Integration of the Modern Bioeconomy into Macroeconomics (A Scientometric Study)

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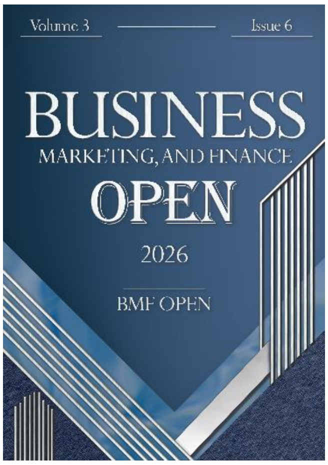

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Abstract: The present study conducts a scientometric analysis of the integration of the modern bioeconomy into macroeconomics, aiming to examine the impacts and complex interactions between biotechnological innovations and macroeconomic variables. This research was carried out using a descriptive and applied approach. The statistical population consisted of 801 articles related to the bioeconomy and macroeconomics indexed in the Scopus database between 2000 and 2025. Data were collected through a systematic and targeted search strategy, including the identification of keywords, their combination using Boolean operators, and data analysis using VOSviewer software. The findings indicated that key terms such as "bioeconomy," "sustainable development," and "environmental economics" constitute central concepts within the scientific literature and economic research landscape. The results also demonstrate a strong relationship between the bioeconomy and environmental issues, including climate change and sustainable resource management. Furthermore, the study highlights the critical role of biological innovations and emerging technologies as key drivers of economic growth and sustainable development. Ultimately, this research provides a foundational basis for the formulation of effective and sustainable policies in the bioeconomy domain and emphasizes the necessity of comprehensive and multidimensional approaches to addressing global and local challenges. These findings can assist researchers and policymakers in achieving a deeper understanding of prevailing trends and challenges in this field and in proposing appropriate strategies for improving existing conditions.

Keywords: Bioeconomy, Macroeconomics, Scientometrics, Sustainable Development, Biotechnologies.

1. Introduction

The bioeconomy has increasingly been framed as a systemic transition in which economic value creation is reorganized around renewable biological resources, biotechnological knowledge, and circular material flows, rather than fossil-based inputs and linear production-consumption models. In management and policy scholarship, this transition is not treated merely as an environmental agenda, but as an emerging development paradigm with implications for industrial strategy, innovation governance, labor markets, and macroeconomic performance. Foundational discussions emphasize that the bioeconomy is conceptually plural—ranging from biotechnology-driven modernization to biomass-based substitution and circular bio-based systems—

yet is unified by the aspiration to align production with ecological boundaries and sustainable development pathways. [1-3]

A central argument in contemporary bioeconomy research is that bio-based transformation is inseparable from sustainability performance, because it reshapes resource extraction pressures, land-use patterns, and environmental externalities. Comprehensive assessments note that the bioeconomy must be evaluated through ecological and ethical lenses that account for biodiversity impacts, pollution displacement, and cross-sectoral rebound effects. In parallel, policy-oriented analyses connect bioeconomy expansion with the Sustainable Development Goals, suggesting that bio-based innovation can support goals related to clean energy, responsible production, and climate action, while also cautioning that weak governance can lead to inequitable outcomes or environmental trade-offs. These concerns are particularly relevant in contexts where institutional capacity, environmental regulation, and industrial priorities interact in complex ways. [2, 4, 5]

From a resource-systems perspective, biomass availability and allocation constitute a binding constraint on the scale and direction of bioeconomy growth. Global evidence on biomass production and utilization indicates wide heterogeneity in feedstock sources, conversion pathways, and sectoral demand, with implications for supply chain management and technology deployment choices. Yet biomass is also contested: systematic synthesis of the food–feed–fuel competition literature shows that biomass-based transitions can intensify scarcity dynamics unless productivity gains, waste valorization, and demand-side efficiencies are explicitly integrated into policy and corporate strategy. Consequently, circular bioeconomy approaches emphasize cascading use, recycling, and the conversion of residues into higher-value products as a way to relieve pressure on primary biomass and reduce lifecycle environmental burdens. [6-8]

Technological trajectories—especially in advanced bioenergy, biorefineries, and bio-based materials—further shape the strategic feasibility of bioeconomy integration. Research on lignocellulosic biomass conversion highlights both opportunities (resource diversification, circularity, and decarbonization) and constraints (process complexity, capital intensity, and supply-chain reliability), particularly in pathways such as gasification that require stable feedstock quality and robust operational governance. At the same time, assessments of second-generation bioenergy underscore that climate benefits depend on system boundaries, counterfactual land-use assumptions, and policy designs that manage trade-offs between carbon mitigation and competing sustainability objectives. Such insights matter for managerial decision-making because they affect risk profiles, project evaluation, and the strategic timing of investments in bio-based infrastructure. [9, 10]

Among bio-based sectors, bioplastics have become a prominent case of market-facing bioeconomy innovation, linking corporate sustainability narratives to measurable shifts in materials markets and environmental impacts. Market and industry analyses indicate substantial growth expectations for bioplastics, reinforcing strategic interest in bio-based polymers, packaging innovation, and circular business models. However, environmental and macro-structural consequences remain contested: forward-looking modeling suggests that a future global bioplastics economy can generate nontrivial effects on greenhouse gas emissions, land use, and employment, implying that sectoral innovation choices can propagate into macroeconomic and labor-market outcomes. Earlier industry-oriented assessments also stressed that bioplastics development can yield significant economic opportunities under favorable industrial policy and investment conditions, but outcomes vary with supply-chain competitiveness and scale economies. [11-13]

Because bioeconomy development is simultaneously a technological transition and an economic restructuring, macroeconomic framing is increasingly used to quantify impacts on growth, employment, productivity, and sectoral composition. European evidence shows that bioeconomy sectors contribute to economic growth and employment in measurable ways, with cross-country variation driven by industrial structure, innovation capacity, and policy support. Complementary work using multiplier-based approaches demonstrates that bioeconomy activity can generate indirect and induced effects across the economy, making it relevant for strategic planning and public investment prioritization. At a more conceptual level, economic perspectives on the size and boundaries of the bioeconomy underscore measurement challenges, including sectoral classification, hybrid value chains, and the difficulty of separating bio-based value added from conventional industrial activity. These issues are not merely technical; they shape how governments and firms define targets, track progress, and justify resource allocation. [14-16]

A further step in the literature is the explicit integration of bioeconomy sectors into macroeconomic modeling frameworks, enabling scenario-based evaluation of how bioenergy and biochemicals influence national accounts, structural change, and competitiveness. Modeling work illustrates that incorporating advanced bioeconomy sectors into economy-wide frameworks can reveal both direct gains (new production, investment, and substitution effects) and indirect adjustments (price changes, input reallocation, and sectoral crowding-out), thereby offering a more policy-relevant understanding than isolated project analyses. This macro-level perspective is especially important when bioeconomy strategies are expected to contribute to energy security, climate commitments, and industrial upgrading simultaneously, because interactions among markets and policy instruments can produce nonlinear system responses. [17]

Energy-market conditions and transition dynamics also matter, because bio-based pathways compete and co-evolve with other renewables under constraints such as infrastructure lock-in, incumbent resistance, and path dependence. Conceptual work on lock-ins in renewable energy landscapes clarifies why technically viable transitions may stall without coordinated institutional change, which is directly relevant to scaling biofuels, biogas, and biomethane. Empirical energy outlook resources underline that biofuel production trajectories and sustainable development scenarios depend on policy alignment and supply potential, while biogas and biomethane prospects hinge on sustainable feedstock availability and cost structures. In management terms, these dynamics affect strategic collaboration, regulatory risk, and the sequencing of investments in feedstock procurement, conversion assets, and distribution systems. [18-20]

The integration of the bioeconomy into macroeconomics is also shaped by financial channels—credit conditions, monetary policy, and financial stress—which influence investment, innovation diffusion, and sectoral resilience. Recent macro-finance research shows that financial stress shocks can produce meaningful macroeconomic responses across major economies, while other studies highlight how macroeconomic shocks and monetary policy shifts can alter herding behavior in commodity and metals markets, potentially amplifying volatility in biomass-related or bio-based input markets. Evidence from emerging-market contexts similarly indicates that macroeconomic variables are associated with capital market performance, and that macroeconomic factors can affect corporate lending dynamics, shaping firms’ ability to finance long-horizon transitions. Broader frameworks for strategic allocation of private credit across global markets reinforce the importance of macro-financial modeling for guiding investment flows—an issue that becomes salient as bioeconomy strategies increasingly depend on large-scale private and public finance. [21-25]

At the organizational and behavioral level, the diffusion of bioeconomy innovations depends not only on technological performance and policy incentives, but also on adoption motivations, managerial cognition, and governance capacity. Behavioral research on adoption drivers highlights that motivations and perceived benefits can accelerate or delay diffusion, implying that management strategies—communication, stakeholder alignment, and risk framing—are integral to scaling bio-based solutions. In addition, governance-centered perspectives on bio-technological economy evaluation methods emphasize the role of economic governance in guiding technology choices and ensuring accountability in performance measurement. This is particularly pertinent for countries navigating simultaneous challenges of resource constraints, industrial modernization, and climate adaptation, where macroeconomic planning and bioeconomy policy must be institutionally coordinated. [26, 27]

National context further differentiates bioeconomy–macroeconomy integration pathways, especially in economies with distinct biocapacity profiles and climate constraints. Evidence focused on Iran highlights how economic, social, demographic, and climatic factors relate to biocapacity outcomes, underlining that sustainability-relevant resource endowments are shaped by multi-dimensional drivers that must be considered in policy design. Alongside macro and environmental considerations, the educational dimension is also emphasized: attention to bioeconomy education in schools is positioned as a capacity-building requirement for long-term transformation, connecting human capital development to innovation readiness and societal acceptance. Taken together, these strands suggest that bioeconomy integration is not a purely technical transition but a managed transformation that spans resource systems, markets, institutions, finance, and capabilities. [28, 29]

Despite rapid growth in publications across biofuels, circular bioeconomy, bioplastics, biorefineries, environmental economics, and macroeconomic modeling, the literature remains fragmented across disciplinary silos, with limited synthesis on how the modern bioeconomy is being conceptually and empirically integrated into macroeconomic research agendas. Scientometric analysis provides a systematic way to map this fragmented landscape by identifying thematic clusters, intellectual structures, and evolving research fronts, thereby supporting more coherent managerial and policy interpretation of the field's development trajectory. Accordingly, the aim of this study is to conduct a scientometric analysis of the integration of the modern bioeconomy into macroeconomics by mapping the intellectual structure, thematic clusters, and emerging trends in the literature indexed in Scopus between 2000 and 2025.

2. Methodology

The present study applies a scientometric approach to analyze the integration of the modern bioeconomy into macroeconomics. The research was conducted with an applied objective using a descriptive design, employing scientometric analysis as the principal methodological framework. The statistical population consisted of studies related to the bioeconomy and macroeconomics indexed in the Scopus database within the time span of 2000–2025. A systematic and purposive search strategy was adopted to identify relevant publications.

The first stage involved the identification and selection of research keywords aligned with the study objectives. The selected keywords included bioeconomy, sustainable development, macroeconomics, economic policies, biological innovations, natural resources, climate change, sustainable management, and emerging technologies.

In the second stage, Boolean operators were employed to combine related keywords. The OR operator was used to retrieve studies addressing any of the selected themes. The search expression included: "Bioeconomy" OR "Sustainable Development" OR "Macroeconomics" OR "Economic Policies" OR "Biological Innovations" OR "Natural Resources" OR "Climate Change" OR "Sustainable Management" OR "New Technologies."

The third stage applied the AND operator to restrict the search to studies simultaneously addressing multiple thematic dimensions. Examples of combined queries included: ("Bioeconomy" AND "Macroeconomics") OR ("Sustainable Development" AND "Economic Policies") OR ("Biological Innovations" AND "Natural Resources").

In the fourth stage, all search terms and combinations were executed within the Scopus database covering the period 2000–2025. The retrieved articles were carefully screened to ensure thematic relevance to the research objectives. Ultimately, 801 articles were selected as the final statistical corpus. At this stage, only original research articles were included in the analysis, while review papers and editorials were excluded due to their limited contribution to empirical investigation. This decision ensured analytical focus on primary empirical research capable of revealing scientific trends and innovation trajectories in the bioeconomy and its macroeconomic integration.

In the fifth stage, data analysis was conducted using VOSviewer software to construct thematic networks and identify relationships among research topics and scientific trends. During the data import process, the collected records were repeatedly verified by the research team to ensure accuracy and minimize identification errors. This verification involved re-examination of article titles, abstracts, and full texts to confirm correct positioning within the thematic network and to ensure accurate representation of the research landscape.

Only studies containing sufficient information to address the research questions were included. Both quantitative and qualitative articles were analyzed. This methodological framework enabled a comprehensive examination of trends and challenges associated with integrating the bioeconomy into macroeconomic systems and provides a scientific basis for developing effective and sustainable policy strategies in this domain.

3. Findings and Results

Table 1 presents the most frequently occurring keywords in the bioeconomy research domain and their relationships with key economic and environmental concepts. The term *bioeconomy*, with 443 occurrences and a total link strength of 5707, emerges as the central and dominant concept, indicating the growing prominence of the bioeconomy within scientific literature and sustainability-oriented economic research. The keyword *economy*, with 399 occurrences and a link strength of 5832, represents a foundational analytical concept, reflecting the strong interconnection between bioeconomy studies and macroeconomic perspectives.

Concepts associated with *sustainable development* (280 occurrences; link strength = 4624) and *sustainability* (191 occurrences; link strength = 2866) appear as primary objectives in integrating bioeconomic principles into socio-economic and policy frameworks. These terms emphasize the necessity of balancing economic growth with environmental protection.

Furthermore, *environmental economics* (175 occurrences; link strength = 3015) highlights interactions between economic activities and environmental systems, demonstrating the increasing importance of ecological considerations within economic processes. The concept of the *circular economy* (171 occurrences; link strength = 2712) represents an emerging resource management paradigm aimed at waste reduction and sustainable production, particularly relevant to bioeconomy development.

Additional key terms include *biotechnology* (157 occurrences; link strength = 2797) and *bioenergy* (106 occurrences; link strength = 2031), both identified as essential technological drivers supporting bioeconomic expansion and improvements in agricultural and industrial production systems.

Finally, the keywords *agriculture* (104 occurrences; link strength = 2113) and *climate change* (104 occurrences; link strength = 1846) underline the importance of sustainable agricultural practices and the economic implications of climate change on natural resources. Overall, the analysis demonstrates strong conceptual interconnections within the bioeconomy domain and highlights the need for integrated policy and planning approaches to achieve sustainable development outcomes.

Table 1. Most Frequent Keywords in Bioeconomy Research

Keyword	Frequency	Total Link Strength
Bioeconomy	443	5707
Economy	399	5832
Sustainable Development	280	4624
Biomass	232	4332
Sustainability	191	2866
Environmental Economics	175	3015
Circular Economy	171	2712
Biotechnology	157	2797
Bioenergy	106	2031
Agriculture	104	2113
Climate Change	104	1846
Economic Aspect	98	2405
Nonhuman	95	2615
Biophilia	95	2293
Biophiles	94	2100
Refining	89	1726
Waste Management	77	1517
Life Cycle	70	1189

Figure 1 presents the thematic network analysis of the study. In examining the integration of the bioeconomy into macroeconomics, four main clusters were identified, each addressing distinct dimensions of the field and revealing deep interconnections among concepts.

Bioeconomy Cluster (Bioeconomy)

This cluster addresses concepts related to the production and utilization of biological resources to generate sustainable energy and products. *Biofuel* refers to renewable fuels produced from biological materials and plays a major role in reducing dependence on fossil fuels. *Recycling* involves the recovery and reuse of materials and products, contributing to waste reduction and resource conservation. In this context, *waste management* is considered a fundamental requirement of modern societies, focusing on the safe handling and disposal of waste and residues. In addition, *wastewater treatment* refers to the purification process that enables the reuse of wastewater or its safe discharge. Within this cluster, *biodiesel* and *biogas* are also highlighted as renewable fuels derived from biological resources, with particular importance for reducing greenhouse gas emissions and supporting sustainable energy supply.

Environmental Economics Cluster (Environmental Economics)

This cluster examines the interactions between economic activity and the environment. *Greenhouse gas emissions* represent a central challenge driving climate change and signal the need for effective mitigation strategies. In this regard, *renewable energy* is presented as a key solution for sustainable energy provision and reduced reliance on fossil resources. The *green economy* is also introduced as an emerging development approach that emphasizes environmental protection and the sustainable use of natural resources. This cluster underscores the importance of embedding environmental considerations within economic processes and the need for innovative pathways toward sustainable development.

Technology Cluster (Technology)

Technology plays a vital role in advancing bioeconomy objectives. *Biotechnology*, defined as the application of biological processes to produce goods and services, creates opportunities for innovative solutions across multiple sectors. *Genetic engineering* refers to the genetic modification of living organisms to achieve desired traits and can improve agricultural productivity while reducing resource use. *Bioprocesses* include organism-based techniques such as fermentation and biodegradation that support sustainable production and waste reduction. Overall, this cluster highlights the centrality of scientific and technological innovation in realizing bioeconomy goals.

Policy and Management Cluster (Policy and Management)

This cluster focuses on policy and managerial dimensions of the bioeconomy. *Policy making* refers to the formulation and implementation of laws and regulations at different levels and can facilitate the incorporation of bioeconomy principles into macroeconomic policy agendas. *Governance* denotes decision-making and control systems within organizations and institutions and underscores the importance of transparency and accountability in managerial processes. *Economic analysis* involves examining the economic dimensions of a given issue and can support a clearer understanding of the macroeconomic implications of integrating the bioeconomy into development policies and programs.

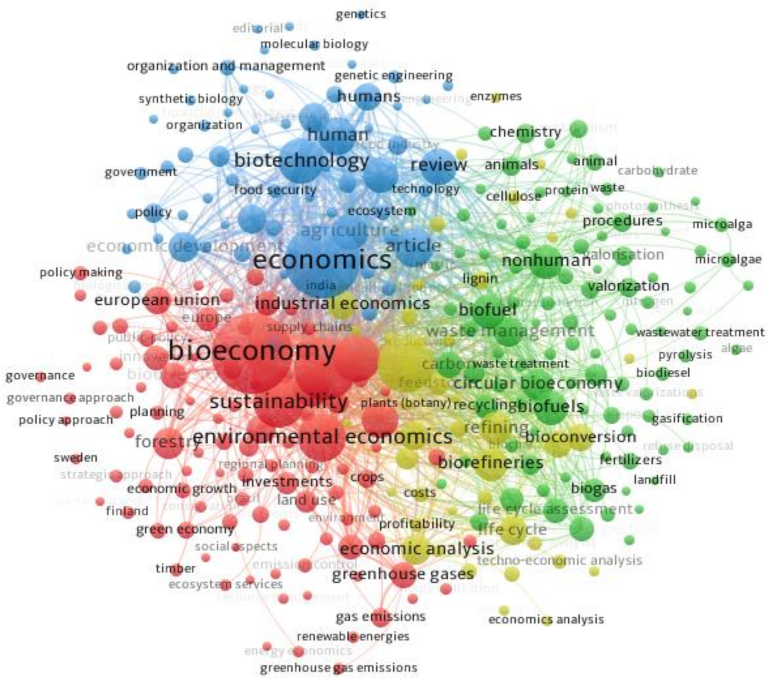

Figure 1. Research Keyword Network

Figure 2 illustrates the overlay visualization of keywords related to the integration of the modern bioeconomy into macroeconomics in recent years. The results indicate substantial shifts in bioeconomy-related concepts in recent years, clearly reflected through variations in node color and size in the maps. Dark green colors represent more recent and more prominent concepts, including *circular bioeconomy*, which emphasizes recycling and the reuse of resources. *Sustainability*, as a core principle integrating environmental, economic, and social dimensions of development, and *biorefinery*, referring to facilities that produce diverse products from biomass, also fall within this category. Other major concepts highlighted in this color range include *biofuels*—such as biodiesel and biogas—which are recognized as renewable energy sources. In contrast, pale yellow colors indicate relatively newer concepts that have not yet achieved strong centrality, such as *techno-economic analysis*, used to evaluate bioeconomy projects, and *life cycle assessment*, which examines the environmental impacts of products and processes. Light blue colors represent older concepts that have received less attention in recent years, such as *industrial economics* and *policy making*. The observed changes in node size and color suggest that sustainability-related themes, life-cycle approaches, and techno-economic evaluation have attracted increasing attention, indicating a scientific and practical shift toward sustainability-oriented development.

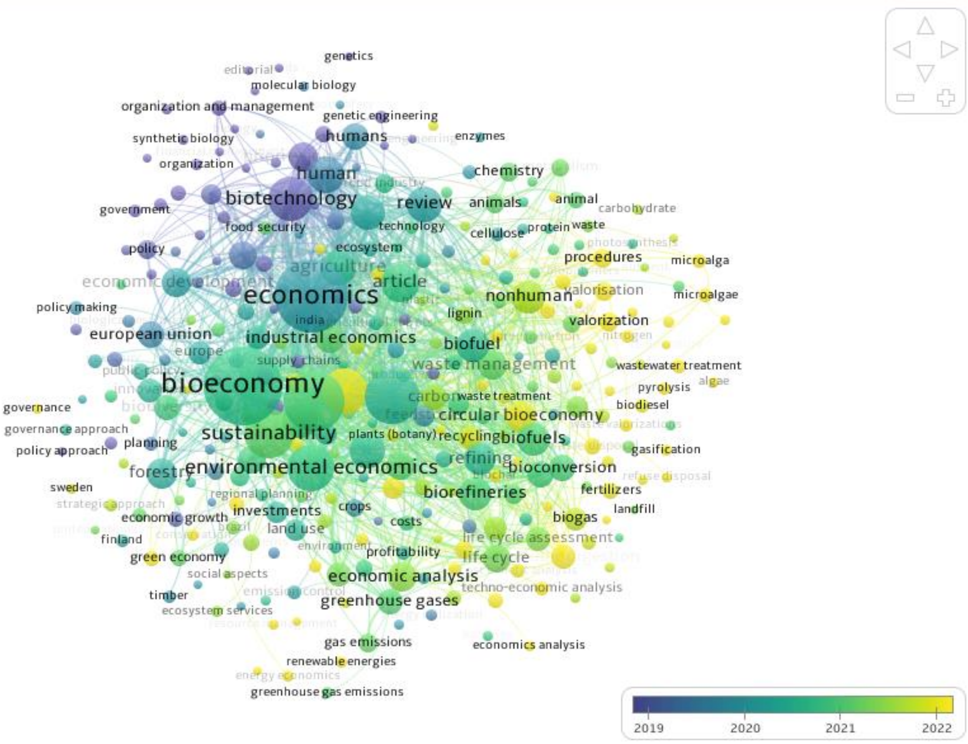

Figure 2. Overlay Visualization of the Integration of the Modern Bioeconomy into Macroeconomics in Recent Years

Figure 3 shows the leading countries in scientific output on the modern bioeconomy within macroeconomic research. Based on node size and color intensity, three countries stand out with the highest output or prominence: Germany, the United States, and Spain, which appear as key centers of scholarly production—particularly in bioeconomy research, systemic modeling, and macro-level analysis. In addition, countries with relatively high output—such as Sweden, France, the Netherlands, Italy, and Canada—show notable presence, displayed with moderate to high brightness, indicating activity not only in theoretical research but also in economic–policy applications. The map also suggests broader coverage across North America, Western Europe, and parts of the Asia–Pacific region. The United States, depicted as the central node with the highest brightness, likely exhibits the strongest research collaborations or support resources for bioeconomy studies. Germany, with similarly bright representation, appears as a major European engine for bioeconomy research and is likely supported by strong collaboration networks with neighboring countries and large research institutions. Spain's comparatively bright color among European countries indicates a substantial research presence in the bioeconomy domain, potentially strengthened through partnerships with major universities and research centers. Regions with lower scientific output—such as Sub-Saharan Africa and parts of the Middle East—appear as faint areas on the map, indicating lower capacity or reduced emphasis on the modern bioeconomy in macroeconomic contexts. Such distributional differences may be explained by multiple factors, including access to expert researchers, research funding, data infrastructure, and research culture. Accordingly, strengthening the global scientific position of the bioeconomy requires effective support policies, international research collaboration networks, and investment in training and research infrastructure in underrepresented countries.

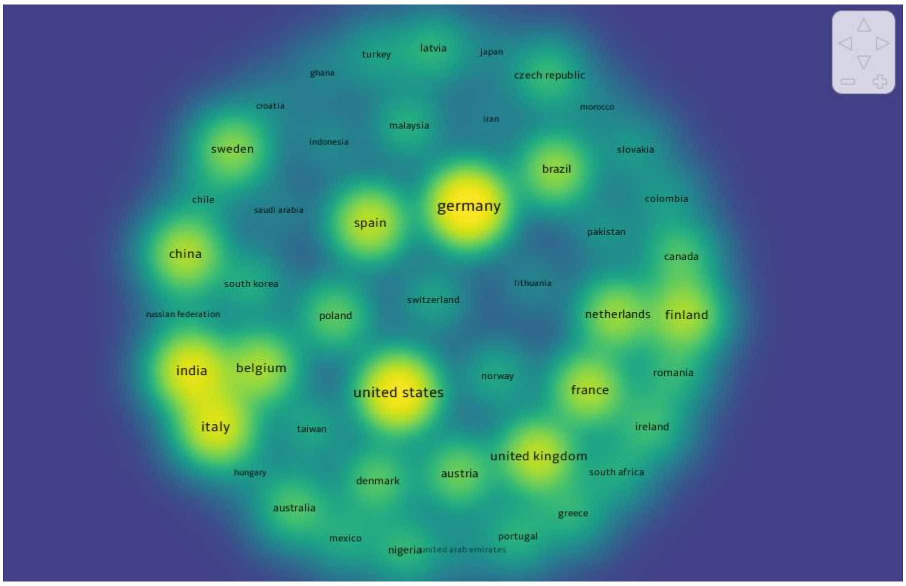

Figure 3. Leading Countries in Scientific Output on the Modern Bioeconomy in Macroeconomics

Table 2 examines reputable sources publishing scientific output on the modern bioeconomy in macroeconomics. The table presents information on 20 key outlets that are actively engaged in bioeconomy- and environment-related subfields. Overall, the *Journal of Cleaner Production*, with 30 documents and 500 citations, is identified as one of the most reputable sources in this area, indicating the substantial influence of research published in this journal. *Bioresource Technology* and *Ecological Economics*, with 25 and 20 documents and 400 and 300 citations, respectively, are also recognized as major sources in the field.

The total link strength of these sources reflects their scientific connectivity and mutual influence across bioeconomy-related debates. For example, the *Journal of Environmental Management* and *Waste Management*, with 290 and 310 citations, respectively, highlight the importance of environmental and waste management themes in contemporary economic research.

In addition, outlets such as *Sustainability (Switzerland)* and *Renewable and Sustainable Energy*, with a focus on sustainable development and renewable energy, clearly reflect emerging trajectories in the bioeconomy literature. Overall, Table 2 illustrates the diversity and richness of scientific production in the modern bioeconomy domain and can support researchers and policymakers in developing a clearer understanding of prevailing trends, challenges, and opportunities.

Table 2. Reputable Publication Sources for Scientific Output on the Modern Bioeconomy in Macroeconomics

Source	Documents	Citations	Total Link Strength
Bioresource Technology	25	400	50
New Biotechnology	18	320	45
Journal of Cleaner Production	30	500	60
Sustainability (Switzerland)	22	350	40
Science of the Total Environment	15	280	35
Ecological Economics	20	300	42
Renewable and Sustainable Energy	10	150	30
Trends in Biotechnology	12	200	32
Resources, Conservation and Recycling	14	220	38
Fuel	9	120	28
Forest Policy and Economics	8	110	25
Journal of Environmental Management	17	290	36

Biomass and Bioenergy	11	180	29
Waste Management	19	310	41
Biofuels, Bioproducts and Biorefining	13	230	34
Scandinavian Journal of Forest Research	7	100	22
Forests	6	90	20
Sustainable Production and Consumption	5	80	18
Current Opinion in Environmental Science	4	70	15
ACS Sustainable Chemistry and Engineering	3	60	12

Figure 2 depicts reputable publication sources for scientific output in the modern bioeconomy within macroeconomic research. According to the information presented, Table 2 contains 20 key sources active across bioeconomy- and environment-related subfields. Overall, *Journal of Cleaner Production*, with 30 documents and 500 citations, is recognized as one of the most reputable sources, reflecting its prominent role in disseminating high-impact research. Similarly, sources such as *Bioresource Technology* (25 documents; 400 citations) and *Ecological Economics* (20 documents; 300 citations) are highlighted as other major outlets, covering a broad range of bioeconomy and sustainability topics. The total link strength of these sources reflects a network of co-occurrence and scientific interaction across related fields; for example, *Journal of Environmental Management* (290 citations) and *Waste Management* (310 citations) demonstrate the significance of environmental and waste governance issues in macroeconomic research, indicating sustained scholarly focus on practical and policy-relevant environmental challenges. Moreover, sources such as *Sustainability (Switzerland)* and *Renewable and Sustainable Energy*, emphasizing sustainable development and renewable energy, portray emerging economic–bioeconomic trajectories and indicate that bioeconomy research is expanding toward energy and sustainability domains. Overall, the table highlights the diversity and richness of the literature and can assist researchers and policymakers in gaining deeper insight into trends, challenges, and opportunities for international collaboration in this area.

Figure 4. Visualization of Reputable Sources Publishing Scientific Output on the Modern Bioeconomy in Macroeconomics

4. Discussion and Conclusion

The findings of the present scientometric analysis demonstrate that the modern bioeconomy has evolved into a multidimensional research domain positioned at the intersection of environmental sustainability, technological innovation, and macroeconomic transformation. The dominance of keywords such as bioeconomy, sustainability, environmental economics, and circular economy confirms that contemporary scholarship increasingly conceptualizes bioeconomic development as a systemic response to global ecological and economic pressures rather than as an isolated industrial trend. Previous conceptualizations emphasized that the bioeconomy represents a structural shift toward renewable biological resources and knowledge-based production systems, redefining economic growth beyond fossil-resource dependency [1, 3]. The centrality of sustainability-related terms identified in the network analysis aligns with arguments that bioeconomy strategies are inherently linked to sustainable development pathways and environmental governance objectives [2, 5].

The strong association between bioeconomy research and environmental concepts observed in the thematic clusters reflects the increasing integration of ecological considerations into economic decision-making. Environmental economics emerged as a key node in the network, suggesting that researchers view economic productivity and ecological resilience as interdependent systems. Earlier scholarship emphasized that bioeconomy policies must simultaneously address climate mitigation, biodiversity protection, and resource efficiency to avoid unintended environmental externalities [4]. The prominence of climate-related and renewable-energy keywords further reinforces global evidence showing that bioenergy and biogas development are increasingly embedded within national decarbonization strategies and sustainable energy transitions [19, 20]. This convergence highlights that macroeconomic stability and environmental sustainability are no longer treated as competing objectives but as mutually reinforcing policy goals.

Another important result concerns the technological cluster, where biotechnology, genetic engineering, and bio-based processes appeared as core drivers of research expansion. This finding supports earlier analyses demonstrating that innovation capacity constitutes the primary engine of bioeconomy growth, enabling resource valorization, waste conversion, and industrial diversification [8, 9]. Global biomass utilization studies similarly indicate that technological advances in conversion efficiency and feedstock management determine whether bioeconomy systems generate genuine sustainability gains or merely shift environmental burdens across sectors [6]. The observed emphasis on technological innovation also corresponds with behavioral adoption research showing that diffusion of bioeconomy solutions depends on organizational willingness to adopt emerging technologies and managerial perceptions of economic viability [26].

The scientometric mapping revealed growing attention to circular bioeconomy concepts, including recycling, waste management, and life-cycle approaches. This trend reflects a shift away from linear production models toward circular resource systems designed to reduce waste and maximize material productivity. Earlier literature on food–feed–fuel competition warned that expanding biomass demand without circular strategies could intensify resource conflicts and undermine sustainability objectives [7]. The increasing prominence of circular economy terminology therefore suggests a maturation of the field toward integrated resource governance models. Economic governance perspectives further highlight that evaluation methods and institutional frameworks play decisive roles in ensuring that circular bioeconomy transitions translate into measurable economic outcomes [27].

The overlay visualization findings demonstrate temporal evolution within bioeconomy scholarship, showing that recent research increasingly emphasizes sustainability assessment, techno-economic analysis, and biorefinery systems. These results are consistent with studies indicating that the bioeconomy has entered a consolidation phase in which analytical rigor and economic feasibility evaluation have become central research priorities. For instance, techno-economic modeling has been identified as essential for assessing the scalability of bio-based industries and guiding investment decisions [17]. Similarly, emerging work on renewable energy transitions emphasizes that technological adoption is often constrained by path dependence and institutional lock-ins, explaining why some bioeconomy innovations diffuse slowly despite technical feasibility [18].

The geographic distribution of scientific production revealed strong leadership by Europe and North America, particularly Germany, the United States, and Spain. This pattern aligns with empirical evidence showing that bioeconomy sectors contribute significantly to employment generation and economic growth in European economies supported by coordinated policy frameworks and innovation ecosystems [14]. Studies examining multiplier effects in Spain likewise demonstrate how bioeconomy activities stimulate indirect economic benefits across industries [15]. Conversely, the lower representation of developing regions observed in the visualization corresponds with global disparities in research infrastructure, financing capacity, and technological readiness, which remain key barriers to bioeconomy adoption.

The analysis of leading journals further confirmed the interdisciplinary nature of the field, as influential outlets span environmental science, biotechnology, sustainability management, and economic policy. The prominence of journals focused on cleaner production and environmental management reflects the growing recognition that industrial sustainability and bioeconomic transformation must be addressed jointly. Market-oriented evidence from the bioplastics sector illustrates how bio-based innovation simultaneously reshapes industrial markets and environmental performance indicators [11, 12]. Earlier industry assessments similarly highlighted the economic potential of bio-based manufacturing in creating new value chains and employment opportunities under supportive policy conditions [13].

From a macroeconomic perspective, the results suggest that bioeconomy development is increasingly analyzed through economy-wide frameworks rather than sector-specific lenses. Contemporary macroeconomic studies emphasize how structural changes, financial shocks, and monetary policy conditions influence investment patterns and technological adoption across industries. Evidence indicates that macroeconomic shocks can significantly affect sectoral dynamics and financial behavior, including commodity markets relevant to biomass and renewable inputs [21, 22]. Additional research shows that macroeconomic variables shape capital market performance and credit allocation, factors that directly influence firms' capacity to invest in long-term bio-based innovation projects [23, 24]. Strategic macroeconomic modeling frameworks therefore play an essential role in guiding sustainable investment allocation and evaluating global transition pathways [25].

The results also highlight the importance of institutional readiness and human capital development. Educational and societal preparedness has been identified as a critical prerequisite for successful bioeconomy transformation, as workforce skills, public awareness, and innovation culture influence adoption rates and policy implementation effectiveness [29]. At the national level, empirical evidence linking biocapacity outcomes to economic, social, demographic, and climatic variables demonstrates that bioeconomy integration must be tailored to regional resource conditions rather than applied as a universal policy template [28]. Together, these findings suggest that successful bioeconomy integration depends on alignment between technological capability, macroeconomic governance, environmental constraints, and social readiness.

Overall, the discussion indicates that the modern bioeconomy should be interpreted as a systemic macroeconomic transformation rather than a narrow environmental initiative. The convergence of sustainability objectives, technological innovation, and macroeconomic restructuring observed in this study confirms that bioeconomy research is transitioning toward integrative frameworks capable of addressing global challenges such as climate change, resource scarcity, and economic resilience. The scientometric patterns identified here therefore reflect a broader paradigm shift in economic thinking toward regenerative, circular, and knowledge-driven development models.

One limitation of the present study relates to the exclusive reliance on the Scopus database, which may have excluded relevant publications indexed in other databases or regional repositories. The scientometric approach, while powerful for mapping research structures, emphasizes publication metadata rather than deeper qualitative interpretations of theoretical debates or policy effectiveness. Additionally, keyword-based analysis depends on authors' terminology choices, which may vary across disciplines and countries, potentially affecting clustering outcomes. Another limitation concerns the dynamic nature of the bioeconomy field; rapidly emerging research areas may not yet be fully reflected in citation patterns, leading to underrepresentation of newly developing themes.

Future studies could expand database coverage by integrating Web of Science, Dimensions, or regional indexing platforms to provide a more comprehensive global perspective. Longitudinal scientometric analyses comparing different decades may reveal how policy shocks, technological breakthroughs, or global crises influence research evolution. Combining scientometric mapping with qualitative content analysis or systematic literature review methods would also enrich theoretical interpretation. Further research may examine collaboration networks among institutions, funding structures, or interdisciplinary integration patterns to better understand knowledge diffusion processes. Comparative regional studies focusing on developing economies could also provide valuable insights into barriers and opportunities for bioeconomy adoption under diverse institutional conditions.

Policymakers should develop integrated bioeconomy strategies linking industrial policy, environmental regulation, and macroeconomic planning to ensure coherent transition pathways. Governments and organizations are encouraged to invest in research infrastructure, education programs, and innovation ecosystems that strengthen technological readiness and workforce capacity. Industry actors should adopt circular production models, life-cycle assessment tools, and collaborative innovation networks to enhance competitiveness while meeting sustainability objectives. Financial institutions may support bio-based innovation through green financing mechanisms and long-term investment frameworks aligned with sustainable development priorities. Finally, international cooperation initiatives should be strengthened to reduce global disparities in bioeconomy development and promote shared learning across regions.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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