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Strategic alignment of policy, innovation, and stakeholders in sustainable biofuel business models: a bibliometric analysis

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Biofuels are critical to global energy transitions and sustainable development, yet biofuel business models (SBBMs) in emerging markets often suffer from weak alignment between policy frameworks, technological innovation, and stakeholder engagement, limiting their contribution to effective environmental governance. This study applies bibliometric analysis to map global research trends (2006–2025), using keyword co-occurrence networks, trend topic mapping, thematic evolution, and three field plot evidence to trace how stakeholder engagement is represented and how strongly it is integrated with policy-technology research streams, complemented by contextual grounding through secondary evidence from Indonesia's B40 program, which represents one of the highest mandatory biodiesel blending initiatives globally. As a bibliometric study, this work offers an indirect and exploratory contribution by synthesizing patterns in the literature rather than testing causal effects or implementation outcomes. The findings indicate strong thematic coupling between policy and technological innovation research streams, alongside a recurring pattern in which stakeholder-oriented concepts are present but comparatively peripheral and weakly integrated with governance alignment themes. These gaps may weaken the inclusivity and resilience of SBBM strategies discussed in the literature and reduce their relevance for complex environmental management challenges. Building on the mapped evidence, the paper proposes an evidence-informed, propositional strategic framework to support alignment across policy, innovation, and stakeholder engagement. The framework offers actionable implications for strengthening environmental governance and guiding more inclusive, resilient biofuel business model design, particularly in emerging market contexts.

KEYWORDS

sustainable biofuel business models, policy-innovation-stakeholder alignment, stakeholder engagement, environmental governance, bibliometric analysis, sustainable development

1 Introduction

The global imperative for sustainable energy transition has positioned renewable energy sources at the forefront of international climate and development discourse. The demand for fossil-derived fuels and chemicals continues, heightening concerns about climate change, global economic stability, and the sustainability dependence on fossil resources (Rosales-Calderon and Arantes, 2019). Therefore, the production of fuels and chemicals from alternative and renewable resources has attracted considerable and growing

attention. Within this transition framework, biofuels have emerged as a critical component, offering both immediate climate mitigation potential and longterm sustainability benefits for energy security and rural development. Biofuel development can improve energy security, rural income and can reduce greenhouse gas (GHG) emissions, but issues related to land and water use and food security are important considerations to be addressed for its largescale application (Kumar et al., 2013; PASPI, 2023). The successful implementation of sustainable biofuel systems requires a comprehensive understanding of three fundamental enablers that collectively determine the viability and effectiveness of biofuel transitions: policy frameworks, technological innovation, and stakeholder engagement. Policy frameworks provide the regulatory foundation and incentive structures necessary for biofuel development. The policies, measures and incentives for the development of biofuel include targets, blending mandates and favorable tax schemes to encourage production and consumption of biofuels (Kumar et al., 2013). Key challenges such as regulatory uncertainty, grid integration, and public acceptance were identified (Söylemez and Söylemez, 2024). These policy mechanisms create market conditions that enable private sector investment and establish clear pathways for scaling biofuel production. Technological innovation represents the second critical enabler, encompassing advancements in feedstock processing, conversion technologies, and integrated biorefinery concepts. These innovations are essential for achieving economic competitiveness and environmental sustainability in biofuel production systems. The third enabler, stakeholder engagement, encompasses the participation of diverse actors including government agencies, private sector entities, civil society organizations, and local communities in biofuel development processes. Together, these enablers shape the design and scalability of Sustainable Biofuel Business Models (SBBMs) (Harjanti et al., 2025).

Despite the recognized importance of these three enablers, current biofuel research has been reported to exhibit an imbalance in scholarly attention, with stakeholder engagement receiving significantly less focus compared to policy and technological dimensions (Zhao et al., 2020). This pattern suggests a critical gap in which social dimensions linked to stakeholder engagement remain comparatively underdeveloped in the research agenda. The existing literature tends to emphasize technological innovations and policy interventions while often underemphasizing the critical dimension of stakeholder engagement. It is obvious that assessing and monitoring such integrative systems will have to account for different stakeholder perspectives and for detailed technology deployment and resource conversion scenarios (Hildebrandt et al., 2020). However, to date, integrative assessment methods that jointly operationalize these elements remain limited and fragmented in the literature (Hildebrandt et al., 2020). This conceptual and methodological imbalance creates significant research gaps that limit the comprehensive development and implementation of Sustainable Biofuel Business Models (SBBMs). Critically, this imbalance also hinders the strategic alignment of policy frameworks, technological innovation, and stakeholder engagement, which is essential for developing resilient and inclusive biofuel business models. The limited

availability of comprehensive frameworks that systematically integrate stakeholder perspectives into sustainable biofuel business model development indicates a significant gap in both theoretical understanding and practical implementation.

Indonesia presents a distinctive and compelling context for addressing this research gap, demonstrating strong leadership in biofuel policy implementation while offering unique insights into the challenges of stakeholder engagement in sustainable biofuel transitions. Indonesia's progressive biodiesel blending mandate trajectory, advancing from B2.5 (2006) through B30 (2019), and recently B40 was launched effective 1 January 2025, positions the country as a global leader in biodiesel policy implementation. This ambitious policy trajectory represents one of the world's highest biodiesel blend mandates, demonstrating substantial practical leadership in biofuel transitions (Wirawan et al., 2024). However, Indonesia's biofuel advancement occurs within a complex stakeholder landscape characterized by multiple sustainability challenges. The Indonesian context reveals the critical importance of stakeholder engagement in sustainable biofuel business model development. Studies recommend prioritizing cross sector collaboration between sectors in developing the biofuel/renewable energy industry (Yudha and Tjahjono, 2019; Jupesta et al., 2011). These recommendations highlight the necessity of comprehensive stakeholder engagement to address the complex interplay between economic, social, and environmental dimensions in biofuel development. Despite Indonesia's empirical leadership in biofuel policy implementation and its significant regional capabilities, its biofuel advancements remain underrepresented in core international scholarly discourse and collaboration networks (Biberici, 2023), as suggested by the bibliometric mapping results reported in this study. This notable mismatch between empirical leadership and limited global academic visibility presents an opportunity to contribute valuable insights to the international biofuel research community while addressing critical gaps in stakeholder engagement frameworks. This context underscores the urgent need for strategic alignment between policy frameworks, technological innovation, and stakeholder engagement to ensure that Indonesia's biofuel leadership translates into resilient and inclusive business model development. Indonesia's B40 experience offers valuable lessons for other emerging markets pursuing ambitious biofuel transitions under complex stakeholder dynamics (Harjanti et al., 2025).

This study addresses the identified research gaps by developing an evidence-informed framework for Sustainable Biofuel Business Models (SBBMs) that systematically integrates policy, innovation, and stakeholder engagement, with particular emphasis on addressing the marginalization of stakeholder perspectives in current research. The primary contribution lies in providing a theoretically grounded framework that positions stakeholder engagement on equal footing with policy and innovation enablers in sustainable biofuel business model development. As a bibliometric mapping study, this manuscript makes an indirect and exploratory contribution by synthesizing patterns in the literature rather than testing causal effects or implementation outcomes. From a practical perspective, the research offers actionable insights for policymakers and industry practitioners in implementing effective stakeholder engagement and strategic

alignment strategies. Building on Indonesia's B40 experience as a contextual anchor, the study provides lessons for developing biofuel business models that balance economic viability, environmental sustainability, and social acceptance through integrated policy, innovation, and stakeholder engagement. To guide this inquiry, the study addresses two key research questions:

- (1) How have global research trends, thematic focus areas, and knowledge trajectories in policy, innovation, and stakeholder engagement evolved and been connected within the SBBM literature, with reflections from Indonesia's B40 biofuel implementation?
- (2) What strategic insights and propositional frameworks can support aligning policy, innovation, and stakeholder engagement to develop sustainable biofuel business models for improved environmental governance?

The methodology employs quantitative bibliometric analysis complemented by contextual and triangulation that links mapped patterns to Indonesia's B40 experience using secondary evidence, with a detailed description of the framework provided in the accompanying section.

2 Materials and methods

2.1 Analytical framework

This research adopts a comprehensive bibliometric approach combined with science mapping techniques to explore the intersection of policy instruments, technological advancement, and stakeholder cooperation in sustainable biofuel business models (SBBMs). Bibliometric analysis serves as an effective quantitative research method to process extensive scholarly metadata present in article titles, abstracts, keywords, references, and author affiliations (van Eck and Waltman, 2010; Hausteine and Larivière, 2015). The methodological framework integrates quantitative bibliometric analysis with visual science mapping to systematically examine the intellectual structure and evolution of research in this multidisciplinary field. To ensure contextual relevance, this approach is triangulated with Indonesia's policy trajectory in biodiesel development, particularly the B40 program that was launched in January 2025 (Christina, 2025), offering a grounded interpretation of the findings within a real-world policy implementation landscape. As a bibliometric mapping study, this approach provides an indirect and exploratory synthesis of patterns in the literature rather than testing causal impacts of specific programs. This systematic approach is particularly valuable for interdisciplinary sustainable biofuel research, enabling efficient screening of large scholarly corpora and ensuring replicability through clear documentation of search strings, inclusion criteria, and analytical tools (Hausteine and Larivière, 2015; Szomszor et al., 2020). Science mapping techniques complement bibliometric analysis by visualizing and interpreting the conceptual, intellectual, and social structures within the research field (Szomszor et al., 2020; Smyrnova-Trybulska et al., 2018). This approach pairs performance indicators (publication and citation trends) with science mapping techniques including coauthor and affiliation networks, citation

matrices, keyword co-occurrence, and strategic diagram analysis, using centrality, density, and clustering metrics to identify leading actors, methods, and knowledge domains (Afzal et al., 2025). The integration of science mapping is particularly crucial for this study because it examines relationships between separately studied areas including biofuel policy, innovation systems, and stakeholder strategies (Hausteine and Larivière, 2015; Alkhamash, 2023). Tools such as Bibliometrix, Biblioshiny, and VOSviewer enhance data management, network analysis, and visual representation in bibliometric studies (van Eck and Waltman, 2010; Aria and Cuccurullo, 2017; Orduña-Malea and Costas, 2021).

This study adopts a multi-layered analytical framework to explore sustainable biofuel business models (SBBMs) through three interconnected dimensions. It examines how policy instruments, regulatory mechanisms, and institutional arrangements influence SBBM development, while also analyzing technological advancements, innovation trajectories, and their diffusion within the sector. In parallel, it investigates stakeholder cooperation, network structures, and collaborative mechanisms that shape collective action. To enhance analytical depth and contextual relevance, Indonesia's B40 biodiesel policy is integrated as a contextual anchor using secondary evidence. This integration allows for triangulation between global research trends and national policy implementations, providing temporal anchoring through policy milestones to interpret bibliometric trends alongside policy milestones. Altogether, this framework offers a comprehensive lens to analyse the interplay of structural, technological, and social in advancing sustainable biofuel transitions.

This research delineates its temporal boundaries from 2006 to 2025 to comprehensively capture the evolution of scholarship on sustainable biofuels and Sustainable Biofuel Business Models (SBBMs) and the trajectory of Indonesia's biodiesel policy. The year 2006 marks the beginning of Indonesia's institutional engagement with biodiesel through the introduction of the B2.5 mandate, representing the first government-endorsed blending policy. This early period coincided with global attention to major climate and sustainability milestones that shaped attention to low carbon energy transitions. Between 2009 and 2015, international agreements such as the Copenhagen Accord and Paris Agreement consolidated policy frameworks and fostered global consensus on emission and temperature control strategies. These developments established a normative foundation that influenced national energy transitions, including those in Indonesia. The period from 2016 onwards aligns with the adoption and operationalization of the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). These goals provided a global mandate for renewable energy innovation and low-emission policy action. The decision to extend the temporal scope through 2025 is strategically grounded in Indonesia's policy trajectory, as the B40 mandate was officially launched in January 2025 (Christina, 2025). This milestone represents a significant policy leap and serves as a concrete temporal anchor for interpreting bibliometric trends alongside national policy milestones. By framing the analysis within this two-decade span, the study ensures alignment between bibliometric trends and key global and national developments.

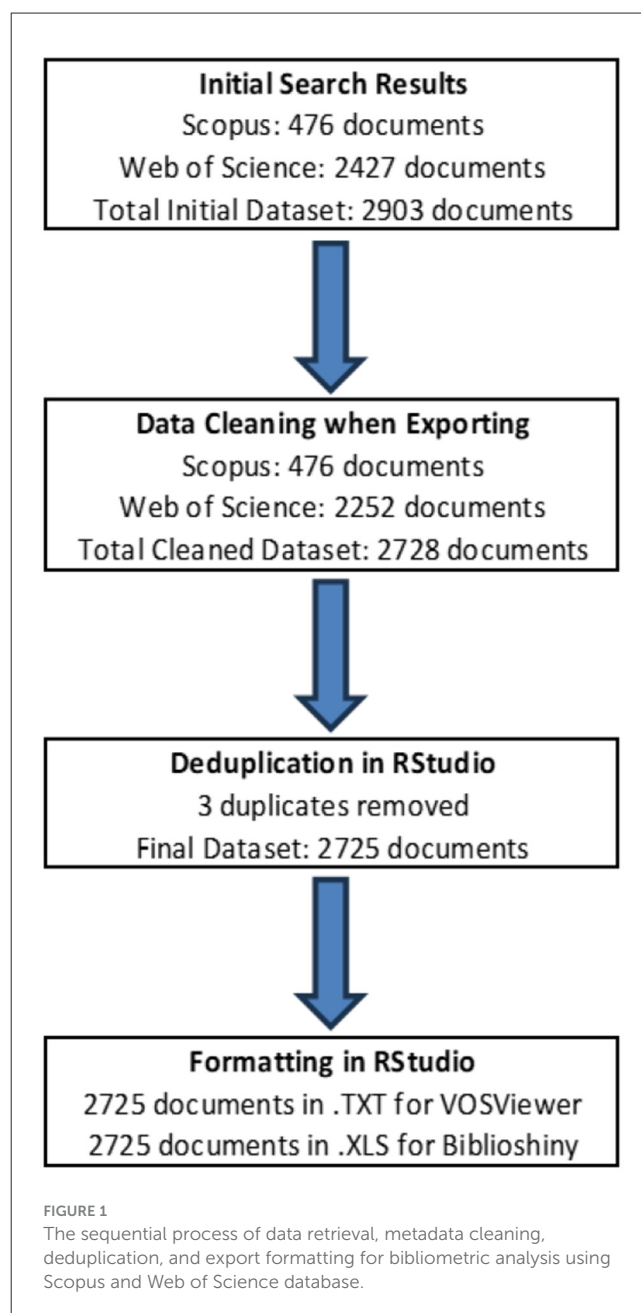
It provides a robust context to evaluate how global signals and national changes are reflected in the evolution of academic knowledge on sustainable biofuels.

2.2 Data sources and database selection

This research draws on two renowned bibliographic databases, Scopus (Elsevier) and Web of Science (Clarivate Analytics), selected for their top-quality indexing, broad disciplinary coverage, and advanced search and filtering tools that enable replicable systematic bibliometric reviews (van Eck and Waltman, 2010; Haustein and Larivière, 2015). Methodological transparency is ensured through explicit reporting of bibliometric data processing steps (retrieval, export filtering, merging, and cleaning), and the workflow is documented in Figure 1 and detailed in Sections 2.3 and 2.4. Scopus provides comprehensive coverage across energy, social sciences, business management, and economics, and offers detailed author and affiliation profiles supporting co-authorship and institutional network analysis (Alkhamash, 2023; Si et al., 2019; Demirbas, 2009a; Costa et al., 2018). Web of Science complements this with strong indexing in environmental science, business, economics, and management, along with robust temporal data structures enabling longitudinal evaluations and scientific mapping (van Eck and Waltman, 2010; Haustein and Larivière, 2015; Abramo and D'Angelo, 2011). Combining Scopus and Web of Science reduces disciplinary gaps and bias while ensuring extensive, high-quality coverage across the natural and social sciences (van Eck and Waltman, 2010; Smyrnova-Trybulska et al., 2018; Orduña-Malea and Costas, 2021; Si et al., 2019; Mann et al., 2006; Davis et al., 2014). Using both databases strengthens data stability and mitigates the risk of overlooking critical sectors in this interdisciplinary field (van Eck and Waltman, 2010; Orduña-Malea and Costas, 2021; Mann et al., 2006). To ensure analytical rigor, this study included only peer-reviewed journal articles, excluding conference proceedings, book chapters, and editorials (van Eck and Waltman, 2010; Costa et al., 2018). Additionally, only English-language publications were considered to guarantee standardized comprehension across the global academic community (Alkhamash, 2023; Si et al., 2019). Search retrieval was conducted in both databases using the same conceptual scope and inclusion criteria, with database-specific field tags and syntax adjustments documented to maintain comparability and replicability. The final dataset forms the foundation for analyses using VOSviewer (version 1.6.20) and Biblioshiny (version 4.1.2), enabling the mapping of citation patterns and intellectual structures within global biofuel research (van Eck and Waltman, 2010; Orduña-Malea and Costas, 2021). Bibliometrix/Biblioshiny supports performance and thematic mapping analyses, whereas VOSviewer is used primarily for network construction and visualization.

2.3 Search strategy and Boolean query design

The search strategy was designed to identify relevant materials in Scopus and Web of Science that aligned with the study's focus



on biofuels, policy and regulation, technological innovation, and stakeholder participation (Alkhamash, 2023; Costa et al., 2018). It included four thematic groups built from systematically structured keywords combining standardized vocabulary with wildcards to yield broad semantic results (Szomszor et al., 2020; Smyrnova-Trybulska et al., 2018). In Scopus, the TITLE-ABS-KEY field was used to extract records from titles, abstracts, and author keywords (Haustein and Larivière, 2015; Alkhamash, 2023). Boolean operators connected terms across four core themes: (i) biofuel (core domain terms); (ii) policy and governance; (iii) technology and innovation; and (iv) stakeholder and collaboration dynamics (van Eck and Waltman, 2010; Si et al., 2019). The query was restricted to peer-reviewed journal articles published between 2006 and 2025 in Business, Energy, Economics, and Social Sciences subject areas, with English as the language of publication

TABLE 1 Search protocol.

Search protocol Scopus database
TITLE-ABS-KEY (("biofuel" OR "bioenergy" OR "renewable fuel") AND ("policy" OR "regulation" OR "governance") AND ("technology" OR "innovation" OR "transition") AND ("stakeholder" OR "strategy" OR "actor" OR "collaboration")) AND PUBYEAR > 2005 AND PUBYEAR < 2026 AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "ECON") OR LIMIT-TO (SUBJAREA, "SOCL")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))
Search protocol Web of Science database
TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("technolog*" OR "innovation*" OR "advancement*"))
OR TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("polic*" OR "regulat*" OR "governance*" OR "legislat*"))
OR TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("stakeholder*" OR "actor*" OR "participant*" OR "involv*" OR "public acceptance" OR "community engagement*"))
OR TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("strateg*" OR "implication*" OR "managerial*" OR "business impact" OR "firm performance*"))
OR TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("transition*" OR "shift*" OR "transform*" OR "decarbonization" OR "energy transition*"))
OR TS= (("biofuel*" OR "bio-energy*" OR "bio fuel*" OR "renewable fuel*" OR "bio-based fuel*"))
AND ("global" OR "international" OR "worldwide" OR "cross-border*"))

(Haustein and Larivière, 2015; Smyrnova-Trybulska et al., 2018). The complete search string formulation is provided in Table 1, detailing its logical structure and parameter limits.

The Web of Science search used segmented operations in the TS (Topic) fields, combining biofuel-related root terms with thematic components such as technology, policy, stakeholder dynamics, and energy transition/global context terms (e.g., energy transition/decarbonization and global/international keywords) (Szomszor et al., 2020; Abramo and D'Angelo, 2011). This modular approach enabled a more granular capture of studies spanning diverse disciplinary lenses (Smyrnova-Trybulska et al., 2018; Alkhamash, 2023). Table 1 outlines the detailed search protocol applied in Web of Science, reflecting a multilevel Boolean structure to isolate relevant literature across interconnected dimensions of the biofuel transition. While Scopus allows this scope to be implemented as a single integrated query, Web of Science requires a modular TS strategy; both protocols were designed to represent the same conceptual scope anchored on biofuel root terms, with database-specific syntax differences documented in Table 1.

The search was conducted on March 23, 2025, with specific criteria restricting results to English-language, peer-reviewed journal articles in relevant subject fields (Si et al., 2019; Costa

et al., 2018). The methodology follows established bibliometric best practices to ensure replicability and validity by focusing on articles addressing the integration of the three focal enablers (policy/governance, innovation, and stakeholder engagement), captured through four keyword blocks including the biofuel domain (Szomszor et al., 2020; Alkhamash, 2023).

2.4 Inclusion criteria and data cleaning process

Included in the dataset were only: (i) publications from 2006 to 2025; (ii) peer-reviewed journal articles (excluding editorials, proceedings, books, reports); (iii) English-language articles; and (iv) records indexed under relevant subject categories, including Business, Energy, Economics, and Social Sciences (Scopus) and Environmental Sciences, Economics, Business, Management, and Energy Fuels (WoS) (van Eck and Waltman, 2010; Costa et al., 2018). The search produced 2,903 records: 476 from Scopus and 2,427 from Web of Science. Web of Science exported 2,252 records, as its internal filters excluded documents lacking abstracts or keywords (van Eck and Waltman, 2010; Alkhamash, 2023). 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). No manual title/abstract screening was conducted by the authors. Relevance control relied on the predefined search query, database filters, and the automated/metadata-based cleaning steps described below. The combined dataset (2,728 records) was processed using RStudio (2024.12.1 Build 563) with the Bibliometrix R package (Haustein and Larivière, 2015; Szomszor et al., 2020), yielding 2,725 unique articles after cleaning (three duplicates removed from 2,728). 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) metadata-based filtering of records missing abstracts/keywords (van Eck and Waltman, 2010; Waltman and van Eck, 2012); and (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). Bibliometrix (RStudio) was used for data import, harmonization, and deduplication, as well as core performance analyses (e.g., descriptive statistics and citation indicators). Biblioshiny (the Bibliometrix web interface) was used for thematic and longitudinal analyses (e.g., trend topics, thematic evolution, and three field plots), while VOSviewer was used to construct and visualize network maps (e.g., keyword co-occurrence, co-authorship, and citation-based clustering).

3 Results

This section presents the results of the bibliometric analysis based on a cleaned dataset of 2,725 peer reviewed journal articles published between 2006 and 2025, following export

filtering and deduplication (Figure 1). The results are organized in a logical analytical sequence, moving from global knowledge configuration and temporal trajectories to dissemination pathways, outlet dominance, country-level embedding, and conceptual fragmentation in the biofuel research literature captured by the dataset.

Publication output exhibits a sustained increase over time, particularly from 2013 onward, indicating expanding scholarly attention to biofuels. The corpus is anchored in internationally visible publication outlets, suggesting that the mapped patterns reflect mainstream scholarly channels rather than niche sources. To contextualize the mapping and network evidence reported in later sections, the chapter first summarizes outlet and country-level performance patterns and then traces how themes and collaboration structures evolve. Notably, some biodiesel-active countries, including Indonesia remain comparatively marginal in publication visibility despite strong policy and implementation leadership in practice; this observation is treated as a publication pattern baseline rather than an evaluation of implementation outcomes.

All bibliometric statistics, thematic analyses, and maps in this chapter were generated from the cleaned dataset using Bibliometrix/Biblioshiny and VOSviewer. Bibliometrix/Biblioshiny was used for performance statistics and thematic/longitudinal analyses (e.g., trend topics, thematic evolution, and three field plots), while VOSviewer was used to construct and visualize network structures (e.g., keyword co-occurrence and collaboration maps). Network size and inclusion were governed by minimum occurrence thresholds and synonym merging settings applied consistently to balance granularity and interpretability; full parameter settings are reported in the Methods section for transparency and reproducibility.

The chapter is structured as follows. Section 3.1 examines the global knowledge configuration of biofuel research and identifies dominant thematic clusters and structural gaps. Section 3.2 traces temporal dynamics and thematic trajectories to show how research priorities evolve over time. Section 3.3 analyzes global knowledge flows and regional leadership through dissemination pathways and outlet patterns. Section 3.4 focuses on Indonesia's position within global biofuel scholarship, highlighting mismatches between practice leadership and publication visibility. Finally, Section 3.5 synthesizes the mapped evidence to identify conceptual fragmentation and strategic voids relevant to sustainable biofuel business models.

3.1 Global knowledge configuration in biofuel research

3.1.1 Policy-technology dominance and stakeholder gaps in biofuel research

The global biofuel discourse reflects a complex interplay between policy ambitions, technological advancement, and sustainability imperatives. Across this discourse, stakeholder-oriented perspectives tend to be less integrated than policy and technology streams, consistent with wider energy transition observations (Markard et al., 2012; Geels et al., 2017). Figure 2

presents a keyword co-occurrence network that maps the dominant thematic configuration of global biofuel research, revealing structurally distinct clusters organized around policy-governance priorities and technology-oriented production and assessment themes.

The network structure indicates that institutional and technological themes occupy more central positions, while stakeholder-related terms appear weakly connected and comparatively peripheral. A policy-governance cluster is dominated by regulatory instruments, carbon mitigation, and national energy strategies, whereas concepts related to public engagement, social acceptance, and community participation are sparsely represented within the network, echoing concerns raised in Southeast Asian policy contexts (Leach et al., 2010; Sovacool and Dworkin, 2015).

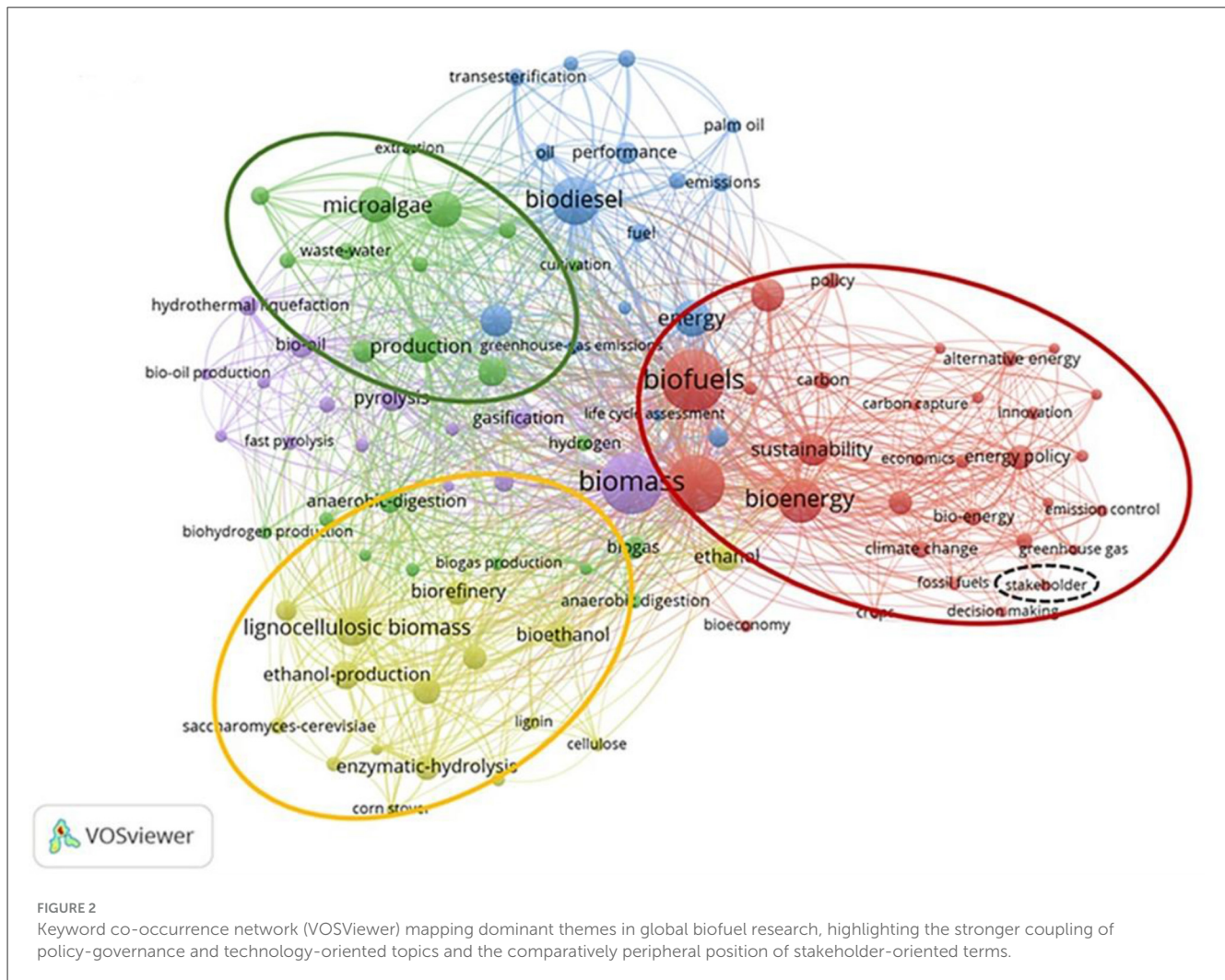
Technology-oriented clusters emphasize lifecycle assessment, biomass conversion, and production efficiency, reflecting strong alignment with techno-economic optimization priorities. While these themes are closely linked to policy agendas, their limited interaction with stakeholder-oriented concepts suggests an imbalance in how sustainability is operationalized and governed in the literature (Cherubini and Strømman, 2011). Additional clusters capture frontier innovation themes (e.g., microalgae, wastewater reuse, and carbon capture) that align with circular bioeconomy principles (D'Adamo et al., 2020), as well as second-generation pathways (e.g., enzymatic hydrolysis) that remain comparatively underutilized in implementation narratives, including in the Indonesian context (González-Gloria et al., 2024).

This configuration is relevant to Indonesia's B40 biodiesel context, where blending mandates are strongly institutionalized through policy instruments, while stakeholder-facing dimensions (e.g., social acceptance and public perception) are less visible in formal narratives. Overall, Figure 2 establishes an analytical baseline: policy and technology themes co-evolve more tightly than stakeholder-oriented research streams. This baseline informs the subsequent analyses of temporal trajectories (Section 3.2), global knowledge flows (Section 3.3), Indonesia's marginal scholarly positioning (Section 3.4), and the mapped strategic void in integrated biofuel business model research (Section 3.5) (Meadowcroft, 2009; Köhler et al., 2019).

3.2 Temporal dynamics and thematic trajectories in global biofuel research

3.2.1 Temporal shifts in biofuel research: innovation-policy trends and stakeholder gaps

This subsection examines the temporal evolution of dominant research themes in global biofuel studies to contextualize the relative positioning of policy, technological innovation, and stakeholder-oriented perspectives. Figure 3 maps the emergence, consolidation, and decline of key topics (2007–2025), indicating shifts in global research priorities based on term frequency visibility over time. Building on this temporal prominence view, Figure 4 traces how topics reorganize and transition across successive periods, revealing continuity, branching, or fragmentation in the policy-innovation-stakeholder linkage.



During the early phase (2007–2012), research attention centered on foundational concepts such as renewable resources, fuel consumption, and environmental efficiency, mirroring initial efforts to position biofuels within broader energy transition debates (Demirbas, 2009b; Timilsina and Shrestha, 2010). From 2013 to 2017, policy-related and innovation-oriented topics gained prominence, signaling a closer coupling between regulatory frameworks and technological development pathways (Cherubini and Strømman, 2011). In the most recent phase (2018–2025), advanced technological themes, including lignocellulosic biomass, pyrolysis, and life-cycle assessment became increasingly dominant, reflecting the maturation of techno sustainability research agenda (Köhler et al., 2019; Zabaniotou, 2018).

Across all phases, stakeholder-oriented terms remain comparatively infrequent and short lived, indicating that social acceptance, public participation, and actor engagement have not evolved in parallel with policy and technological themes. This pattern aligns with prior empirical reviews, which note that stakeholder engagement in biofuel systems is often confined to regulatory and industrial actors, with limited civil society involvement (Djatmika et al., 2023). Evidence from diverse national contexts, including Brazil and Hawaii, similarly highlights gaps in participatory governance, undermining policy legitimacy

and long-term sustainability outcomes (Grangeia et al., 2022; Rush et al., 2025). The temporal pattern observed globally resonates with Indonesia's biofuel development trajectory. While the B40 program demonstrates strong institutional coordination and private sector alignment, broader societal inclusion remains weakly articulated within formal policy and research frameworks. Overall, Figure 3 reinforces the temporal asymmetry between rapidly advancing policy innovation themes and persistently marginal stakeholder-oriented research, strengthening the rationale for strategic frameworks that explicitly integrate policy, innovation, and stakeholder engagement.

3.2.2 Longitudinal evidence of policy-innovation bonding in biofuel research

Figure 4 maps the thematic evolution of global biofuel research across five periods (2006–2008; 2009–2015; 2016–2018; 2019–2020; 2021–2025), complementing Figure 3 by revealing cross period topic transitions and reconfiguration rather than frequency-based prominence alone. In doing so, the flow structure highlights two structural features of the knowledge trajectory: (i) a path dependent consolidation of the policy-innovation stream; and (ii) the continued lack of

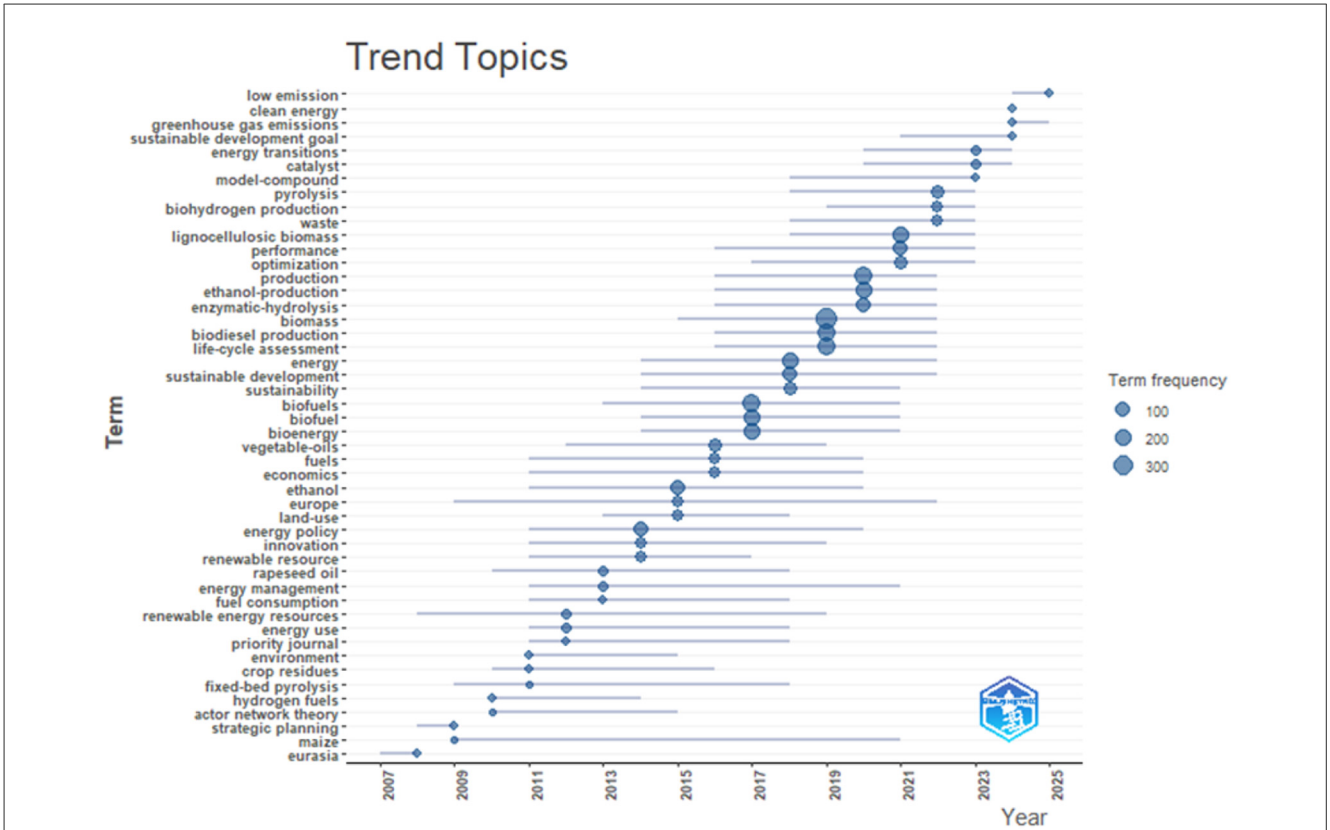


FIGURE 3 Trend topics in global biofuel research (2007–2025), illustrating the temporal emergence, consolidation, and decline of dominant policy and technology-oriented themes based on frequency-based visibility over time, alongside the comparatively limited and discontinuous presence of stakeholder-related topics Source: Biblioshiny analysis.

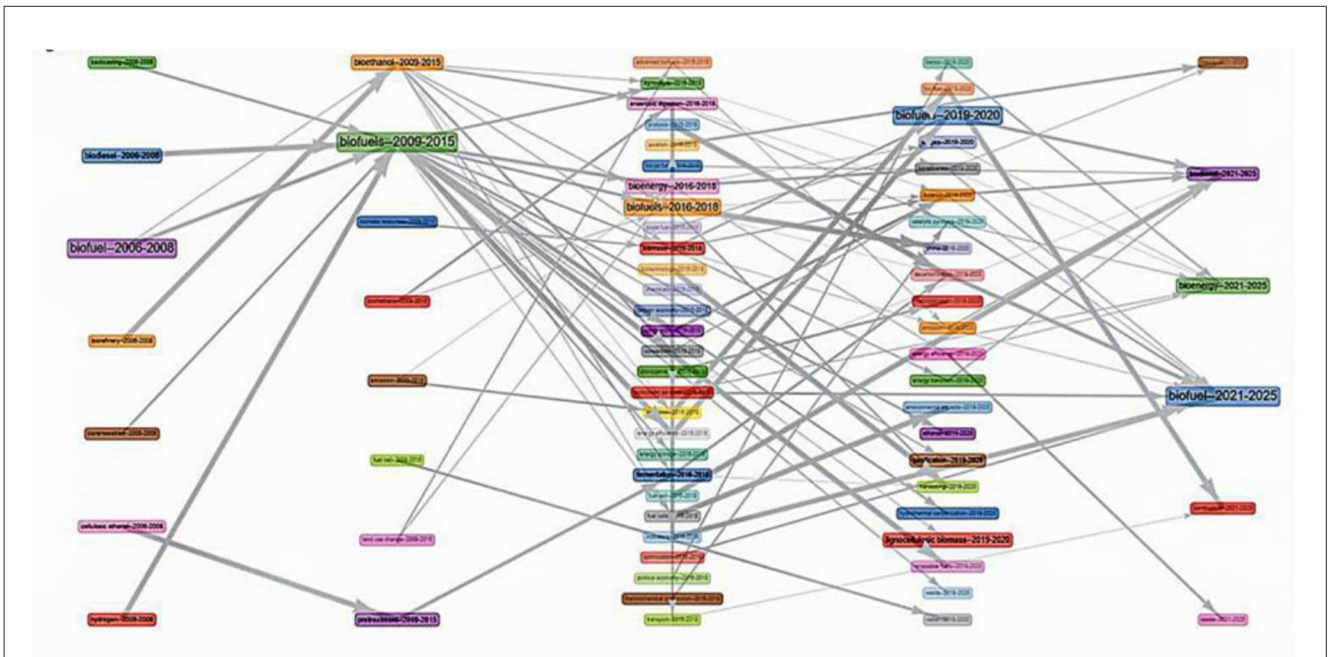


FIGURE 4 Thematic evolution of global biofuel research across five periods (2006–2008; 2009–2015; 2016–2018; 2019–2020; 2021–2025), mapping topic transitions and linkages across periods. Source: Biblioshiny analysis.

stakeholder-oriented concepts acting as bridging themes between dominant clusters.

In 2006–2008, early clusters are anchored by foundational biofuel-related themes, reflecting agenda setting and early sector formation. In 2009–2015, the diagram shows a major consolidation around broad, system level “biofuels” themes, with thick outgoing links into subsequent clusters. This period functions as a structural backbone that stabilizes the field’s dominant vocabulary and channels early fuel specific topics into later governance and innovation-oriented pathways. In 2016–2018, the Sankey becomes denser and more vertically stacked, signaling diversification within an increasingly consolidated stream. Intermediate themes particularly those associated with technology deployment and evaluative/assessment logics, appear to translate earlier “biofuels” framing into more operationalized research directions. In 2019–2020, sustainability transition framings intensify and topics are recombined into “green” narratives while remaining strongly connected to the established policy/technology backbone, indicating reframing and recombination rather than rupture. In 2021–2025, flows consolidate further into large biofuel and sustainability associated clusters, reinforcing the persistence of policy-innovation coupling as the dominant knowledge trajectory.

Crucially, across these five phases, stakeholder-oriented concepts do not emerge as stable pathways or bridging nodes that connect policy and innovation clusters. From a thematic evolution perspective, this pattern suggests non diffusion rather than simple absence: stakeholder constructs do not travel across periods in ways that reshape or integrate the dominant trajectory. Overall, Figure 4 supports the manuscript’s argument that global biofuel research has progressively consolidated around policy-innovation pathways, while stakeholder engagement remains weakly embedded, an imbalance that motivates the need for more inclusive Sustainable Biofuel Business Models (SBBMs), including in contexts such as Indonesia’s B40 program.

3.3 Global knowledge flows and regional leadership

3.3.1 Structural pathways of knowledge dissemination

Figure 5 presents a ThreeField Plot (TFP) mapping the interrelations among author countries, dominant keywords, and leading publication sources in global biofuel research. Rather than indicating topic prominence, the TFP captures the field’s knowledge dissemination architecture by showing how country hubs connect to keyword clusters and how these, in turn, route into major publication outlets. In this configuration, India, China, and the United States appear as the most connected country nodes, indicating their strong positioning within the main dissemination pathways. Indonesia does not appear among the most connected country nodes in these dissemination routes, suggesting limited routing of its policy experience into mainstream country-keyword-source linkages (examined further in the dedicated Indonesia-focused subsection).

The keyword field is dominated by fuel and feedstock-centric terms such as “biofuel,” “biomass,” and “biodiesel,” which show strong linkages to leading outlets, reinforcing a technocentric

orientation in mainstream dissemination channels. By contrast, governance and inclusion-related terms (“policy,” “sustainability,” “stakeholder”) exhibit comparatively weaker connectivity in the mapped pathways, indicating that these themes are less consistently embedded within the primary publication routes.

At the source level, the strongest dissemination links converge on high output technical journals (e.g., *Renewable and Sustainable Energy Reviews*; *Bioresource Technology*), indicating that mainstream biofuel discourse is primarily routed through technocentric publication channels in this mapping. Overall, Figure 5 provides structural support for the manuscript’s argument that global biofuel knowledge dissemination is concentrated within a limited set of country hubs and routed through dominant technical outlets, while governance and stakeholder-related terms remain comparatively less embedded in the primary dissemination pathways.

3.3.2 Regional and thematic dominance in biofuel publications

To complement the dissemination pathways mapped in Figure 5, Table 2 provides an outlet level performance view by listing the most productive journals and their publication volume. The table identifies ten core journals dominating the global biofuel research landscape, the majority of which emphasize technological and engineering dimensions. Highly productive outlets such as *Renewable and Sustainable Energy Reviews* (678 articles), *Bioresource Technology* (251), and *Energies* (202) indicate a strong concentration of publications in journals oriented toward renewable energy systems, bioengineering, and biomass-related technologies.

This concentration should be interpreted as a structural characteristic of publication outlets rather than as evidence of causal influence: dominant journals disproportionately channel technocentric research themes, aligning with the outlet routing observed in the Three Field Plot. In contrast, more policy and governance-facing journals such as *Energy Policy* and *Journal of Cleaner Production* appear with substantially lower publication volumes (fewer than 50 articles). This distribution suggests that governance and stakeholder relevant perspectives are less frequently represented within the field’s highest-output outlets, consistent with their weaker embedding in mainstream dissemination channels.

Overall, Table 2 triangulates the evidence in Section 3.3 by confirming that global biofuel publications are concentrated within a narrow set of high output, technically oriented journals. As an outlet-level complement to Figure 5, it provides further support for the manuscript’s argument that dominant publication structures privilege technocentric themes, while governance and stakeholder perspectives remain comparatively less integrated into mainstream biofuel research channels.

3.4 Indonesia’s scholarly absence amid biofuel leadership

Following the macro-level mapping of dissemination pathways in Section 3.3, this section adopts a nested “zoom in” logic

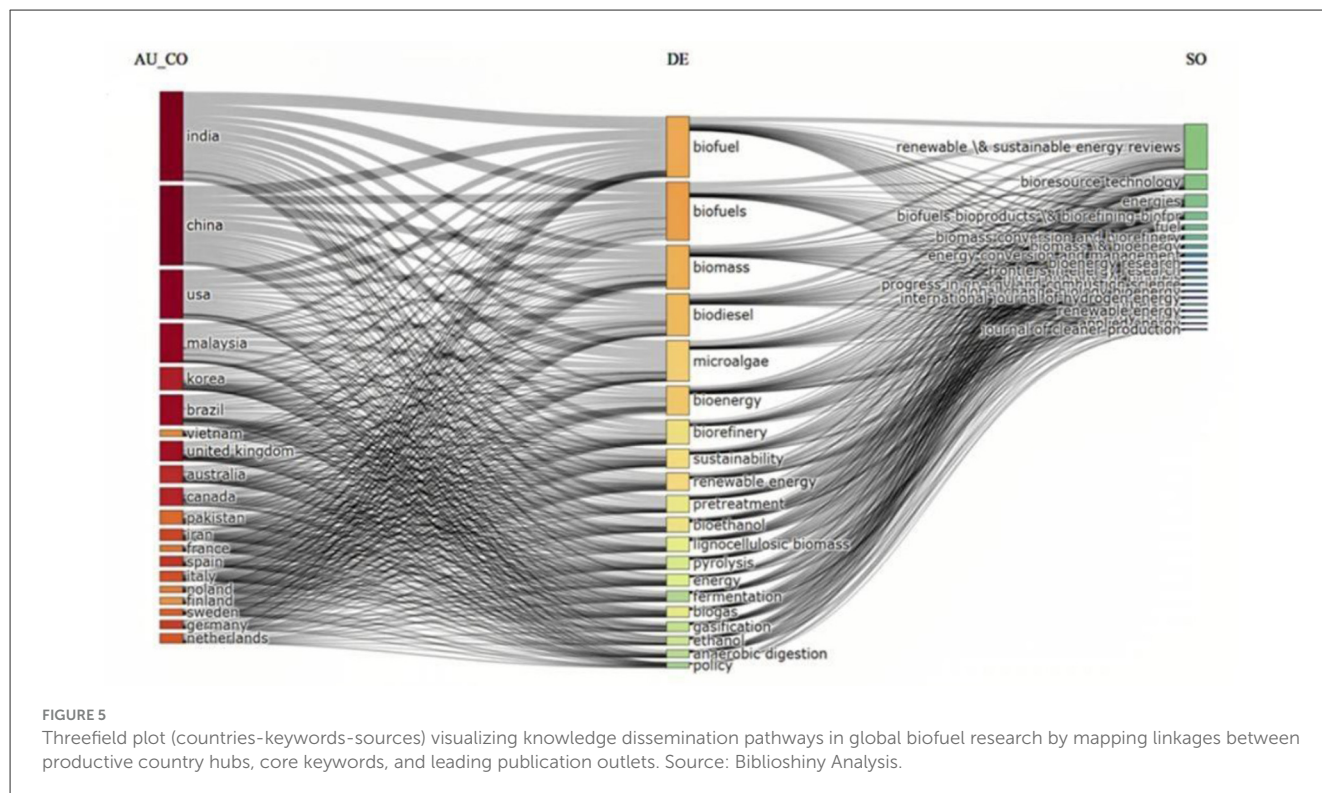


TABLE 2 Leading journals in global biofuel research and their publication volume, illustrating the technocentric orientation of dominant publication outlets.

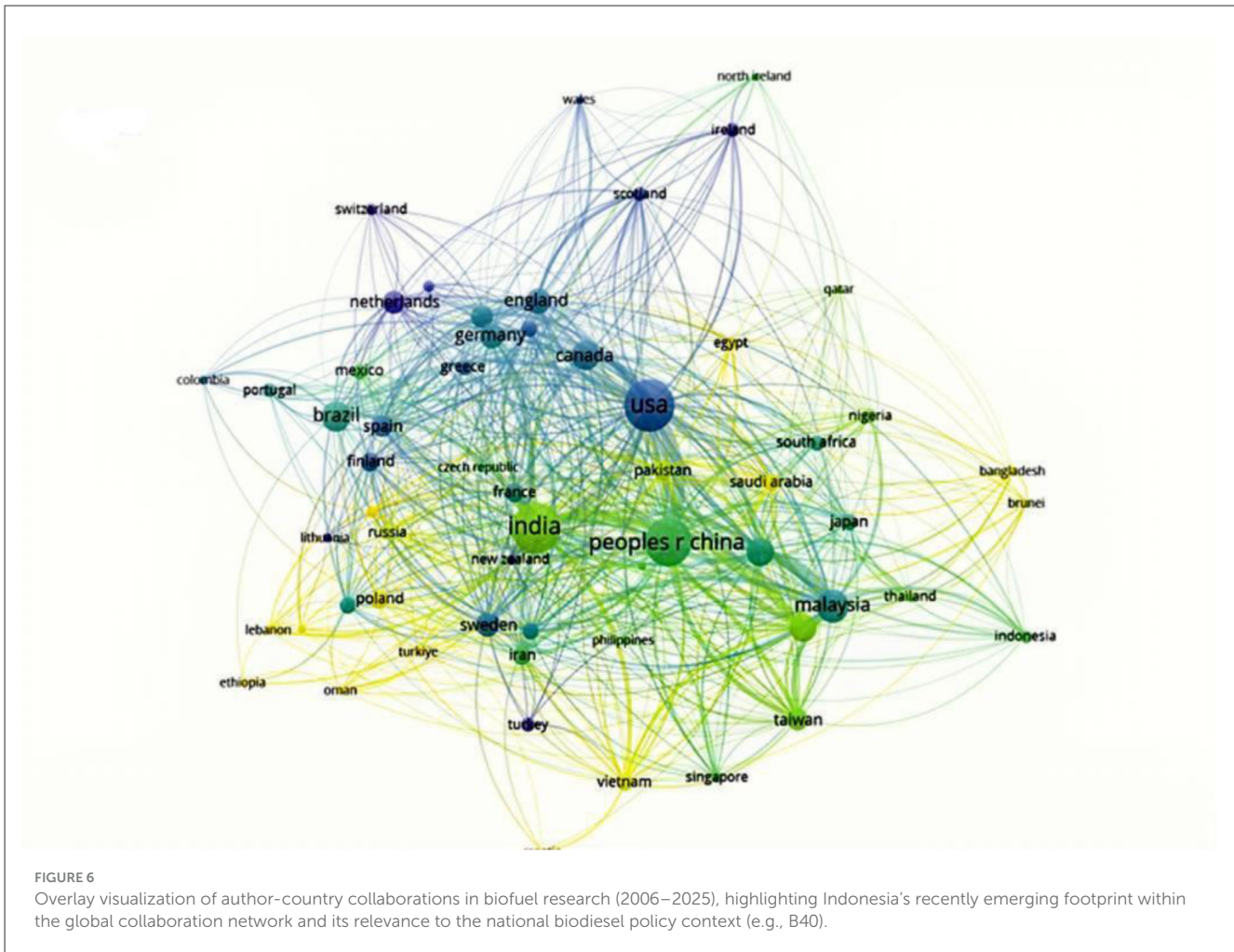
No.	Journal name	No. of articles	Scope/discipline	Publisher	Scopus quartile
1	Renewable and Sustainable Energy Reviews	678	Renewable energy, sustainability	Elsevier	Q1
2	Bioresource Technology	251	Biotechnology, bioengineering	Elsevier	Q1
3	Energies	202	Energy systems, renewable energy	MDPI	Q2
4	Biofuels, Bioproducts and Biorefining	119	Bioengineering, chemical engineering	Wiley	Q2
5	Fuel	93	Fuel technology, chemical engineering	Elsevier	Q1
6	Biomass Conversion and Biorefinery	75	Biomass, chemical engineering	Springer	Q2
7	Biofuels-UK	58	Biofuels, renewable energy	Taylor & Francis	Q3
8	Biomass and Bioenergy	55	Biomass, bioenergy, renewable energy	Elsevier	Q1
9	Biotechnology for Biofuels	55	Biotechnology, biofuels	BioMed Central (Springer Nature)	Q1
10	Energy Policy	50	Energy policy, environmental studies	Elsevier	Q1

to examine Indonesia’s integration within the global biofuel collaboration network. We first position Indonesia at the country level (Figure 6) and then assess author-level embedding to identify whether country visibility translates into integration within influential collaboration hubs (Figure 7).

3.4.1 Indonesia’s limited presence in global technocentric research

Figure 6 visualizes global author-country collaborations in biofuel research, positioning Indonesia within the country-level collaboration map of the field (Neo, 2024). In the overlay

visualization, the lighter color tones (e.g., yellow) indicate more recent publication activity, suggesting that Indonesia’s contributions have become more visible in the latest period captured by the dataset. However, the relatively small size of Indonesia’s node compared to dominant research nations such as China, India, and the United States indicates limited integration within the core global collaboration networks (Reuters, 2024). This highlights a structural gap between Indonesia’s practical leadership in biodiesel implementation, often cited as among the highest blending mandates globally and its comparatively modest footprint in internationally co-authored, peer-reviewed biofuel scholarship. As shown

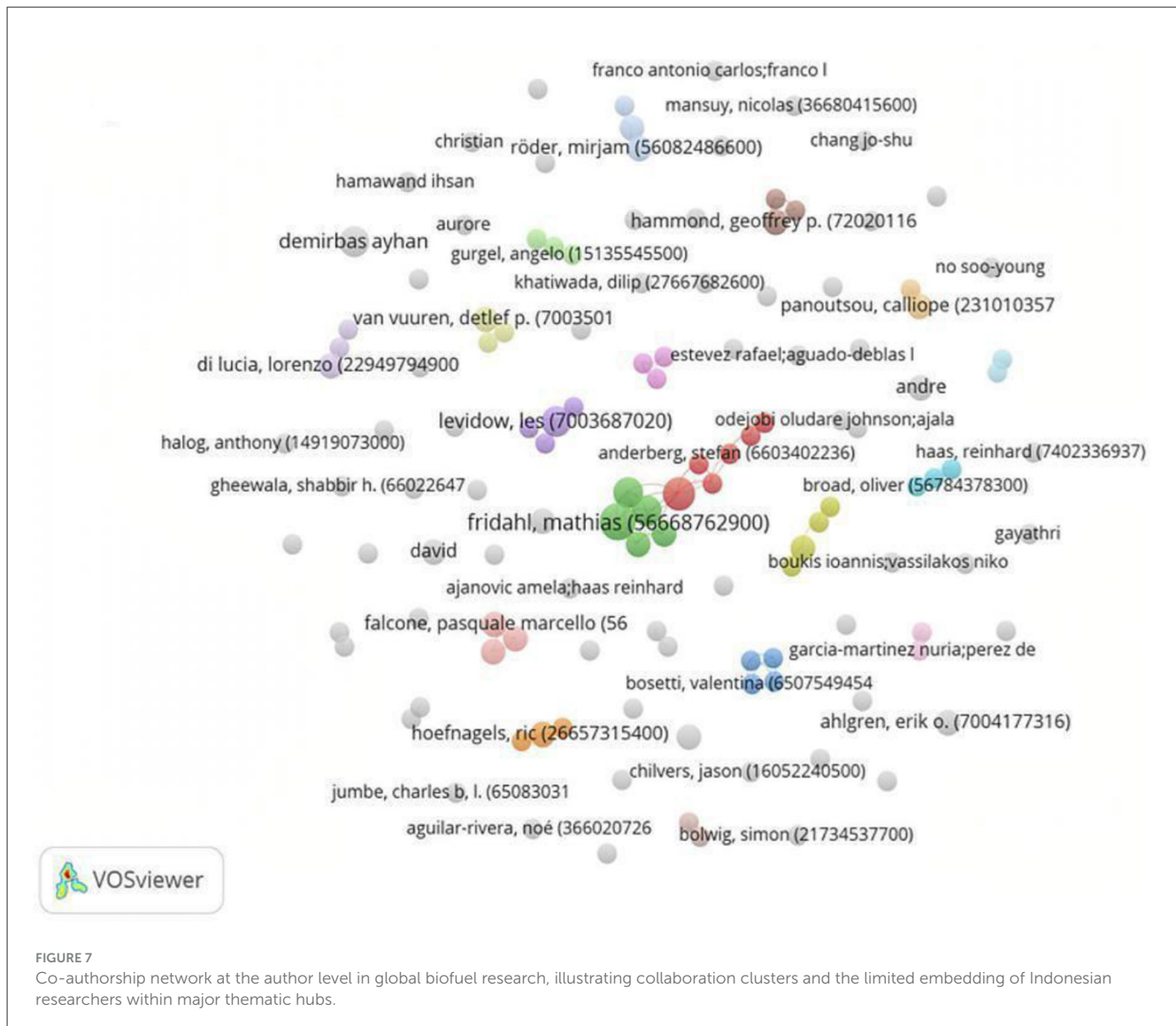


in Figure 6, the broader research ecosystem remains largely technocentric and concentrated, with collaboration pathways that more strongly connect established publishing countries, while many Global South contributors (including Indonesia) appear less connected. Such limited country-level visibility constrains how effectively Indonesia's implementation experience (including B40 and future trajectories) can circulate into the global knowledge base that shapes sustainable biofuel debates. Indonesia's entry into the Global Biofuels Alliance signals ambition to contribute to international cooperation (BioEnergyTimes, 2025), but deeper scholarly integration, through sustained cross border co-publication and collaboration, remains a necessary complement to policy and innovation progress, consistent with this study's strategic focus on aligning policy, innovation, and stakeholder engagement.

While Figure 6 positions Indonesia at the country level within the global collaboration landscape, a country's visibility does not necessarily translate into strong integration of its scholars into influential research hubs. To examine this micro level embedding and identify where Indonesian authors sit within the field's core collaboration structures, the next subsection analyzes the author-level co-authorship network (Figure 7).

3.4.2 Indonesia's marginal role in biofuel research collaboration

Figure 7 presents the global co-authorship network among biofuel researchers, visually capturing collaboration intensity and clustering across the field at the author level. A key insight from this visualization is the limited embedding of Indonesian scholars within major collaboration hubs. While central nodes such as Fridahl, Levidow, and Hoefnagels appear as densely connected actors linked to techno-economic modeling, governance, and energy policy scenario studies, Indonesian researchers remain peripheral, with few ties into highly connected, internationally co-authored clusters. This micro-level pattern complements the country-level view in Figure 6, even where Indonesia appears in the global map, its authors are not yet positioned within the network core that shapes influential research agendas and frames dominant biofuel transition narratives (Neo, 2024; Reuters, 2024). Figure 7 therefore provides structural evidence of barriers to knowledge exchange, visibility alone is insufficient without strong co-publication ties. The sparse co-authorship density suggests that implementation experience (including Indonesia's biodiesel trajectory) may remain weakly represented in the collaborative knowledge pathways that inform global biofuel innovation debates. Strengthening cross-border research partnerships, particularly at



the policy-innovation interface would help reposition Indonesia from a primarily practice leading context to a more recognized contributor within global biofuel knowledge trajectories, aligning with this study's focus on policy-innovation-stakeholder coherence.

3.4.3 Practice vs. publication in global rankings

Table 3 provides a quantitative snapshot of the top 10 countries contributing to global biofuel research based on publication volume. The data shows that China, India, and the United States lead global scholarly output, reinforcing the concentration of biofuel knowledge production within a relatively small group of highly productive research systems. While Figures 6, 7 map Indonesia's position within collaboration networks, Table 3 adds an output-based lens by showing whether such visibility is matched by publication volume in global rankings. Notably, Indonesia does not appear in the top 10, despite its globally prominent role in biodiesel implementation through the B40 mandate. This divergence substantiates a practice publication

gap, national policy leadership and implementation experience are not proportionally translated into internationally visible scholarly outputs. Compared with countries such as Malaysia and Brazil, which demonstrate stronger research visibility, Indonesia's absence suggests that practical policy achievements have not yet been systematically codified and disseminated through the dominant academic channels. Importantly, Table 3 complements the network-level findings in Figures 6, 7 by adding a ranking-based indicator of scholarly visibility. Together, these results indicate that Indonesia's emerging network visibility does not yet translate into a commensurate position in global publication rankings, strengthening the rationale for alignment strategies that connect policy execution, innovation ecosystems, and inclusive knowledge dissemination.

Taken together, the network-based evidence (Figures 6, 7) and output rankings (Table 3) indicate that Indonesia's limited scholarly visibility is not merely a matter of collaboration intensity or publication volume, but reflects deeper structural and conceptual misalignments in how biofuel research integrates policy,

TABLE 3 Top 10 countries by scientific output in global biofuel research based on publication volume (Scopus + Web of Science dataset, 2006–2025).

Rank	Country	No of docs	% of total publication
1	China	1,522	15.40
2	India	1,333	13.49
3	USA	952	9.63
4	Malaysia	526	5.32
5	Brazil	415	4.20
6	UK	387	3.92
7	South Korea	367	3.71
8	Canada	350	3.54
9	Australia	304	3.08
10	Spain	192	1.94

technology, and stakeholder dimensions, an issue further examined through the strategic co-occurrence mapping in Section 3.5.1.

3.5 Knowledge foundations and conceptual fragmentation in global biofuel research

3.5.1 Mapping the strategic void in biofuel research

To advance Sustainable Biofuel Business Models (SBBMs), the literature needs to move beyond siloed technological innovations by connecting policy/governance logics, sustainability objectives, and stakeholder-oriented considerations within a more integrated strategic framing. [Figure 8](#) maps a strategic keyword co-occurrence structure and indicates two dominant yet weakly bridged clusters. The right-side cluster is anchored in operational and engineering-oriented terms, such as biodiesel production, ethanol production, life-cycle assessment, and lignocellulosic biomass, suggesting sustained attention to conversion pathways and assessment logics. In contrast, the left-side cluster concentrates on broader socio-environmental and institutional themes, such as sustainability, energy policy, and bioenergy, but connects to the production/LCA cluster through comparatively thin bridging links, signaling limited conceptual integration across policy and implementation layers.

4 Discussions

4.1 Global knowledge trajectories and alignment implications for SBBMs

The findings presented in Sections 3.1 and 3.2 reveal a clear consolidation of global biofuel scholarship around a dominant policy-innovation trajectory. Longitudinal and thematic analyses ([Figures 3, 4](#)) indicate that, across the five temporal phases examined, research themes repeatedly stabilize around regulatory frameworks, life cycle assessment, and technology-oriented solution pathways. This pattern reflects a growing

scholarly emphasis on aligning technological development with policy instruments as a central mechanism for advancing biofuel transitions ([Markard, 2020](#)).

Despite this consolidation, stakeholder engagement remains comparatively peripheral and weakly embedded within the dominant knowledge structure. Co-occurrence and thematic evolution evidence ([Figures 2–4](#)) shows that stakeholder-related concepts exhibit limited connectivity and do not evolve into stable cross period bridging pathways linking policy and innovation streams. Rather than diffusing across thematic clusters, stakeholder constructs tend to remain fragmented, suggesting that participatory and multi actor governance perspectives have not yet become integral components of the mainstream biofuel research trajectory.

These literature-mapped patterns directly address RQ1 by demonstrating that global biofuel research prioritizes policy-innovation convergence while comparatively underrepresenting stakeholder-oriented integration. From a strategic perspective, this imbalance may constrain the relevance of existing knowledge for complex sustainability challenges that require not only technological readiness and regulatory support, but also social legitimacy and coordinated actor participation.

The observed asymmetry has important implications for Sustainable Biofuel Business Models (SBBMs). In this study, SBBMs are understood as business models that create and capture value while simultaneously advancing environmental, social, and economic sustainability objectives through the alignment of policy frameworks, innovation capabilities, and stakeholder engagement. When stakeholder dimensions remain weakly connected to policy and innovation domains, biofuel transitions risk becoming technocratically robust yet socially fragile.

This synthesis also motivates RQ2. While bibliometric analysis does not assess implementation outcomes, the Results provide a bibliometric evidence base, that is, literature-mapped structural and longitudinal signals, that informs the development of the strategic alignment framework presented in Section 4.2. To avoid the impression of ex post justification, the framework is positioned as a hybrid proposition: inductively motivated by the patterns identified in Sections 3.1–3.5 and deductively structured using established transition-governance scholarship on institutional coordination and multi actor participation.

4.2 Propositional strategic framework for policy-innovation-stakeholder alignment

Building on the findings in Section 3, this study proposes an integrated strategic framework to address the fragmentation observed between policy, innovation, and stakeholder domains. The framework advocates for a triadic enabler alignment model that positions policy enablers, innovation enablers, and stakeholder enablers as interdependent pillars essential for advancing Sustainable Biofuel Business Models (SBBMs). This approach moves beyond the dominant technocentric paradigm (see [Figure 8](#)) by embedding participatory governance alongside technological and regulatory mechanisms, ensuring legitimacy and long-term resilience ([Markard et al., 2012](#); [Baasch and Maschke, 2025](#)).

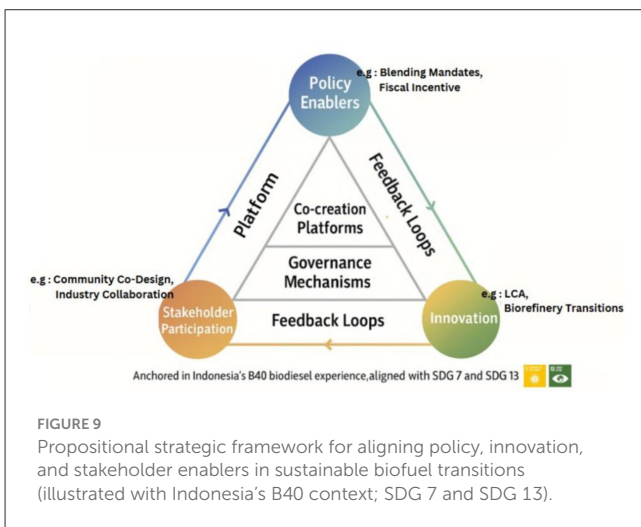
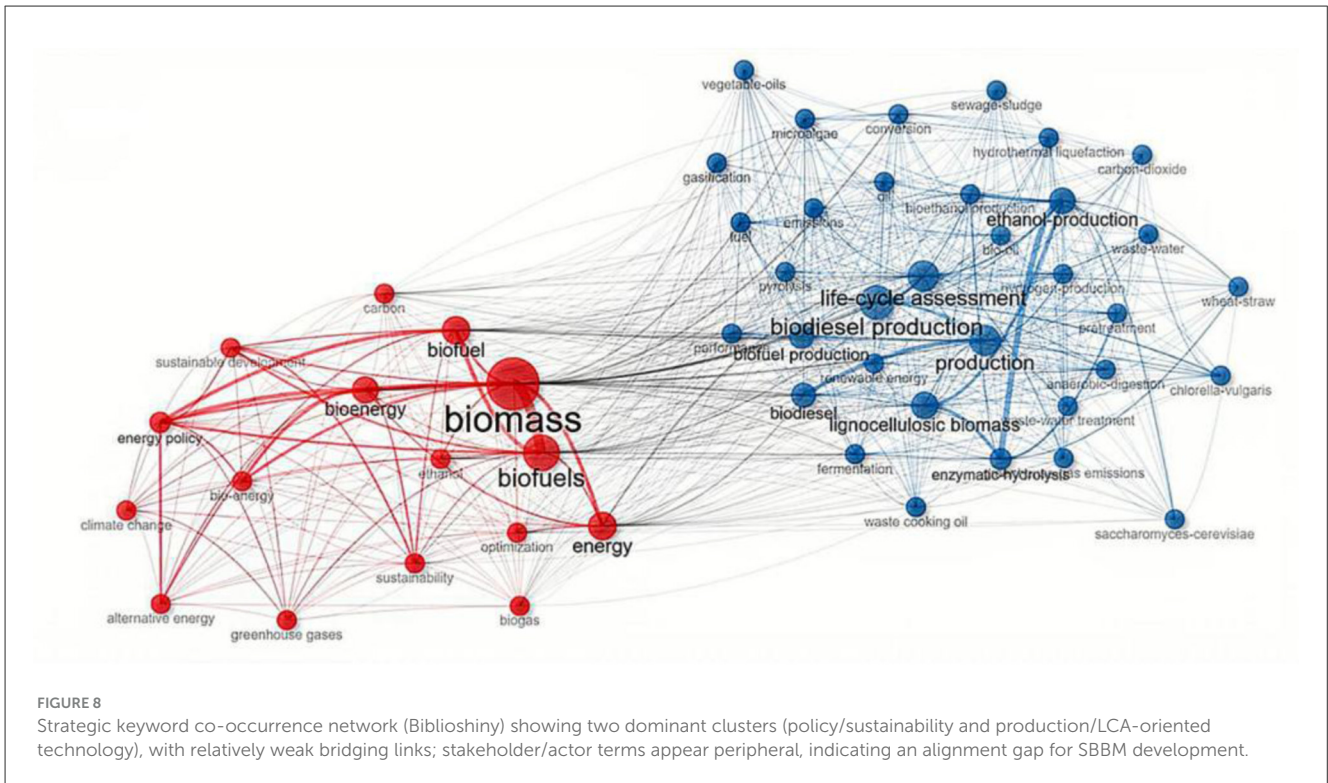


Figure 9 translates these mapped bibliometric imbalances into a structured alignment proposition. Policy enablers (e.g., blending mandates, fiscal incentives) provide the regulatory scaffolding and market signals necessary for biofuel transitions (IEA, 2023). Innovation enablers (e.g., life cycle assessment, biorefinery technologies, circular bioeconomy tools) drive technological advancement and environmental performance (Cherubini and Strømman, 2011; Osman et al., 2024). Stakeholder enablers (e.g., community co-design, industry collaboration, local engagement platforms) ensure inclusivity, aligning biofuel initiatives with societal values and expectations (Farla et al., 2012; Rush et al., 2025).

Crucially, the framework identifies co-creation platforms, multilevel governance mechanisms, and feedback loops as key

integrative tools to unify these enablers. Co-creation platforms facilitate joint knowledge production and shared decisionmaking between state actors, industry, and civil society (Wittmayer and Schöpke, 2014; Bokolo, 2023). Multilevel governance mechanisms promote policy coherence across national, regional, and local levels, ensuring alignment with community needs (Peters and Pierre, 2004; Dorado-Rubín et al., 2025). Feedback loops between practice and policy enable adaptive learning and iterative improvement of biofuel strategies (Geels and Schot, 2007; Morales, 2024). These elements address gaps observed in global biofuel literature (Sections 3.1–3.3), where stakeholder participation remains marginal, and policy-innovation synergies rarely incorporate inclusive governance (Markard et al., 2012; Baasch and Maschke, 2025).

To avoid the impression of ex post justification, the framework is explicitly positioned as hybrid and propositional: it is inductively motivated by the literature-mapped patterns in Sections 3.1–3.5, while offering a deductively structured set of alignment mechanisms and enablers for transition governance. In this sense, Indonesia's B40 program is referenced as an illustrative application context (Section 3.4), where strong policy and innovation advances may remain vulnerable if stakeholder integration is not institutionally embedded. It emphasizes that sustainable biofuel business models require not only technical and regulatory excellence but also institutional mechanisms that embed societal co-ownership in transition processes (Farla et al., 2012; Rush et al., 2025).

By foregrounding participatory governance alongside policy and technology, the proposed framework directly responds to the study's second research question and provides actionable guidance for business leaders and

policy-makers in designing inclusive and resilient biofuel transition pathways.

4.3 Theoretical and practical implications for sustainable biofuel business models (SBBMs)

This study advances the theoretical discourse on sustainable biofuel business models (SBBMs) by highlighting the structural imbalance between policy–innovation integration and stakeholder engagement. Building on the propositional alignment framework in Section 4.2 (Figure 9), this subsection clarifies what the framework contributes theoretically and practically by translating the mapped bibliometric patterns into implications for SBBMs. The bibliometric evidence indicates that global scholarship remains predominantly technocentric, with participatory governance perspectives only weakly incorporated. This reinforces prior critiques that transition studies often privilege technical and regulatory solutions over social inclusivity (Turnheim et al., 2015; Newell et al., 2023). By proposing a triadic alignment framework that positions stakeholder participation as a co-equal enabler alongside policy and innovation, the study offers an evidence-informed, propositional lens for examining systemic sustainability transitions in which stakeholder participation is treated as an enabling condition rather than a peripheral add-on. It also aligns with calls for more integrative, multi-actor approaches in managing sociotechnical change (Schot and Steinmueller, 2018; Haddad et al., 2022).

From a practical standpoint, the findings offer business leaders and policymakers actionable guidance for operationalizing inclusive biofuel strategies. Rather than reiterating the framework components, the practical implication is that co-creation platforms, multi-level governance mechanisms, and feedback loops provide concrete governance levers for bridging policy, technology, and societal expectations in biofuel transitions. Indonesia's B40 biodiesel experience illustrates both the potential and limitations of technocentric transitions in the absence of broad stakeholder alignment. Embedding these strategic levers can enhance the legitimacy, adaptability, and long term resilience of biofuel business models, particularly in emerging economies aiming to meet SDG 7 and SDG 13 targets. Future efforts should prioritize testing and refinement of this integrative framework through cross-sectoral partnerships and pilot initiatives, consistent with the study's bibliometric scope.

5 Conclusion

This study offers an integrated perspective on the dynamics of biofuel business model development, revealing that global research on biofuels continues to emphasize policy frameworks and technological innovation while largely neglecting stakeholder participation. Bibliometric evidence shows that academic discourse remains dominated by technocentric trajectories, with strong policy–innovation coupling but minimal attention to inclusive governance or participatory frameworks. These mapped

structural and longitudinal patterns address RQ1 by showing not only which themes dominate, but also how policy–innovation pathways consolidate across periods while stakeholder-oriented concepts remain weakly embedded and rarely operate as bridging themes.

The proposed triadic alignment model contributes to the literature by positioning stakeholder participation as a core enabler alongside policy and innovation, addressing this gap. In this study, Sustainable Biofuel Business Models (SBBMs) are understood as business models and transition pathways that align (i) institutional support and policy design; (ii) innovation and environmental performance; and (iii) stakeholder engagement and social legitimacy. This model advances theoretical understanding of sustainable biofuel business models by linking policy enablers (e.g., blending mandates, fiscal incentives), innovation enablers (e.g., life cycle assessment, advanced biofuels), and stakeholder participation (e.g., co-creation platforms, community engagement) in a cohesive framework. This contribution complements and extends transformative innovation policy theory (Schot and Steinmueller, 2018; Haddad et al., 2022), highlighting the need for participatory governance to ensure resilient and legitimate transitions.

From a practical standpoint, the study provides business leaders and policymakers with a strategic roadmap that integrates co-creation platforms, multi-level governance mechanisms, and feedback loops to bridge gaps between policy, innovation, and stakeholder alignment. These mechanisms offer actionable guidance for designing biofuel business models that are operationally effective, socially inclusive, and aligned with Sustainable Development Goals 7 and 13. The study underscores the importance of embedding these strategic levers into national biofuel programs, particularly in emerging economies like Indonesia that seek to balance technological advancement with societal expectations. This synthesis addresses RQ2 by offering an evidence-informed, propositional alignment framework derived from mapped bibliometric patterns rather than from tested implementation outcomes.

However, the study is not without limitations. The bibliometric analysis, while comprehensive, is confined to publications indexed in Scopus and Web of Science, potentially excluding relevant insights from gray literature, non-English publications, and local case studies. Furthermore, the absence of primary data collection limits the empirical validation of the proposed framework.

Future research should therefore focus on empirically testing the triadic model through case studies, cross sectoral comparisons, and longitudinal assessments of policy–innovation–stakeholder integration. Further investigation into how inclusive governance structures can be operationalized in different socio political contexts would enrich the understanding of sustainable biofuel transitions. Such follow-on studies can clarify boundary conditions and implementation mechanisms, strengthening the external relevance of the proposed alignment logic across diverse institutional settings. In sum, the study highlights that durable SBBMs depend on triadic alignment (coordinating policy design, innovation performance, and stakeholder co-ownership), so that biofuel transitions become not only technically feasible but also institutionally legitimate and socially resilient.

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. MA: Writing – review & editing, Supervision. RR: Writing – review & editing, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships

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