matching (DOI, title, author) (Szomszor et al., 2020; Orduña-Malea and Costas, 2021; Aquino et al., 2022); (iii) quality filtering of records missing abstracts/keywords (van Eck and Waltman, 2010; Waltman and van Eck, 2012); (iv) field standardization for author names, institutions, citation metrics (Costa et al., 2018; Davis et al., 2014). The cleaned dataset was exported in. TXT (for VOSviewer mapping) and. XLSX (for Biblioshiny analysis), ensuring full interoperability and replicability (Costa et al., 2018; Abramo and D'Angelo, 2011).

3 Results

The results are organized into nine subsections. First, global research flows and priorities are mapped (3.1), followed by the identification of thematic clusters and fragmented knowledge structures (3.2). The temporal evolution of research and emerging topics are then traced (3.3), complemented by detailed term-level trend analysis (3.4). Connections between CE and GI in biofuel research are examined (3.5), alongside influential publications and citation patterns (3.6). Integration of thematic and collaboration insights outlines CE–GI research pathways (3.7). Finally, the thematic structure of CE–GI sustainability research (3.8) and international collaboration networks (3.9) are presented.

3.1 Mapping global research flows and priorities

The three field plot in Figure 2 illustrates how author countries, research themes, and journals interconnect within the global literature on CE and GI approaches to biofuels. This mapping establishes the broader landscape in which thematic and network patterns have developed. On the left axis, several countries emerge as major contributors, with China and India demonstrating the most extensive linkages to diverse thematic areas. China, in particular, shows strong

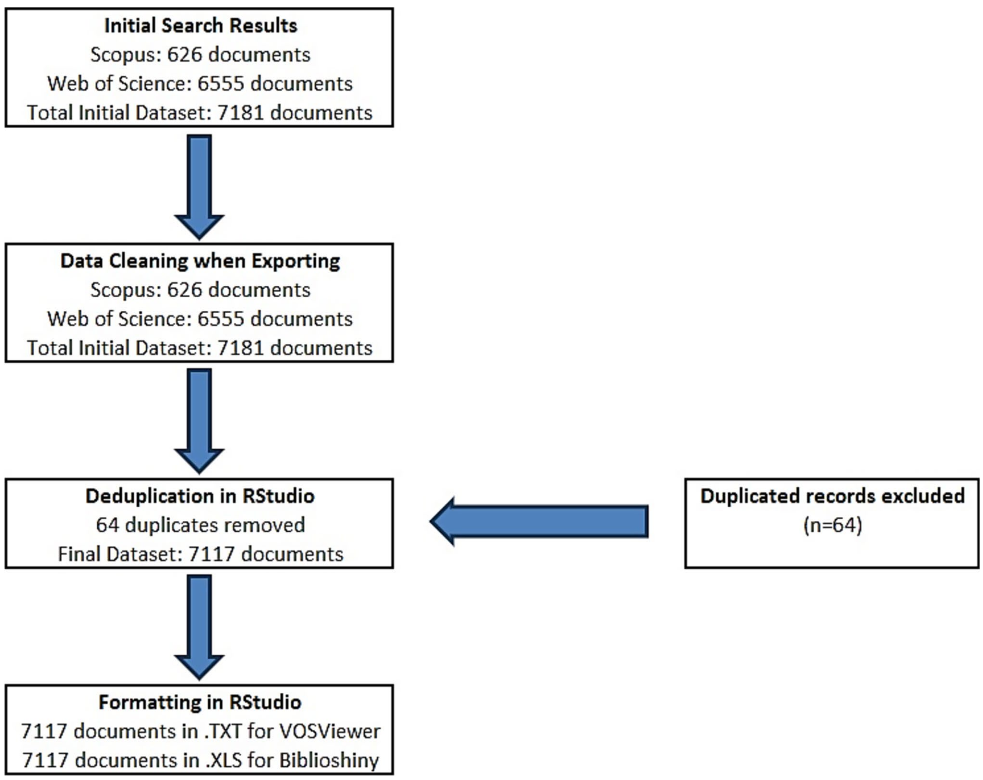

FIGURE 1
Workflow of data collection, cleaning, deduplication, and formatting for bibliometric analysis.

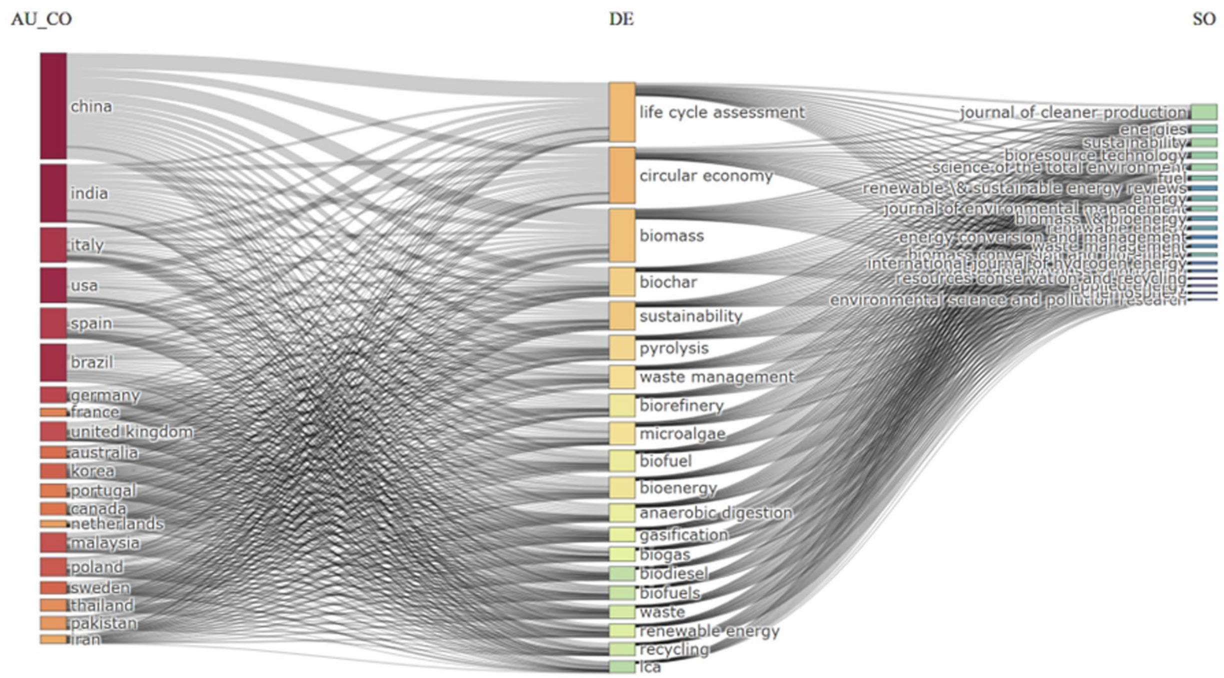

FIGURE 2
Three field plot linking countries, keywords, and sources in global biofuel-related circular economy and green innovation research.

connections across keywords ranging from life cycle assessment and circular economy to biomass and biochar, underscoring its central role in shaping both technological innovation and sustainability discourse in the field. Other prominent contributors include Italy, the United States, Spain, and Brazil, reflecting a geographically dispersed but uneven distribution of research activity. The middle axis highlights the dominant keywords defining research priorities. Central terms such as life cycle assessment, circular economy, biomass, sustainability, and pyrolysis indicate that the literature maintains a dual focus on advanced conversion technologies and systemic sustainability assessment. The inclusion of biorefinery, waste management, and bioenergy further underscores the field's emphasis on valorizing waste streams and improving process efficiency, while keywords like biodiesel and biofuels illustrate continued attention to practical renewable fuel outcomes. On the right axis, a concentration of publications appears in key journals, notably Journal of Cleaner Production, Energies, Bioresource Technology, and Renewable and Sustainable Energy Reviews. These sources (Journal of Cleaner Production, Energies, Sustainability, Bioresource Technology, Science of the Total Environment, Fuel, Renewable and Sustainable Energy Reviews, Energy, Journal of Environmental Management, Biomass and Bioenergy, Renewable Energy, Energy Conversion and Management, Waste Management, Biomass Conversion and Biorefinery, International Journal of Hydrogen Energy, Waste and Biomass Valorization, Resources, Conservation and Recycling Applied Energy, Chemosphere, and Environmental Science and Pollution Research) serve as primary venues for disseminating research bridging CE principles and GI strategies in the biofuel sector.

Taken together, this three field mapping depicts a mature and multi-dimensional research ecosystem, marked by concentrated contributions from a subset of countries, broad thematic coverage, and a defined set of high impact publication outlets. These patterns provide the foundation for subsequent analyses exploring how research themes have evolved over time and how conceptual and collaborative networks shape the field's development.

3.2 Thematic clusters and fragmented knowledge structures

Figure 3 presents the keyword co-occurrence network derived from global biofuel research literature (2020–2025), mapping the thematic structure at the intersection of circular economy (CE) and green innovation (GI). The network reveals clear, color-coded clusters representing major research themes while also exposing the fragmented connections among them. The green cluster focuses on biomass conversion technologies, with prominent keywords such as pyrolysis, biochar, gasification, and hydrogen. This reflects strong research interest in advanced thermochemical methods for transforming biomass waste into renewable fuels. Although this cluster demonstrates technological depth, its relative separation from broader CE concepts suggests limited integration with systemic sustainability strategies. The red cluster captures circular economy and sustainability assessment themes, anchored by circular economy, life cycle assessment, and sustainability. This area represents a systemic perspective that emphasizes holistic evaluation frameworks such as life cycle assessment (LCA) to measure environmental impacts. However, its thematic distance from conversion technology clusters highlights weak linkages between process innovation and comprehensive CE assessment. The blue cluster emphasizes waste valorization and environmental management, characterized by keywords like wastewater, microalgae, nitrogen, adsorption, and water recovery. This suggests a specialized focus on environmental remediation and nutrient recovery, which, while relevant to CE, often remains siloed

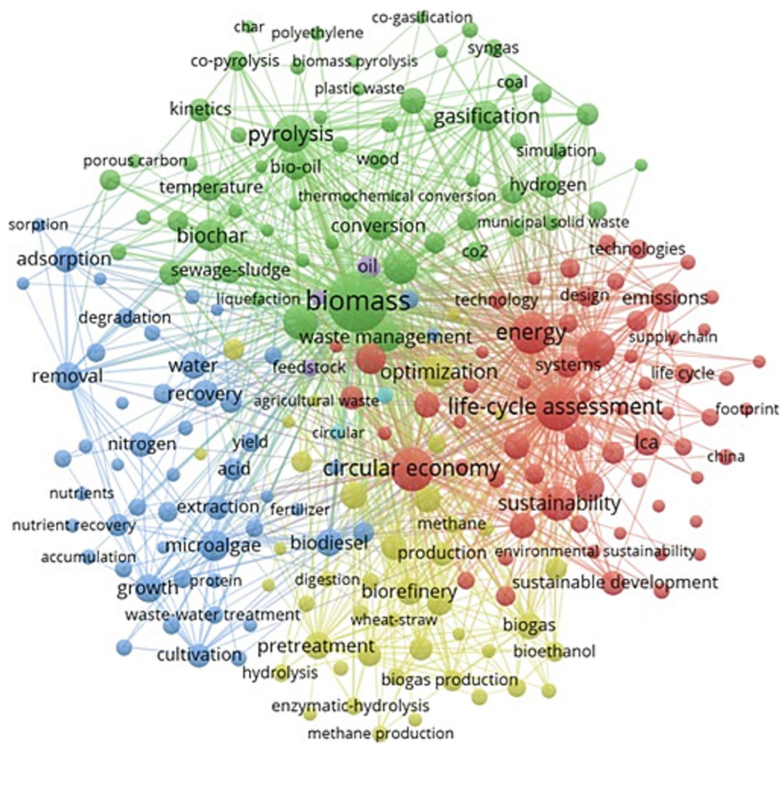

FIGURE 3
Co-occurrence map (2020–2025) showing four themes (conversion, CE–LCA, waste, policy); limited inter-cluster ties indicate CE–GI fragmentation.

from biofuel production research. The yellow cluster encompasses policy and technological optimization themes, featuring keywords such as technologies, optimization, biorefinery, biogas, bioethanol, and policy framework. This indicates research attention on enabling policy environments and system-level planning to support biofuel development. Nonetheless, the partial separation from both sustainability assessment and biomass conversion clusters underscores fragmentation in linking policy design with practical valorization strategies. Notably, terms such as biodiesel appear at the intersection of clusters, highlighting their cross-cutting relevance across technological, environmental, and sustainability themes. The presence of these bridging terms suggests opportunities for greater thematic integration.

Overall, the co-occurrence network shows that while biofuel research has developed well-defined thematic areas, conversion technologies, sustainability assessment, environmental management, and policy frameworks, these remain fragmented. Limited cross-cluster integration indicates a persistent gap in uniting technological innovation, CE principles, policy development, and sustainability evaluation. Addressing this fragmentation is essential for advancing more holistic and effective circular economy and green innovation solutions within the biofuel industry.

3.3 Temporal evolution and emerging research focus

Figure 4 displays the overlay visualization of the keyword co-occurrence network, illustrating the temporal evolution of thematic areas in biofuel research from 2020 to 2025. Colors represent the average publication year for each keyword, enabling identification of established topics and more recent, emerging research priorities. Core terms such as biomass, life cycle assessment, and energy predominantly appear in cooler blue- green shades, reflecting their longstanding presence and consistent development within the literature. These mature themes form the foundational basis of biofuel research, encompassing feedstock management, conversion processes, and sustainability assessment frameworks. In contrast, keywords such as pyrolysis, biochar, and circular economy exhibit warmer green - yellow tones, indicating increased prominence in more recent studies. Their positioning highlights an emerging research emphasis on advanced thermochemical conversion technologies and the systematic adoption of circular economy principles in biofuel production. Additional emerging terms include gasification, hydrogen, co-pyrolysis, and plastic waste, suggesting growing interest in diversifying feedstocks and valorizing complex waste streams through innovative processing methods. Further, terms like pretreatment, biorefinery, and enzymatic hydrolysis also appear with newer average years, demonstrating heightened attention to integrated, process-level optimization. Sustainability-related keywords such as sustainable development and environmental sustainability similarly show more recent temporal profiles, underscoring sustained and evolving discourse on policy frameworks and environmental impact evaluation.

Overall, the overlay map reveals a research landscape that is evolving from established biomass conversion and assessment themes toward newer, more integrated approaches that combine technological

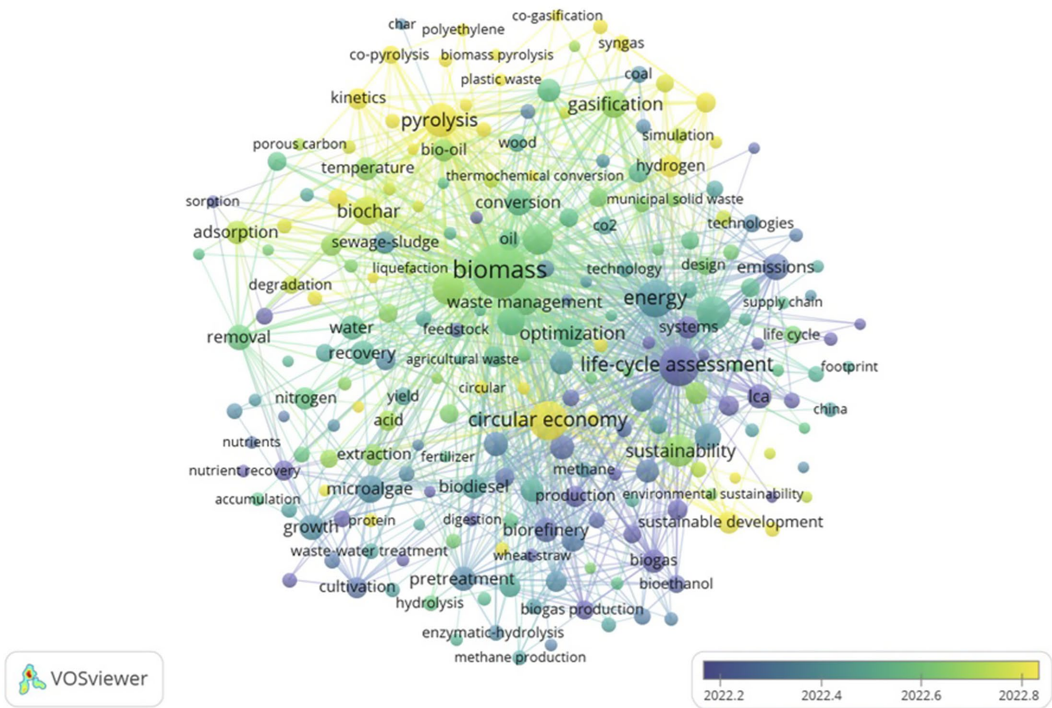

FIGURE 4
Temporal overlay highlighting established cores (biomass/LCA) and newer fronts (pyrolysis, biochar, CE, gasification), indicating growing CE–technology integration.

innovation, waste valorization, and circular economy strategies to advance sustainable biofuel systems.

3.4 Term-level trends and detailed topic evolution

To complement the overlay visualization of thematic emergence, the trend topics analysis provides term-level insights into the temporal evolution and prominence of keywords in biofuel research focused on circular economy (CE) and green innovation (GI) from 2020 to 2025. Figure 5 shows the distribution of research terms over time, highlighting both sustained and newly emerging areas of scholarly attention. The diagram reveals a broad thematic spread, with key terms reflecting both technological innovation and systemic sustainability perspectives (Chen et al., 2022; Yang et al., 2022). Central topics such as biomass, pyrolysis, waste, performance, optimization, and conversion exhibit strong and continuous presence across the timeline, indicating consistent research focus on advancing biofuel production processes and valorizing diverse feedstocks. Life cycle assessment, energy, and emissions also maintain significant visibility, underscoring the field's commitment to environmental impact evaluation and alignment with broader sustainability goals. The term anaerobic digestion similarly reflects interest in waste-to-energy strategies that support circular economy principles. Notably, the right side of the timeline shows the emergence of new and increasingly prominent terms such as sustainable development goals, economic policy, resource management, innovation, environmental impact, climate change, and urban area. These terms highlight a shift toward systemic, policy-relevant, and cross-sectoral themes, suggesting that the biofuel research agenda is evolving beyond purely technological questions to engage with integrated sustainability planning, governance, and socio-economic considerations. Terms such as environmental impact, impact assessment, and valorization further reinforce this transition toward holistic evaluation frameworks that account for environmental, social, and economic dimensions. The appearance of location-specific terms like city and Sweden indicates growing attention to localized, context-sensitive solutions, which is essential for effective CE implementation in the biofuel sector.

Overall, the trend topics analysis confirms that biofuel research is experiencing a thematic broadening. While core technological innovations remain vital, there is clear evidence of an expanding research agenda that incorporates CE strategies, policy integration, and systemic sustainability assessment. This evolution supports the goal of developing truly circular, low carbon biofuel systems capable of meeting diverse environmental and socio economic challenges.

3.5 Mapping CE–GI connections in biofuel research

Understanding how circular economy (CE) principles and green innovation (GI) solutions relate within biofuel research is essential for identifying opportunities to create more integrated, sustainable production systems. Factorial analysis offers insight into these conceptual relationships by visualizing how key themes cluster and align (Figure 6). The conceptual map reveals that keywords reflecting CE frameworks, including circular economy, sustainable development, life cycle assessment, and sustainability, form a coherent grouping. This

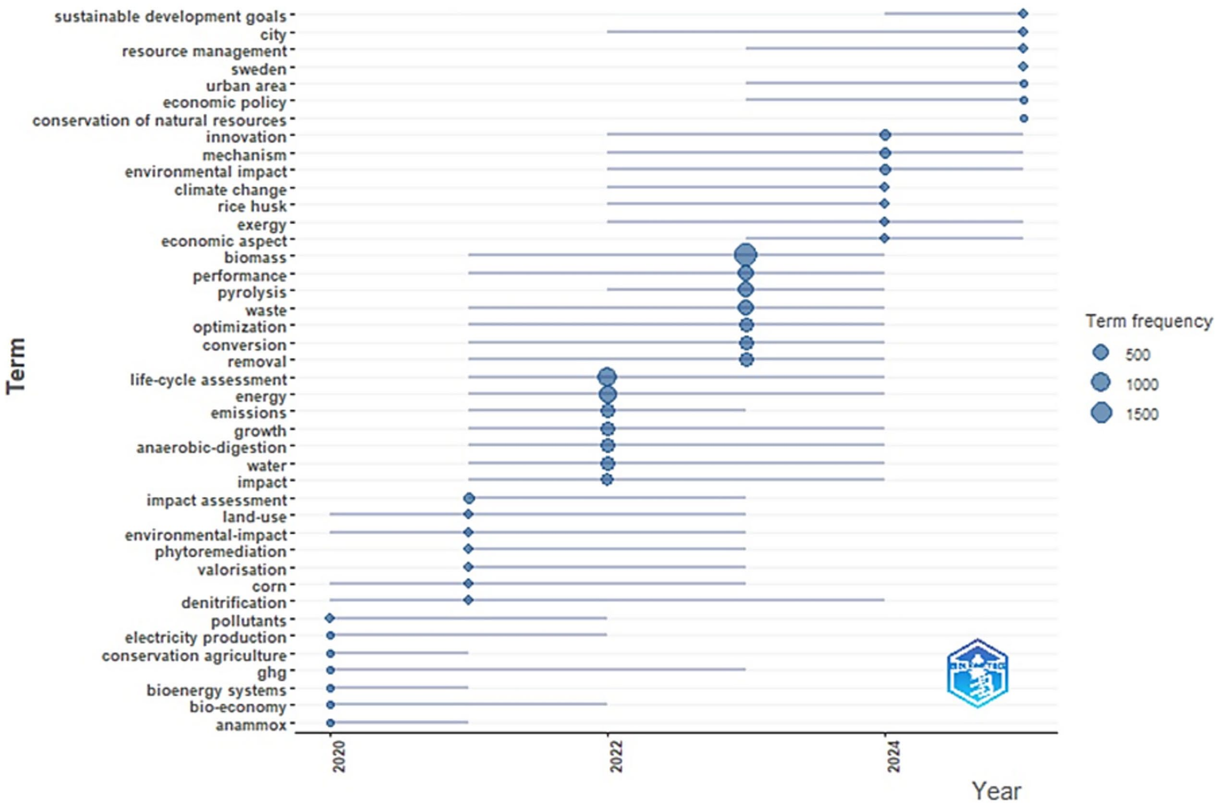

FIGURE 5
Trend topics analysis (2020–2025) showing the temporal evolution and prominence of biofuel-related terms, highlighting emerging priorities in circular economy and green innovation research.

cluster points to a shared emphasis on systemic planning, policy guidance, and holistic environmental assessment, all critical for designing sustainable biofuel strategies at a strategic level. In contrast, terms associated with GI approaches, such as biomass, conversion, pyrolysis, and waste management, appear in a separate cluster focused on technological innovation and operational improvements. This indicates strong development of practical solutions for improving feedstock utilization, waste valorization, and process efficiency. Between these two areas lies a subtle but important space for integration. Keywords like management, optimization, and energy occupy more central positions, suggesting potential bridging points where policy frameworks and technological strategies can come together.

Overall, the analysis shows that while both CE and GI concepts are well established in biofuel research, they remain only partially connected (Lopez et al., 2025). Addressing this conceptual separation offers an opportunity for the field to move beyond parallel efforts, aligning technological advances with sustainability goals in a genuinely circular biofuel industry. Strengthening these connections will be vital for achieving environmental targets while supporting economic and policy objectives.

3.6 Influential publications and citation patterns in biofuel CE–GI research

Figure 7 presents the ten most globally cited documents in the field of circular economy (CE) and green innovation (GI) applied to the biofuel industry. These highly cited papers reflect the intellectual foundations and prevailing scientific priorities that shape global research directions. The analysis shows that the most influential publications emphasize integrated sustainability assessment, waste valorization, and technological process optimization. For example, Rahman et al. (2022) with over 560 citations focuses on holistic renewable energy strategies, while Vanapalli et al. (2021) highlights the conversion of plastic and organic waste to biofuel within circular frameworks. Papers by Koul et al. (2022) and Sharma et al. (2020a, 2020b) similarly stress resource conservation, waste management, and life cycle assessment (LCA) methodologies as key enablers of sustainable biofuel production. These citation patterns underscore a strong global orientation toward reducing environmental impact through advanced waste management strategies and process innovation. The prominence of LCA approaches across top cited documents demonstrate a mature and data-driven commitment to evaluating the environmental benefits and trade offs of biofuel pathways. Crucially, this citation profile also suggests that while CE and GI themes are well established in the biofuel literature, research remains focused on general feedstocks (e.g., municipal waste, crop residues) and broadly applicable technological routes. This highlights a potential knowledge gap in adapting these concepts to tropical contexts with dominant feedstocks such as palm oil, where high blend targets (e.g., B40 in Indonesia) demand tailored CE-GI strategies.

Overall, mapping the most cited documents provides evidence of robust global research attention to CE and GI integration in biofuel,

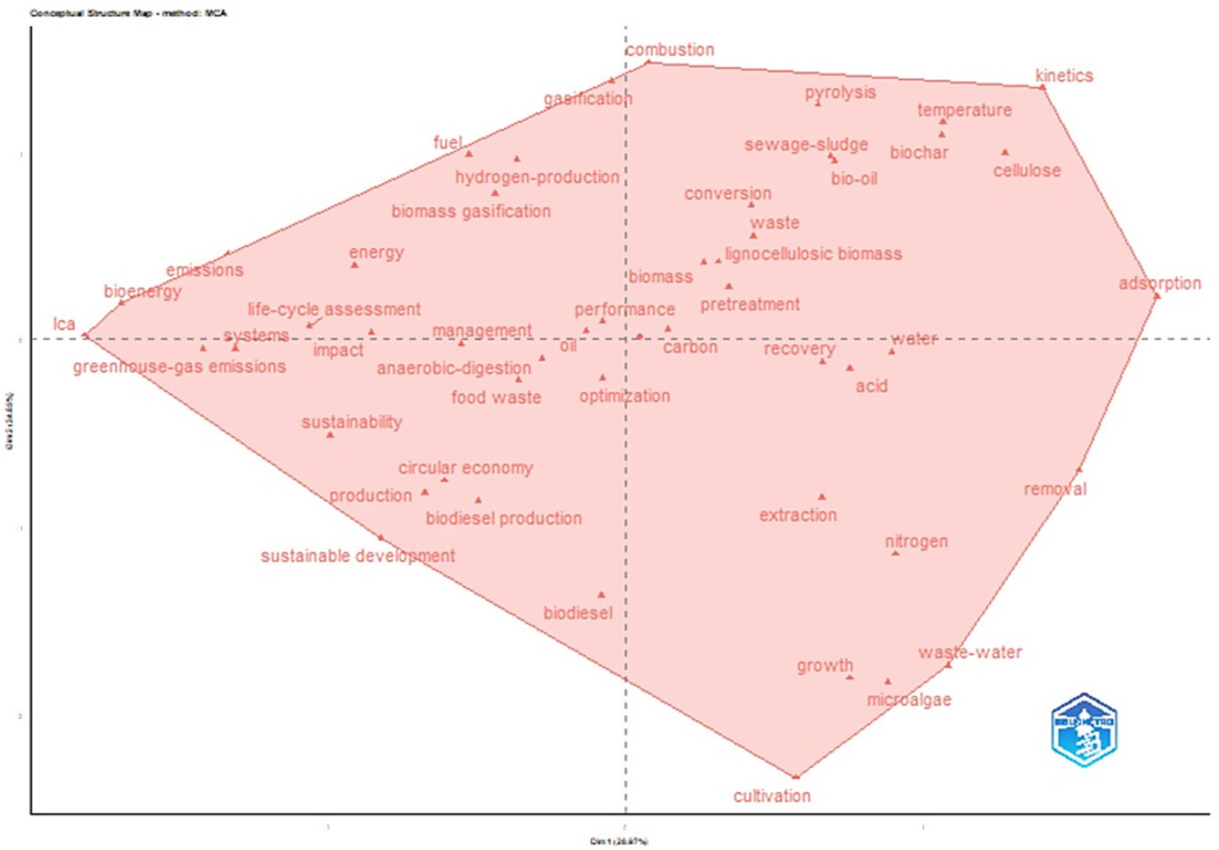

FIGURE 6
Conceptual map highlighting the separation and potential linkages between circular economy strategies and green innovation technologies in biofuel research.

while also motivating more context-specific exploration to support sustainability transitions in emerging markets.

3.7 Integrating thematic and collaboration insights for CE–GI research pathways

The combined results highlight how global biofuel sustainability research is evolving to address circular economy (CE) and green innovation (GI) goals, while also revealing persistent gaps in thematic integration and collaboration patterns. The analyses demonstrate well established thematic clusters for both CE-oriented frameworks, such as circular economy, life cycle assessment, and sustainability assessment, and GI focused technologies including biomass conversion, pyrolysis, and waste valorization. However, these domains remain only partially integrated conceptually, with limited evidence of strong bridging themes. The co-authorship network (Figure 8) reinforces this fragmentation. While the map shows some highly collaborative clusters around leading authors such as Rahman Abidur, Farrok Omar, Haqu, and Vanapalli, many other researchers appear in smaller or weakly connected positions. These dominant groups focus heavily on green innovation themes like biomass valorization and anaerobic digestion, reflecting strong technical expertise but limited direct linkage with policy-level circular economy planning. Such patterns indicate a structural gap between technology development and systemic sustainability frameworks. This limits the potential for integrated, interdisciplinary solutions that align policy objectives with practical innovation, which is critical for implementing circular biofuel systems (Borras et al., 2010). Addressing these gaps is particularly important for countries like Indonesia, where the B40 transition aims to combine technological advances in biofuel blending with ambitious sustainability targets. The results underscore the need for cross disciplinary research agendas, stronger international and local collaboration, and knowledge transfer mechanisms that can bridge CE policy frameworks with GI technological solutions (Iacovidou et al., 2021). These strategic pathways will be essential to achieve a truly circular and innovative biofuel system supporting both environmental and economic goals.

3.8 Thematic structure of CE and GI research in biofuel sustainability

The thematic map (Figure 9) shows the distribution of key research topics in biofuel sustainability, revealing how circular economy (CE) frameworks and green innovation (GI) technologies are positioned within the field (Devi et al., 2022). Motor themes. Including biomass, pyrolysis, waste, life cycle assessment, performance, and optimization, represent well developed and highly central topics that drive research. Many of these, such as biomass,

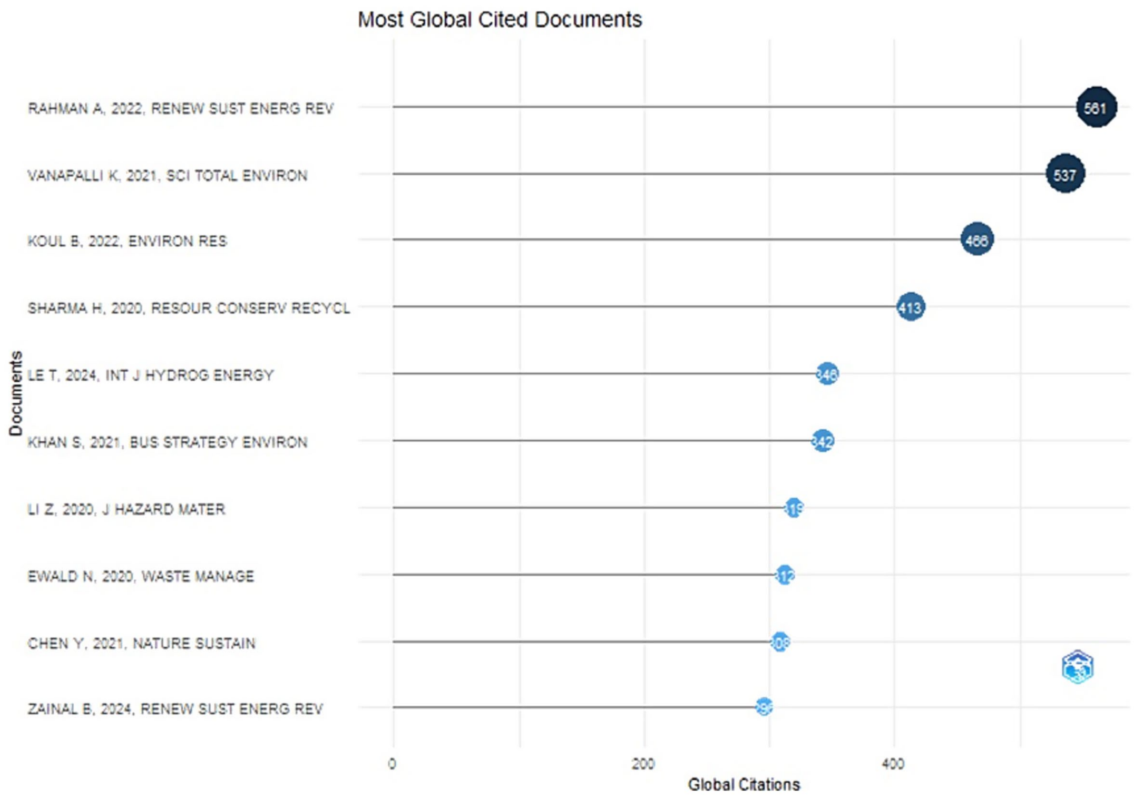

FIGURE 7
Most globally cited documents on circular economy and green innovation in the biofuel sector.

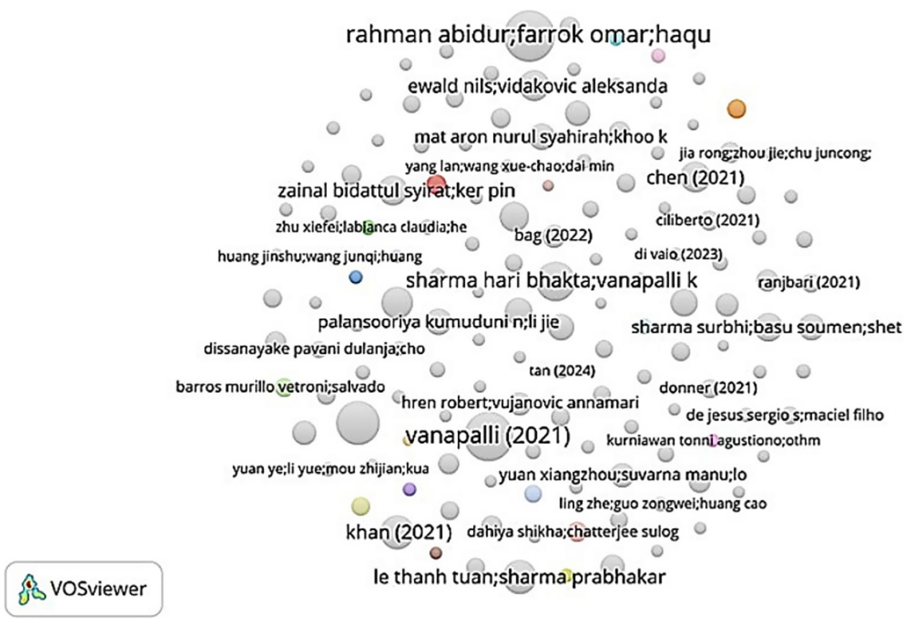

FIGURE 8
Co-authorship network of biofuel sustainability researchers, highlighting collaborative clusters, dominant author groups, and fragmentation that shapes CE–GI integration pathways.

pyrolysis, and waste, reflect a strong focus on technological innovation and conversion processes central to green innovation (GI). Simultaneously, the presence of life cycle assessment among motor themes indicates growing attention to systemic environmental evaluation, an important element of CE thinking (Hu et al., 2021). Basic themes like circular economy, sustainable development, and

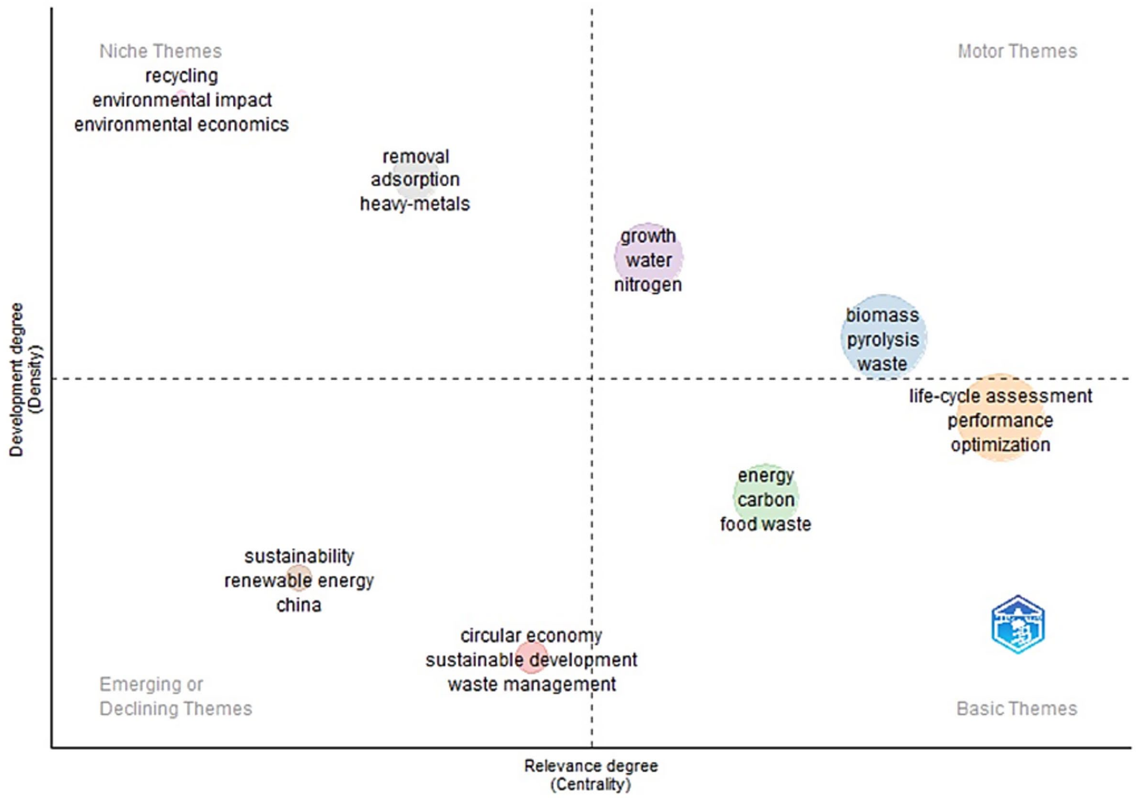

FIGURE 9
Thematic map of biofuel sustainability research, showing the distribution of topics as motor, basic, niche, and emerging themes.

waste management show high centrality but lower density, suggesting they serve as foundational sustainability concepts that are widely cited but less methodologically developed in empirical research (Siwal et al., 2021). These themes provide the broader CE frameworks guiding sustainable transitions but may lack detailed operational strategies in the biofuel context. Niche themes such as recycling, environmental impact, and environmental economics are highly developed but less central to the core research structure (Galán-Martín et al., 2021). They indicate specialized investigations relevant to sustainability goals but with narrower scope, suggesting that while such topics deepen understanding of CE principles, they are not yet fully integrated with the dominant GI technology focused literature. The emerging or declining themes quadrant includes sustainability, renewable energy, and China, showing lower density and centrality (Tan et al., 2024a, 2024b). These themes may represent evolving or shifting areas of interest, with sustainability itself appearing as a broad concept needing more consistent operational focus in biofuel research.

Overall, the map highlights a field with well developed GI technological research driving innovation in conversion processes, while CE frameworks remain essential but less densely developed as empirical research themes. This suggests ongoing challenges in bridging technological solutions with systemic sustainability planning, pointing to opportunities for better integrating CE principles with GI strategies in advancing sustainable biofuel systems.

3.9 Country collaboration network

Figure 10 presents the country-level collaboration network in biofuel-related circular economy and green innovation research. The visualization highlights a pronounced clustering of countries into two main blocs. The first, denoted in red, is anchored by China, India, and several Southeast Asian and Middle Eastern nations, showing dense interconnections among rapidly industrializing economies with significant biofuel production potential. The second, shown in blue, comprises European and Latin American countries, characterized by strong internal linkages and well established sustainability research traditions. Notably, the network structure reveals relatively limited cross bloc collaboration, with only sparse bridging connections between these clusters. This suggests persistent regional silos in knowledge exchange, technology transfer, and policy coordination related to CE and GI solutions for the biofuel sector (Ghobakhloo et al., 2023; Andersson and Börjesson, 2021). Countries such as Indonesia, despite its strategic interest in high blend biodiesel transitions (e.g., B40) are present in the Asian cluster but do not occupy central positions in global collaboration patterns. These findings underscore the importance of fostering greater international research partnerships that can bridge technological, policy, and sustainability expertise across regions (Moretto et al., 2020; Ardebili, 2020). Strengthening cross-cluster collaboration is vital for advancing the integrated circular economy and green

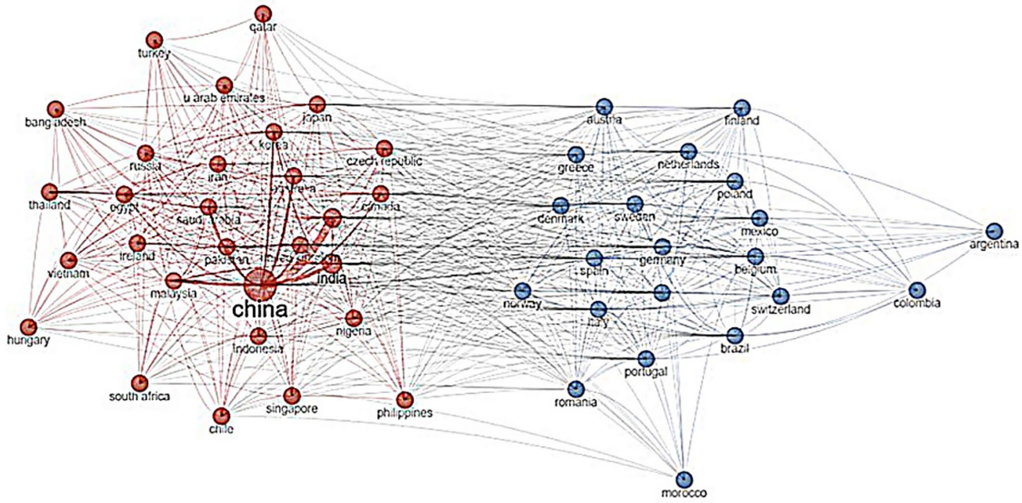

FIGURE 10
Country collaboration network highlighting regional clusters and partnerships in biofuel circular economy and green innovation research.

TABLE 1 Research gaps and opportunities for integrating circular economy and green innovation in the biofuel industry.

Gap theme	Description	Evidence from mapping results
Fragmented CE–GI integration	Circular Economy and Green Innovation concepts remain in separate clusters with weak intersections, especially between conversion tech and LCA.	Keyword Co-occurrence Network (Figure 2), Thematic Map (Figure 7)
Limited policy–technology linkage	Policy/regulation keywords are sparse and disconnected from core innovation and sustainability clusters.	Overlay Visualization (Figure 3), Thematic Map (Figure 7)
Regional collaboration gaps	Indonesia and Southeast Asian countries are absent or marginal in global collaboration networks.	Country Collaboration Network (Figure 8)
Underexplored feedstocks/processes	Clusters emphasize pyrolysis, gasification, and generic biomass terms but rarely palm oil or tropical biodiesel-specific streams.	Co-occurrence Network (Figures 2, 3), Thematic Map (Figure 7)
Knowledge concentration in few authors	Highly cited documents and co-authorship networks are dominated by non-Southeast Asian researchers with limited visibility of Indonesian authors.	Most Globally Cited Documents (Figure 6), Author Co-authorship Network (Figure 5)
Weak technology transfer focus	Technology transfer, adoption, and implementation themes appear peripheral or low-density.	Factorial Analysis (Figure 5), Overlay Visualization (Figure 3)

innovation frameworks necessary to support scalable, sustainable biofuel production in diverse socio-economic and policy contexts (Rathore et al., 2022).

To consolidate the insights drawn from Sections 3.1 to 3.9, this study synthesizes the key findings into a summary table that identifies critical research patterns, opportunities, and strategic gaps. The results reveal strong global momentum in circular economy and green innovation research for the biofuel sector, with clear thematic evolution, established methodological anchors such as life cycle assessment, and clusters of collaboration shaped by regional priorities and capacities. At the same time, the analyses underscore persistent challenges, such as limited cross-regional integration, uneven technological focus, and underexplored sustainability dimensions, that are particularly relevant for countries seeking to advance higher-blend biodiesel transitions in line with circular economy principles. Table 1 below distills these findings into actionable themes, highlighting both the maturity of certain research areas and the opportunities for bridging gaps through policy alignment, technological exchange, and collaborative innovation. This synthesis also serves as the concluding section of the Results, providing a foundation for the subsequent Discussion chapter to interpret these trends and propose strategic directions for research, industry, and policy.

4 Discussion

The discussion is structured in two parts. First, we interpret the global evolution of knowledge at the intersection of circular economy and green innovation for biofuels (4.1), highlighting theoretical and practical implications for sustainability transitions. Second, we address collaboration gaps and outline strategic pathways, situating Indonesia's B40 biodiesel transition as a focal case (4.2). Together, these subsections connect global insights with local challenges, emphasizing how integrated CE–GI approaches can inform policy, innovation, and cross-border cooperation.

4.1 Global knowledge evolution in circular economy and green innovation for biofuels

The global analysis reveals an evolving knowledge landscape at the nexus of circular economy (CE) principles and green innovation (GI) in sustainable biofuels. Over the past 5 years, research themes have broadened from a core focus on biomass conversion technologies to a more systemic integration of sustainability assessment and policy frameworks (Bastos et al., 2020). Established topics such as biomass utilization, biofuel conversion processes (e.g., pyrolysis, anaerobic digestion), and life cycle assessment (LCA) have long formed the foundation of this field (Koul et al., 2022; Sharma et al., 2020a, 2020b; Nematian et al., 2021). These remain prominent, reflecting enduring efforts to improve feedstock valorization and gauge environmental impacts. At the same time, newer themes, notably circular economy frameworks, waste-to-fuel strategies, and policy-driven sustainability goals have gained traction, indicating a deliberate shift toward holistic solutions (Rahman et al., 2022). This thematic evolution addresses the global thematic evolution in CE–GI for biofuels by showing how the literature has grown from primarily technological pursuits into a multi-dimensional approach that couple technology with circularity and climate imperatives. Notably, keywords like circular economy and sustainable development goals are increasingly prevalent in recent publications, signaling an alignment of biofuel research with broader sustainability agendas (Apostu et al., 2023; Velvizhi et al., 2022a, 2022b). The emergence of terms related to policy, resource management, and socio economic impacts further suggests that scholars are moving beyond lab-scale innovation, engaging with questions of governance and systemic change (Hsu et al., 2021). Overall, the global biofuel literature is maturing into an interdisciplinary domain, one that still drives technical innovation in bioenergy, but increasingly embeds these advances within the circular economy paradigm of resource efficiency and closed loop systems (Vanapalli et al., 2021; Wojnowska-Baryła et al., 2020). This responds directly by mapping how CE–GI themes have expanded and interwoven over time to support sustainable biofuel development (Olabi et al., 2023; Kurniawan et al., 2023).

Despite this encouraging thematic expansion, our analysis also uncovers fragmentation in the knowledge structure. The bibliometric co-occurrence and network analyses show that research clusters remain partly siloed. On one hand, a robust cluster of GI-focused technological research centers on improving conversion efficiency and exploring diverse feedstocks, for example, through pyrolysis, biochar production, gasification, and other advanced biofuel processes (Sharma et al., 2020a, 2020b; Yang et al., 2021a, 2021b). On the other hand, a parallel cluster emphasizes CE-oriented approaches, including LCA, sustainability assessment, and waste management, which introduce a systemic perspective (Koul et al., 2022). The two clusters, however, exhibit only weak linkages. This indicates that, globally, the integration of cutting edge biofuel technologies with comprehensive CE frameworks is still limited (Huang et al., 2023). Studies tend to either pursue innovative biofuel production techniques or focus on evaluating sustainability and circularity, but seldom fully combine the two. For instance, technological research on converting waste biomass to fuel often operates independently of research on circular policy design or whole-system environmental impact, leading to gaps in knowledge transfer between the domains (Chojnacka et al., 2021). Our factorial analysis confirmed that CE and GI concepts are well-established yet "partially connected" (Lopez et al., 2025; Yadav et al., 2020): keywords like circular economy and sustainability form one coherent grouping, while terms like biomass conversion and pyrolysis form another, with only a few bridging concepts (e.g., optimization, energy) linking them (Arent et al., 2022). Addressing this conceptual separation is vital for the field to move beyond parallel tracks. The discussion of these findings points to a theoretical contribution of our study: highlighting the need for an integrated framework that bridges technological innovation with circular economy strategies (Breyer et al., 2022; García-Depraect et al., 2022). By identifying this persistent fragmentation, we contribute to sustainability transition theory, suggesting that truly circular biofuel systems require cross-pollination between engineering innovations and systemic CE thinking (Rahman et al., 2022; Biswal and Balasubramanian, 2023). Bridging these silos can enrich the theoretical discourse on "circular bio innovation," where engineering advances are evaluated and guided by circularity metrics and where policy frameworks actively incorporate technological potentials (Akram et al., 2023).

4.2 Collaboration gaps, strategic pathways, and Indonesia's B40 transition

The collaboration network analysis reinforces the existence of silos and adds a geopolitical dimension to the challenge. We found that scientific collaboration in CE–GI biofuel research clusters into regional blocs (Sánchez-García et al., 2024). One cluster is Asia-centric, led by countries like China and India, which are rapidly expanding biofuel research and production capacity. Another cluster groups European and Latin American countries, known for strong sustainability research traditions and established biofuel programs (Siddique et al., 2022). Cross cluster collaboration is relatively scarce, with limited bridging between these regions. This indicates that knowledge exchange between, Asia's technology focused research and Europe's policy sustainability expertise is not occurring at the depth needed (Peyravi et al., 2024). Importantly, Indonesia, the world's largest biodiesel producer and a key case in this study, appears in the Asian cluster but not as a central node (Christina, 2019; Christina, 2025; Zhao et al., 2020). In other words, Indonesia has significant stakes in biofuel sustainability but has not been a leading actor in global research collaboration networks. This could be due to fewer high profile publications or limited international partnerships originating from Indonesia's institutions. It reveals a knowledge gap and an opportunity, Indonesia's biodiesel transition could benefit immensely from stronger linkages to global research networks, tapping into international expertise in areas like lifecycle analysis, advanced feedstock processing, and circular business models. Conversely, Indonesia's on the ground experience with large scale biodiesel deployment (unique among emerging economies) offers valuable lessons that could inform global research, if those experiences were more frequently shared in collaborative publications (Tsai et al., 2021). The current isolation, however, risks "reinventing the wheel" or missing out on state of the art solutions. Our findings thus suggest practical pathways such as fostering international research partnerships (for example, between Indonesian scientists and leading groups in Europe working on biofuel LCA, or with experts in Brazil on biodiesel from tropical feedstocks). By bridging these collaboration gaps, Indonesia can access advanced GI solutions and adapt global CE best practices to its context, while contributing its own innovations (such as high blend biodiesel usage and palm-based fuel technologies) to the global knowledge pool. Strengthening such cross regional collaboration is essential to develop interdisciplinary and transnational strategies for circular biofuel systems, aligning with both local needs and global sustainability standards (APROBI Indonesian Biofuel Producers Association, 2022).

The real world case of Indonesia's biodiesel program provides a concrete context to interpret these global findings, illustrating both the opportunities and challenges of aligning CE–GI research with practice (Foteinis et al., 2020). Indonesia's biodiesel initiative is among the most ambitious in the world, mandated through a series of escalating blend policies. The country successfully implemented a B30 mandate (30% biodiesel in diesel) by 2020 (Dimawarnita et al., 2021), which at the time was the highest biofuel blending rate achieved by any major economy. This B30 program is credited with significant contributions to Indonesia's climate targets and energy security. According to the Indonesian Biofuels Producers Association (APROBI), the B30 mandate in 2020 was projected to reduce carbon emissions by 26 million tons CO_2 equivalent, accounting for an impressive 68% of the energy and transport sector's targeted emission reduction that year (APROBI Indonesian Biofuels Producers Association, 2021). It also began to curb Indonesia's costly diesel imports by substituting locally produced biofuel for fossil diesel. These outcomes exemplify GI in action, innovating with bio-based fuel to achieve environmental benefits and economic resilience, and align with CE objectives by utilizing domestic renewable resources to close the loop on energy supply (López-Sánchez et al., 2022). In January 2023, Indonesia took a further step by introducing B35 (35% blend), and by early 2025 the B40 program was being rolled out nationwide, with an allocated 15.6 million kiloliters of palm biodiesel for the year (Christina, 2025; Antara News, 2024b), up from roughly 13 million kL in 2024. Government officials anticipated full B40 implementation by March 2025, aiming to reduce reliance on imported diesel and leverage Indonesia's ample palm oil supply for energy needs. This progression from B30 to B40 underscores Indonesia's role as a pioneering laboratory for high-blend biofuel adoption (Indonesia Investments, 2025; Reuters, 2024; Pietrzak et al., 2021; Xiaosan et al., 2021). It demonstrates the practical relevance of our bibliometric findings: the dominant research themes of biomass conversion and waste valorization are directly reflected in Indonesia's use of palm oil (a biomass resource) to produce biodiesel, while the emphasis on sustainability assessment resonates with Indonesia's need to monitor the environmental trade offs of this biofuel expansion.

Crucially, the Indonesian case also highlights why integrating circular economy strategies with such green innovations is imperative. Building on Indonesia's successful B40 transition, Figure 11 presents the applied CE–GI convergence framework to guide the next phase toward B60–B100. In this framework, CE and GI act as independent levers; their joint effect is mediated by the CE–GI nexus toward a Sustainable Biofuel Model. Technology readiness, regulatory stringency, sustainability-oriented culture, and supply chain capability moderate all links.

The CE–GI nexus is the strategic mechanism that translates circular resource choices and innovation investments into a viable sustainable biofuel business model. Absent this nexus, GI-led scale up can raise exposure to feedstock risk, land use pressure, and cost volatility; with it, firms convert efficiency and LCA gains into durable economic and social value. Its effectiveness is conditional on technology readiness, regulatory stringency, sustainability culture, and supply chain capability, making nexus building a core management priority for scaling blends sustainably.

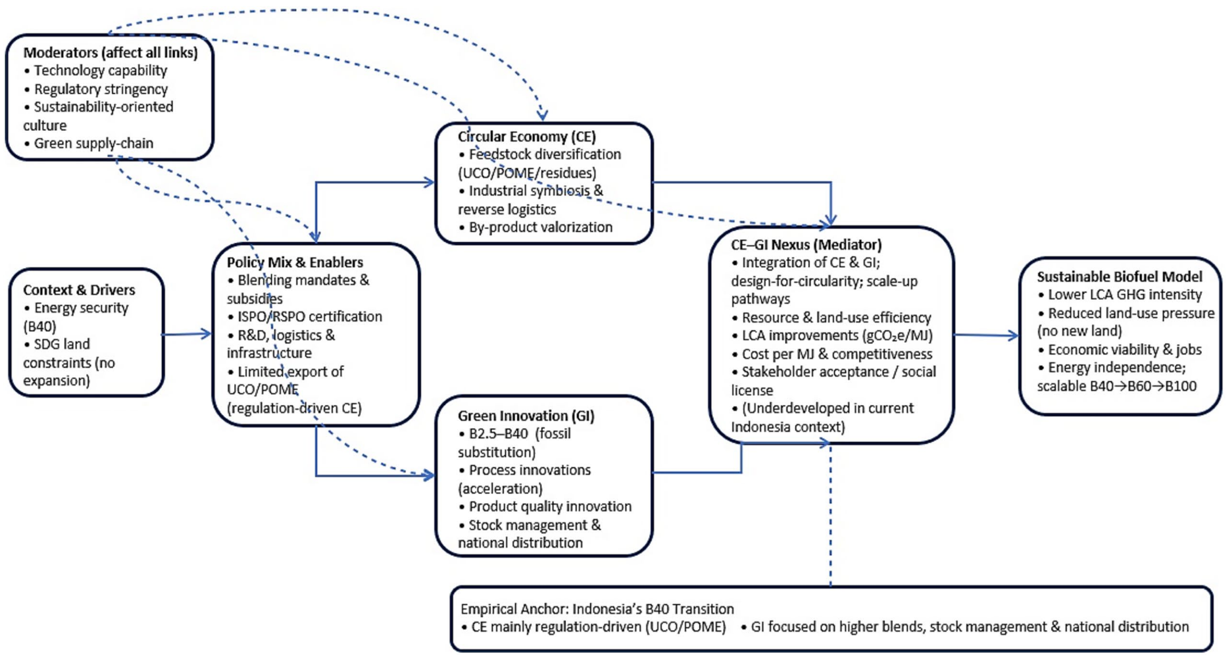

FIGURE 11
CE–GI convergence framework (Indonesia); the nexus mediates effects toward a Sustainable Biofuel Model.

Indonesia's biodiesel is produced mainly from palm oil, a resource whose cultivation has well documented sustainability concerns if not managed carefully (Jong, 2021; Azhar and Tang, 2024). The expansion of palm oil plantations can lead to deforestation and biodiversity loss, which would undermine the very environmental goals that biofuels seek to advance. A circular economy approach would call for maximizing the use of waste and residues, improving resource efficiency, and mitigating negative externalities in the biodiesel supply chain (Rabbat et al., 2022). Our results show that global research has increasingly focused on waste-to-biofuel technologies and multi dimensional impact assessments, which offer exactly the kind of insights Indonesia needs to ensure its biodiesel program is sustainable (Jia et al., 2023). For example, top cited studies in the field (e.g., Vanapalli et al., 2021; Rahman et al., 2022) emphasize converting plastic and organic wastes to biofuels and applying rigorous LCA to bioenergy systems. Such approaches could be highly relevant for Indonesia as it seeks to diversify feedstocks beyond crude palm oil, by using palm fatty acid distillate (PFAD), waste cooking oil, or even agricultural residues, to produce biodiesel or other biofuels (Casas et al., 2023; Donzella et al., 2024). In practice, there are signs that Indonesia is indeed exploring these circular pathways. The state-owned oil company, Pertamina, has developed processes to produce "green diesel" (chemically akin to B100 renewable diesel) from palm oil through refinery hydrogenation. In 2021 Pertamina's Cilacap refinery began producing a pure bio-hydrocarbon diesel from 100% palm oil (dubbed B100 Green Diesel), at an initial capacity of 3,000 barrels per day with plans to double output (Biofuels International, 2020). This fuel, produced via hydrogenated vegetable oil (HVO) technology, can fully replace fossil diesel in engines without blending. Technologically, this is a GI milestone, applying innovative refinery processes to create a drop in biofuel that circumvents some of the blending limitations of traditional fatty acid methyl ester (FAME) biodiesel. If scaled up, such innovations can be game changers for achieving the national target of B100. They illustrate how Indonesia's practical efforts are aligning with global GI research trends, specifically the push for advanced biofuels and biorefinery approaches noted in our bibliometric analysis (Mangla et al., 2019).

However, the Indonesian experience also validates the concerns highlighted in our global analysis regarding fragmentation and gaps. The push for ever higher biodiesel blends has outpaced improvements in agricultural yield and supply chain sustainability. A recent critical report warned that without parallel innovations in sustainable palm oil cultivation, Indonesia's biodiesel mandate could incentivize "business as usual" expansion of plantations, exacerbating deforestation risks Gaur et al., 2020). Indeed, experts note a contradiction: policies exist to restrict new palm oil expansion (e.g., a moratorium on new plantations), yet the biodiesel program's demand might require a substantial increase in palm fruit output, potentially pressuring land resources (Liu et al., 2021). By one estimate, achieving B50 and ultimately B100 with current practices could necessitate millions of additional hectares of oil palm cultivation, unless yields improve or alternative feedstocks are utilized. This is where knowledge integration and strategic planning become crucial. The global research gap we identified, the insufficient connection between technological GI solutions and CE systemic planning is manifest here. For Indonesia to reach B50 or B100 sustainably, collaborative innovation bridging agronomy, technology, and policy is needed. Encouragingly, Indonesian officials recognize some of these challenges. The government is developing a roadmap for gradual transition to B100 that presumably factors in stepwise advancements in production and feedstock management (Antara News, 2024a). There is also discussion of capping the blending program at B50 if necessary, should palm oil yields and land use efficiency not improve adequately (Lopez et al., 2023). Such a stance implicitly calls for GI in agriculture (higher yield palm varieties, better smallholder practices) and CE measures (recycling of waste oil, use of degraded land for energy crops) to support the fuel mandate. In alignment with that, initiatives like mandatory sustainability certification (e.g., strengthening Indonesia's ISPO standards for palm oil by 2025) (Antara News, 2024a) are being put in place to ensure that the biodiesel feedstock is produced in accordance with environmental and social criteria. Building on those safeguards, Indonesia already operates a financing instrument that can be tuned without creating a new scheme. Since 2015, the Palm Oil Plantation Fund Management Agency (BPDPKS) has collected export levies and used them to bridge the price gap between biodiesel and fossil diesel as the backbone of the mandate; the monthly Biodiesel Market Index Price (HIP Biodiesel) published by the energy ministry provides the reference for disbursement. Under this feedstock-neutral arrangement, UCO/POME-based biodiesel that qualifies for the mandate receives the same BPDPKS support as CPO-based volumes, so the practical lever is to fine-tune BPDPKS parameters (within the existing rules) to gently privilege traceable waste/residue inputs while preserving the program's social-acceptance and scaling objectives (Kharina et al., 2016; BPDP, 2018). These measures echo the global trend of integrating sustainability governance into biofuel development, precisely the convergence of policy and technology tracks that our bibliometric study highlighted as underdeveloped but necessary.

The Indonesian case thus serves to ground the bibliometric findings in reality. It demonstrates that achieving a circular and innovative biofuel system is a complex endeavor requiring alignment of multiple domains, technology, environmental science, economics, and public policy (Vuc, 2024). From a theoretical standpoint, our study contributes a nuanced understanding of how such alignment can be supported by knowledge. We show that while the global research community has generated a rich array of tools and strategies (from biomass conversion techniques to LCA frameworks), these must be synthesized into coherent strategies for them to effectively guide national transitions like Indonesia's. Theoretically, this implies advancing the concept of a "circular bioeconomy," an intersection of CE and biofuel innovation, where not only are waste resources recycled into energy, but the innovation ecosystem itself is circular (encouraging feedback loops between policy needs and technological R&D) (Yang et al., 2021a, 2021b; Chen et al., 2020). Practically, our findings have several implications for stakeholders in Indonesia and similar contexts. First, there is a clear need for cross disciplinary collaboration: engineers, environmental scientists, and policy analysts should be working together on biofuel projects to ensure that new technologies are evaluated for sustainability and that policies create incentives for the right innovations (for example, rewarding use of waste feedstocks or higher efficiency processes). The current fragmentation in research suggests that such interdisciplinary projects are still too scarce. Second, enhancing international collaboration and knowledge transfer is critical. Indonesia's B40 to B100 aspirations can draw on lessons from other countries' experiences with biofuels (for instance, Brazil's long history with bioethanol, or the EU's implementation of sustainability criteria in biofuels) (Raihan and Tuspekova, 2022; Al-Mawali et al., 2021). Our country network analysis indicates Indonesia could play a more active role in global biofuel research networks, which would facilitate exchange of best practices, whether it is advanced catalysis for biodiesel from waste oils, or robust monitoring of land use change via international climate partnerships. Strengthening ties with global centers of excellence would also help Indonesia address local knowledge gaps, such as adapting LCA methods to tropical agriculture or developing community scale biodiesel innovations (areas where current global literature is thin, as indicated by the limited focus on palm oil in top cited papers).

In summary, the discussion underscores that the global evolution of CE and GI research in biofuels provides both inspiration and guidance for real world transitions, but also highlights challenges that manifest on the ground. Indonesia's journey from B30 to B40, on toward B50 and B100 exemplifies a bold application of GI (deploying renewable fuels at national scale) and the intent of CE (reducing fossil fuel dependence and reusing biological resources). The bibliometric insights show that globally we have many pieces of the puzzle, technologies to convert diverse wastes to fuel, frameworks to assess sustainability, and policy models for circular resource use. Yet, these pieces must be better integrated and contextualized. The Indonesian case, kept in a global perspective, suggests that achieving a circular biofuel future will require closing the very gaps our study identified. It calls for an innovation ecosystem where engineering advances are systematically evaluated for their circularity, where policy is informed by up to date scientific evidence, and where international collaboration mitigates knowledge asymmetries. While for other biofuel-producing countries, regardless of feedstock (palm, soy, rapeseed/sunflower, UCO), the same lesson holds: GI-led blend escalation must be paired with CE-guided innovation to build a sustainable biofuel business model. Applying the CE–GI convergence lens provides portable, stepwise pathways, mainstreaming wastes/residues, reverse logistics and industrial symbiosis, and robust standards/traceability to scale higher blends without new land expansion and with lower system risk

. This study advances the literature by proposing an integrative framework that bridges the traditionally fragmented perspectives of Circular Economy (CE) and Green Innovation (GI). Prior research has treated these as parallel streams; our unified CE–GI paradigm offers a more holistic lens to explain sustainability transitions by linking resource circularity, technological innovation, and sustainability outcomes. The framework contributes to CE by embedding innovation-driven mechanisms, and to GI by situating innovation trajectories within broader socio ecological cycles. It also enriches sustainability transition theory by stressing the alignment of global knowledge with local adaptive practices, particularly in emerging economies such as Indonesia, where energy transition is both developmental and environmental. The practical contribution is in translating the bibliometric findings into strategic recommendations, for Indonesia, this means investing in research that bridges policy and technology (such as joint initiatives on palm agroforestry and bio refinery processes), enhancing collaborations (through partnerships with global experts and local multi-stakeholder forums), and embracing adaptive policies that encourage innovation while safeguarding sustainability. As Indonesia and other countries strive toward ambitious targets like B100 and beyond, the alignment of global knowledge streams with local action will determine how successfully we can unlock circular economy pathways via green innovation in the biofuel sector, achieving not just energy security, but a truly sustainable energy transition that meets environmental and socio economic objectives worldwide.

This study has three main limitations. First, it relies on Scopus and Web of Science, which capture peer-reviewed and indexed outputs but exclude grey literature, policy reports, and regional studies that may offer practice-oriented insights. Second, the search design, restricted to English language publications within 2020–2025, may under represent foundational debates, locally published evidence, and non-English terminology, thereby skewing the thematic focus toward technology-oriented discourses prevalent in international literature. Third, bibliometric analysis is inherently structural, mapping clusters, trends, and networks but unable to capture contextual drivers such as institutional barriers, political economy dynamics, or cultural factors. Future research could address these limitations by integrating multilingual corpora, extending the temporal scope, and combining bibliometric with qualitative approaches.

5 Conclusion

This global bibliometric study has shown that while circular economy (CE) and green innovation (GI) are increasingly referenced in biofuel research, their integration remains partial and fragmented. Thematic analyses revealed strong progress in GI, especially technological advances in biomass conversion, fuel quality optimization, and high blend compatibility that enable renewable energy substitution. By contrast, CE principles, like valorizing waste streams, closing resource loops, and embedding lifecycle sustainability, are present but less mature, often addressed in isolated studies or conceptual frameworks rather than fully operationalized in practice. The Indonesian case of the B40 biodiesel mandate exemplifies this dynamic. Indonesia has made significant strides in green innovation, scaling biodiesel blending from B30 to B40 by 2025 through industry focused fuel quality improvements and large-scale production. Yet circularity remains limited, with feedstocks still dominated by first generation palm oil, and only nascent efforts to incorporate used cooking oil (UCO) or other residues. Similar partial progress is visible globally: Malaysia and Thailand have launched programs to blend UCO into biodiesel, while some European countries use recycled industrial fats, agricultural waste, or even plastic-derived oils. But these streams remain small scale, fragmented, and dependent on further GI, such as improved collection systems, conversion technologies, and supply chain integration to make biofuel systems genuinely circular and scalable. These patterns underscore a central finding: achieving sustainable biofuel transitions requires overcoming the persistent gap between technological innovation and systemic circularity.

Future research should prioritize bridging the gap between technological innovation and circular systems in biofuel development, especially in rapidly growing renewable energy markets like Southeast Asia. Scholars and practitioners should focus on designing integrative frameworks that embed circular economy principles, such as waste valorization, by product recycling, and lifecycle impact assessment, directly into biofuel policy and technology planning. Indonesia's B40 transition offers a valuable case study for examining how blending mandates can drive technological improvement but also illustrates the challenges of ensuring feedstock sustainability and minimizing land use impacts. Comparative research across countries would help identify both shared barriers and context-specific solutions for scaling circular biofuel systems. Importantly, future work should adopt transdisciplinary approaches that connect engineering, agronomy, environmental science, and policy analysis to design solutions that are both technically feasible and socially acceptable. Researchers should also prioritize south - south knowledge production and exchange, fostering partnerships among emerging economies that share similar challenges and opportunities in sustainable biofuel deployment. By pursuing these directions, the research community can help unlock genuinely circular and innovative biofuel pathways that support climate goals, energy security, and equitable economic development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

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

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