Journal of Infrastructure, Policy and Development 2024, 8(12), 9051.
https://doi.org/10.24294/jipd.v8i12.9051

Article

Seeds of change: A bibliometric study on sustainable technologies and business strategies in agriculture

Rocco Pavesi, Luigi Orsi*, Luca Zanderighi

Department of Environmental Science and Policy, Università degli Studi di Milano, 20123 Milano, Italy
*** Corresponding author:** Luigi Orsi, luigi.orsi@unimi.it

CITATION

Pavesi R., Orsi L., Zanderighi L. (2024). Seeds of change: A bibliometric study on sustainable technologies and business strategies in agriculture. Journal of Infrastructure, Policy and Development. 8(12): 9051.
https://doi.org/10.24294/jipd.v8i12.9051

ARTICLE INFO

Received: 9 September 2024
Accepted: 25 October 2024
Available online: 5 November 2024

Abstract: The transition to sustainable agricultural practices is critical in the face of escalating climate challenges. Despite significant advances, the integration of green technologies within agribusiness remains underexplored. This study undertakes a comprehensive bibliometric analysis, utilizing data from the Web of Science Core Collection (1990–2023), to elucidate the integration of green technologies within agribusiness strategies. The research highlights key trends, influential authors, prominent journals, and significant thematic clusters, including biogas, biochar, biotech remediation, sustainable agriculture transition, low-carbon agriculture, and green strategies. By employing R, Bibliometrix, and VOSviewer, the study provides a nuanced understanding of the research landscape, emphasizing the critical role of strategic planning, policy frameworks, technological innovation, and interdisciplinary approaches in promoting sustainable agricultural development. The findings underscore the growing scholarly interest in sustainable practices, driven by global initiatives such as the UN's 2030 Agenda and the Paris Agreement. This study contributes to the literature by offering qualitative insights and policy implications, highlighting the necessity for a holistic integration of green technologies to enhance the environmental and economic viability of agribusinesses.

Keywords: green technologies; sustainable agriculture; agribusiness strategies; bibliometric analysis

1. Introduction

Transitioning to sustainable business practices in agriculture is crucial due to the increasing challenges posed by climate change. The agricultural sector's vulnerability underscores the need for integrating green technologies to ensure both environmental sustainability and economic viability (Sun, 2022). Historically, a gap between agricultural management and environmental engineering has resulted in fragmented insights, missing the synergy between agribusiness innovation and ecological sustainability: bridging these domains is essential for integrating technological sustainability into agricultural business models (Zhong et al., 2022). Integrating advanced digital technologies and reducing carbon emissions is critical for addressing climate change and promoting sustainable practices (Li, 2023). Green education fosters sustainable agricultural development amid ecological challenges (Fan, 2024). Effective resource allocation for green agricultural innovation is vital for progress, as well as rural industrial integration, digital financial inclusion, and foreign direct investment are positive drivers of sustainable agricultural development by promoting green technologies and enhancing productivity (De Noni et al., 2013; Dong et al., 2023; Mazzocchi et al., 2020).

Recent bibliometric studies have explored various facets of sustainability. For instance, Safruddin (2024) examined the economic sustainability of green agricultural practices, while Tamala et al. (2022) mapped scientific research on sustainable oil and gas production. Nirmal et al. (2023) explored advanced technologies like blockchain and IoT within sustainable supply chains, Chen et al. (2023) integrated BIM and IoT for sustainable building frameworks, and Laranja Ribeiro et al. (2021) investigated the evolution of Green Information Technology (GIT). Although recent literature has individually addressed greener processes, agricultural technology innovation, and sustainable business management, comprehensive studies that integrate these areas are still lacking.

This study sets itself apart by undertaking a comprehensive bibliometric analysis aimed at elucidating the integration of green technology within agribusiness, a topic currently underexplored in academic literature. This paper goes beyond numerical analyses to incorporate qualitative insights, policy considerations, and management implications, providing a holistic view of how green technologies can revolutionize agribusiness. In the following sections, we delineate our methodology for data analysis. This is followed by a comprehensive presentation of our primary discoveries, including a detailed overview of the scrutinized articles, their references, and graphical representations of bibliographic coupling, and co-occurrence assessments. Subsequent discussions explore the core outcomes. The concluding section elucidates our findings, underscores the study's constraints, and explores potential trajectories for future research in sustainable green technologies within agribusiness strategy.

2. Methodology

2.1. Search strategy

For a reliable bibliographic analysis, selecting the right database is crucial. Web of Science (WoS) is widely considered the "gold standard" for evaluating academic performance and ranking universities (Harzing and Alakangas, 2016). Compared to Scopus and Google Scholar (GS), WoS offers more precise uniformity in references and superior citation analysis visuals (Aria and Cuccurullo, 2017; Falagas et al., 2008). WoS also maintains rigorous journal selection, ensuring higher-quality publications (Leydesdorff et al., 2013). In contrast, GS, despite its broader coverage, includes low-quality publications and grey literature, potentially skewing bibliometric analyses (Delgado-López-Cózar et al., 2014). Therefore, WoS was chosen for its comprehensive, accurate, and quality-controlled bibliometric analysis. Articles were retrieved from the WoS "Core Collection" for the period 1990 to 2023. This time frame captures the critical period of the 1990s when businesses began integrating sustainability into their strategies, marking the evolution of green technologies and green growth (Hart, 1997; Laranja Ribeiro et al., 2021; Tamala et al., 2022). This allows the research to examine the convergence of green technologies and business practices over time, offering insights into this transformative field.

The search utilized keywords encompassing various aspects of green, clean, sustainable, and energy-efficient technologies in conjunction with terms related to agriculture, such as "agriculture", "agribusiness", "sustainable farming", "green tech", "clean tech", and "renewable tech" among the many. Studies highlight the significance of new plant breeding technologies, high-tech agriculture, and precision farming in promoting sustainable agricultural development and enhancing food security, justifying the inclusion of these agricultural terms and technologies (Nguyen et al., 2023; Qaim, 2020; Xu et al., 2020). Additionally, business-related terms such as "strategy", "business model", "entrepreneur model", "business strategy", "innovative strategy", and "business plan" were included. The inclusion of these terms is supported by research emphasizing that integrating green technologies into business strategies is fundamentally a strategic innovation challenge, essential for achieving long-term sustainability goals (Ikram et al., 2021; Ma et al., 2024; Mignol and Bankel, 2022). **Figure 1** provides a graphical representation and summary of the methodology and criteria used in the preparation of the study The search was restricted to the Web of Science (WoS) categories of "Economics", "Management", "Business", and "Environmental Sciences," and limited to English-language articles published between 1990 and 2023. This approach ensured a targeted exploration of literature directly relevant to the scope of the study. The final sample included 240 papers authored by 1088 scholars, and published across 113 academic journals.

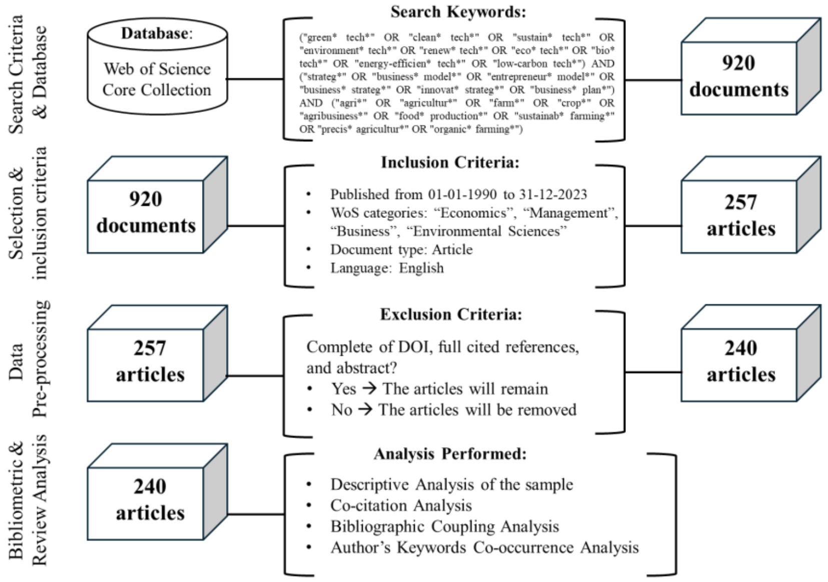

Figure 1. Methodological flowchart.

2.2. Data analysis

For our bibliometric study, the use of R and RStudio was crucial. R provided essential techniques and graphical methods for data analysis and visualization. RStudio, as an integrated development environment (IDE), enhanced the user experience with features like syntax highlighting and debugging tools, improving workflow efficiency (Aria and Cuccurullo, 2017). The Bibliometrix R package, designed for comprehensive science mapping analysis, was employed within RStudio to quantitatively analyze bibliometric data. This integration facilitated efficient execution, in-depth analysis, and visualization of the data. A notable enhancement was the use of Biblioshiny, a user-friendly web interface for Bibliometrix. Biblioshiny significantly streamlined data cleaning, allowing efficient exclusion of documents that did not meet quality criteria, resulting in a final dataset of 240 papers (Aria and Cuccurullo, 2017). Beyond data cleaning, Biblioshiny provided insights into publication trends, prolific authors, institutions, and countries, setting a solid foundation for detailed bibliometric analysis. VOSviewer played a crucial role in constructing and visualizing bibliometric maps. This software specializes in visualizing bibliometric networks and clustering papers based on bibliographic coupling, co-citation counts, and keyword co-occurrence. These methods offered a deeper understanding of the thematic structures within the dataset.

2.3. Method of analysis

Bibliometric tools offer a quantitative analysis of academic literature, mapping discipline-specific trends and relationships (Appio et al., 2014). For this study, we focused on bibliographic coupling and keyword co-occurrence analysis due to the emerging nature of the field. Bibliographic coupling, which connects documents that cite the same references, is particularly useful for studying young or emerging fields as it provides a forward-looking perspective (Boyack and Klavans, 2010). Co-occurrence analysis of keywords helps understand the thematic structure and identify interconnected concepts or trends within the research field (Sedighi, 2016; Van Eck and Waltman, 2010). These methods were chosen to provide a comprehensive view of the research landscape, capturing the development and interconnections of themes in this evolving area of study.

3. Results

3.1. Descriptive analysis of the sample

The provided data indicates a growing trend in the number of publications over the years on the integration of green technologies within business strategies in the agricultural sector. **Figure 2** elucidates a steady increase in interest. In recent years, in fact, the growing focus on sustainable agricultural practices has been driven by a combination of environmental, economic, and policy-related factors. The steep increase in scholarly interest, particularly post-2015, can be attributed to several global developments. The 2030 Agenda leveraged the integration of sustainable practices within agricultural business models, emphasizing food security and environmental stewardship (Walsh et al., 2020). Additionally, the Paris Agreement reinforced the urgency of decarbonization and climate action, prompting agricultural businesses to innovate with green technologies (Jakučionytė-Skodienė and Liobikienė, 2022). The COVID-19 pandemic further triggered a re-evaluation of global food systems, resilience, and sustainability, highlighting the need for robust and sustainable agricultural practices (McNeely, 2021). At the same time, advances in digital and biotechnological innovations have made green technologies more accessible and affordable, encouraging broader adoption in the agribusiness sector (Qaim, 2020). Economic incentives such as subsidies, carbon credits, and international grants have also supported this shift, reducing financial barriers to the implementation of new technologies (Mignon and Bankel, 2022). Furthermore, the increasing frequency of extreme weather events has underscored the vulnerability of agriculture to climate change, driving a scholarly focus on sustainable innovations. Together, these factors have elevated the discourse on environmental and social responsibility within the agricultural sector, necessitating a profound focus on how green technologies can be nested into business strategies.

This reflects a paradigm shift toward prioritizing sustainability in the face of rapid environmental changes and societal expectations. Given this trend, it is likely that the intersection of sustainability and business strategy in agriculture will continue to receive increasing attention, driving further research and publications in the years to come.

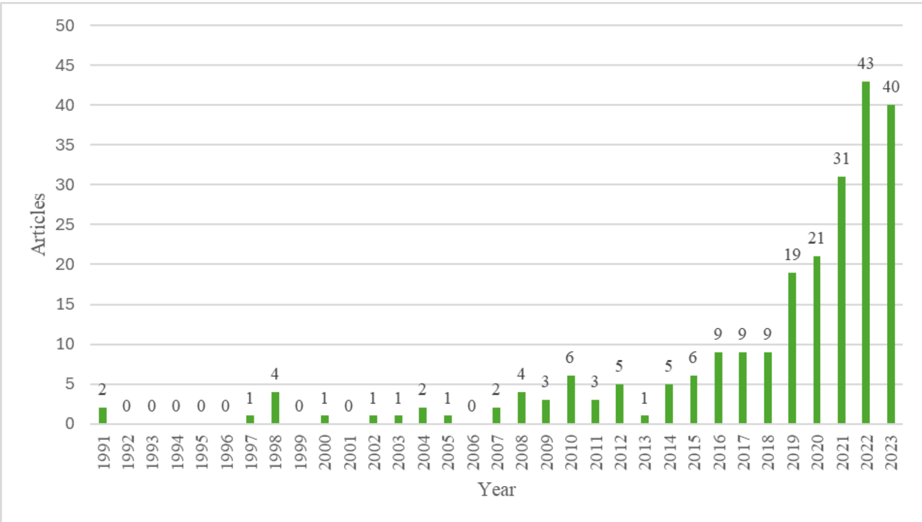

Figure 2. Annual scientific production.

Table 1 displays the top 10 journals for the papers considered in this analysis, revealing a dynamic landscape of academic publications focused on integrating green technologies into business strategies within the primary sector. This collection of journals highlights the interdisciplinary nature of sustainability research, characterized by a high-impact scholarly contribution across various fields. Despite the apparent Western centrism based on the publishers' countries of origin, each journal maintains a strong international profile, underscoring its global relevance and influence. The diverse focus areas of these journals mirror the complex and multifaceted nature of sustainability research, emphasizing the need for a comprehensive approach that combines environmental, technological, social, and economic perspectives. An examination of the journals' aims and scopes reveals three main clusters:

1) Sustainable innovation: Journals like "Journal of Cleaner Production," "Sustainability," and "Environmental Development and Sustainability" concentrate on technical solutions and innovations for cleaner production and broader sustainability practices.

2) Pollution and impact studies: Journals such as "Science of the Total Environment," "Environmental Science and Pollution Research," "Chemosphere," and "Environmental Research" focus on ecological research, pollution studies, and the broader environmental impacts of industrial activities.

3) Environmental policy: Journals like "Energy Policy" and "Journal of Environmental Management" explore energy policies, management strategies, and regulatory implications essential for implementing green technologies within business operations.

These groupings reflect the critical areas of research necessary for advancing sustainable practices and integrating green technologies in the primary sector.

Table 1. List of the top 10 journals.

Journals	Country	Publisher	IF 2022	Articles
Journal of Cleaner Production	NL	Elsevier	11.1	26
Sustainability	CH	MDPI	3.9	25
Science of the Total Environment	NL	Elsevier	9.8	14
Environmental Science and Pollution Research	USA	Springer	5.8	12
Energy Policy	NL	Elsevier	9.0	7
Journal of Environmental Management	NL	Elsevier	8.7	6
Environmental Development and Sustainability	USA	Springer	4.9	4
Fresenius Environmental Bulletin	DEU	Parlar SP	0.6	4
Chemosphere	NL	Elsevier	8.8	3
Environmental Research	NL	Elsevier	8.3	3

The integration of green technologies within business strategies in the agricultural sector is a vital area of research, underscored by the citations of influential papers. **Table 2** highlights the top ten most cited papers within this domain, providing valuable insights into the foundational works driving this field forward. These papers all come from a range of prestigious journals, collectively reflecting a rich diversity of theoretical frameworks, empirical analyses, and practical innovations: particularly, Journal of Cleaner Production appears multiple times, highlighting its crucial role in advancing sustainability practices, on the other hand the presence of Technology Analysis and Strategic Management and Technological Forecasting and Social Change emphasizes as well the importance of strategic and forward-looking approaches in managing transitions towards sustainable technologies. By analyzing these papers, we can identify three main recurring themes: the first theme centers on the foundational theoretical and strategic frameworks. Caniëls and Romijn (2008), Kemp et al. (1998) and Kostoff et al. (2004) and contribute significantly to this area. Kemp introduces strategic niche management, emphasizing the importance of protective spaces for innovation. Kostoff provides a systematic approach to identifying disruptive technologies through literature-based discovery, stressing strategic planning's role in fostering innovation. Caniëls and Romijn consolidate key studies on strategic niche management, suggesting ways to facilitate sustainable technology diffusion through societal experiments. The second theme explores the nuanced relationship between policy, governance, and economic implications of adopting green technologies. Elahi et al. (2022), Hall et al. (2011) and Mishra et al. (2021) delve into this area. Elahi highlights innovative management strategies to mitigate climate-induced agricultural damages. Mishra discusses the economic and policy dimensions of sustainable practices, focusing on carbon cap and tax-regulated sustainable inventory management.

Hall integrates technological, commercial, and social uncertainties in Brazilian biofuels, demonstrating innovation's role in addressing opportunities and challenges in emerging economies. Eventually, the third theme illustrates the importance of innovation in driving market dynamics and enhancing sustainability. Chen et al. (2012), Cundy et al. (2016), Schau et al. (2009) and Scoones (1991) focus on this area. Schau provides insights into the environmental effects and costs of fuel consumption in the Norwegian fishing industry. Chen reviews the progress and challenges in scaling biogas technologies in China. Cundy emphasizes integrating green technologies with site risk management solutions through gentle remediation options (GROs). Scoones highlights wetlands' essential role in supporting local economies in Africa and the need for sustainable management practices.

Table 2. List of the top 10 cited papers.

Title	Author(s)	Journal	Year	Global cit
Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management	Kemp, R., Schot, J. and Hoogma, R.	Technology Analysis and Strategic Management	1998	1568
Disruptive technology roadmaps	Kostoff, R. N., Boylan, R., and Simons, G. R.	Technological Forecasting and Social Change	2004	215
Extreme weather events risk to crop-production and the adaptation of innovative management strategies to mitigate the risk	Elahi, E., Khalid, Z., et al.	Technovation	2022	189
Energy consumption in the Norwegian fisheries	Schau, E. M., Ellingsen, H., et al.	Journal of Cleaner Production	2009	124
The progress and prospects of rural biogas production in China	Chen, L., Zhao, L., et al.	Energy Policy	2012	118
Optimum sustainable inventory management with backorder and deterioration under controllable carbon emissions	Mishra, U., Wu, J. and Sarkar, B.	Journal of Cleaner Production	2021	118
Brownfields to green fields: Realising wider benefits from practical contaminant phytomanagement strategies	Cundy, A., Bardos, R., et al.	Journal of Environmental Management	2016	107
Wetlands in Drylands: Key Resources for Agricultural and Pastoral Production in Africa	Scoones, I.	Ambio:	1991	99
Strategic niche management: towards a policy tool for sustainable development	Caniëls, M. C. J., and Romijn, H. A.	Technology Analysis and Strategic Management	2008	96
Managing technological and social uncertainties of innovation: The evolution of Brazilian energy and agriculture	Hall, J., Matos, S., Silvestre, B., et al.	Technological Forecasting and Social Change	2011	94

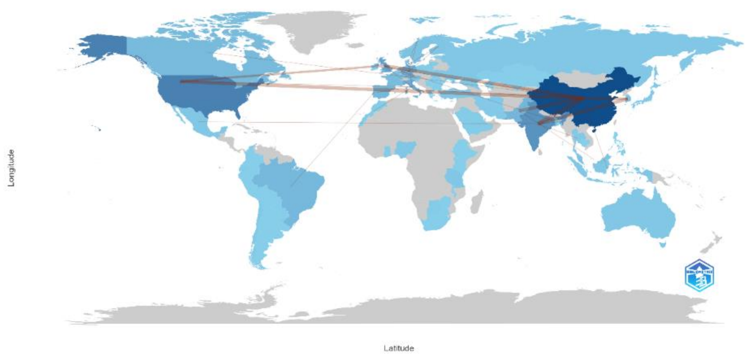

Figure 3. Country collaboration map.

The integration of green technologies within business models in the primary sector has seen varied levels of academic contributions from different countries over the years. Analyzing the annual publications by country up to 2023 reveals several key trends and insights. China has emerged as the leading contributor in recent years, with a significant increase in publications, peaking at 126 articles in 2023. This upward trend indicates a strong emphasis and substantial investment in sustainable practices and green technology research within the country. India's contributions have also shown a steady rise, with the number of publications reaching 70 articles in 2023, reflecting a growing academic interest and possibly increased funding in this field. The USA has maintained a consistent level of contributions, with 61 articles published in 2023, underscoring its ongoing commitment to research in sustainable agricultural technologies. The UK and Italy have also been notable contributors, with each country publishing 39 and 34 articles respectively in 2023. Their steady output suggests a continuous focus on this research area, although at a lower intensity compared to China, India, and the USA. **Figure 3**, a global map illustrating the academic collaborations between countries, highlights the interconnected nature of this research field. Significant collaboration lines are observed particularly between China, the USA, India, and the UK, suggesting a robust network of co-authorship and shared research initiatives. This international collaboration is crucial for advancing the academic field here understudied, as it facilitates the exchange of knowledge, resources, and innovative practices across borders. Despite the contributions from these leading countries, it is notable that many other countries have limited or no contributions to this field. Several factors could explain this discrepancy. Economic constraints might be a barrier for countries with limited resources, as research in green technologies often requires significant investment. Different policy priorities might also play a role, with some countries focusing more on immediate economic growth rather than long-term sustainability initiatives. The lack of expertise and infrastructure to develop and maintain research in green technologies can be challenging, particularly for countries with emerging academic and research institutions. Additionally, countries with fewer publications may not have established strong international research collaborations, limiting their contributions and visibility in this field.

3.2. Bibliographic coupling network analysis

Bibliographic coupling provides a prospective view of emerging research trends by connecting documents through mutual citations, rather than focusing on cited papers (Boyack and Klavans, 2010; Vogel and Güttel, 2013). This analysis examines 240 documents referenced in publications on green technologies in companies' strategies within the primary sector. To enhance network interpretability, a minimum of 10 citations per paper was set, resulting in 119 applicable publications. Further refinements excluded unconnected documents, yielding a final sample of 72 papers. The network analysis, conducted using VOSviewer, shows a density of 0.05 and a modularity index of 0.57 across ten clusters: the density value represents a relatively sparse network (Vogel and Güttel, 2013), while the modularity value suggests a good quality of division into clusters (Wu et al., 2019). Four clusters with fewer than five papers each were excluded due to low relevance, resulting in six final clusters.

3.2.1. Bibliographic coupling cluster 1: Biogas

The studies included in this first cluster all emphasize the critical role of strategic planning, policy support, and integrated frameworks in overcoming barriers and promoting the widespread adoption of biogas technology, contributing to sustainable energy solutions and environmental sustainability. Ali et al. (2023) and Bhatia et al. (2020) highlight the necessity of government support and strategic planning to overcome economic and technical obstacles in Pakistan and India, respectively, emphasizing the role of policy frameworks and financial incentives in promoting biogas technology. Both studies underscore the importance of reducing governmental and economic barriers to enhance the productive use of biogas. Ikram et al. (2022) and Khan and Ali (2022b) focus on strategic frameworks for implementing green technologies. Ikram's SWOT and GAHP analysis provide a comprehensive strategy for green technology planning in Pakistan, identifying high productivity potential and security issues as critical factors. Similarly, Khan employs a hybrid methodology using fuzzy SWOT and TOPSIS to advocate for the circular bio-economy approach in Pakistan's agriculture sector, highlighting the significance of ease of adoption and price competitiveness. Aggarwal et al. (2021) and Kothari et al. (2020) explore the challenges and policy gaps in India's bioenergy sector. Kothari notes the inefficiencies of traditional bioenergy practices and the potential of modern technologies to fill the demand-supply gap, while Aggarwal discusses the renewed interest in biogas production to reduce oil imports and meet energy demands, stressing the need for a sustainable biogas policy aligned with UN sustainable development goals. Arthur et al. (2021) and Winquist et al. (2021) extend the discussion to the broader implications of biogas technology in Europe and Ghana: while the former highlights the potential of biogas to address carbon emissions and support circular economy practices, contingent on stable and predictable energy policies, the latter provides a quantitative analysis of biogas potential from various waste sources in Ghana, demonstrating significant environmental benefits and policy implications.

3.2.2. Bibliographic coupling cluster 2: Biochar

The papers of cluster 2 overall suggest that while biochar offers substantial environmental, economic, and social benefits, its effective implementation requires interdisciplinary approaches and tailored strategies considering local conditions and stakeholder needs. Luo et al. (2020) highlight biochar's efficacy in immobilizing heavy metals like cadmium and arsenic in soils, emphasizing the relationship between biochar's physicochemical properties and its environmental benefits. Qin et al. (2022) extend this by illustrating biochar's broader role in global strategies for carbon neutralization, agricultural management, and environmental restoration, advocating for cross-disciplinary research to address evolving challenges. Xu et al. (2022) study specific biochar modifications to enhance cadmium sorption, revealing significant improvements through both biological and chemical modifications. Hansson et al. (2021) add a socio-economic perspective, discussing the implementation challenges and trade-offs in biochar projects in least-developed countries (LDCs), particularly Tanzania, and their potential for mitigating climate change and enhancing local resilience. Gan and Yu (2008) and Ramos et al. (2020) offer complementary insights into biomass and biochar applications; Gan critiques the current emphasis on biomassburning power generation in China, suggesting decentralized, household-based biomass technologies as more beneficial. In contrast, Ramos focuses on cork waste gasification as a sustainable energy production method, demonstrating lower environmental impacts compared to conventional energy production. Finally, Fadda et al. (2022) and Owsianiak et al. (2018) expand the scope to food processing and life cycle assessments, respectively, highlighting the sustainable use of natural antioxidants in edible oils and the importance of spatial differentiation in life cycle assessments for biochar application.

3.2.3. Bibliographic coupling cluster 3: Biotech remediation

The third bibliographic coupling cluster underscores the potential and challenges of various green and bioremediation technologies in addressing soil contamination by heavy metals and other pollutants. A prominent theme is the use of phytoremediation, which leverages plants' natural abilities to accumulate and stabilize contaminants. For instance, Cundy et al. (2016) discuss gentle remediation options that integrate plant, fungi, and bacteria-based methods to manage contaminated sites, highlighting the economic and societal benefits alongside environmental gains. Similarly, Fiorentino et al. (2017) emphasize the effectiveness of giant reed in phytoremediation, noting its biomass production and soil fertility enhancement capabilities. Zhang et al. (2021) explores different cropping patterns in phytoremediation, finding that monocultures of Sedum alfredii yield better economic and remediation outcomes compared to intercropping. Oyetibo et al. (2017) and Srivastava et al. (2019) extend the discussion to bioremediation strategies that employ microorganisms to degrade persistent organic pollutants and heavy metals, advocating for their application in broader environmental contexts such as estuarine systems. The integration of bioremediation with traditional methods, as suggested by Karimi et al. (2022) and Zhu et al. (2010), offers a holistic approach to mitigating both organic and inorganic contaminants. Khodaverdiloo et al. (2020) and Narayanan and Ma (2023) highlight the complexities of heavy metal tolerance in plants and the necessity of agronomic practices to enhance phytoremediation efficacy in challenging environments like arid and semi-arid soils. Blagojev et al. (2021) and Cicatelli et al. (2017) further investigate biosorption and assisted phytoremediation, respectively, presenting the effectiveness of agricultural waste biomass and bacterial consortia in enhancing metal uptake and soil decontamination.

3.2.4. Bibliographic coupling cluster 4: Sustainable agriculture transition

The matter of contention in this cluster revolves around the recognition of the multifaceted nature of sustainable agricultural transformation, which requires an integration of technological innovation, social learning, policy support, and economic incentives. Elahi et al. (2022) and Li et al. (2021) emphasize the adaptation to climate change through the adoption of innovative management strategies and low-carbon technologies, respectively, highlighting the critical role of farmer perceptions and education in mitigating adverse weather impacts and promoting sustainable practices. Similarly, Lewis et al. (2011) and Li et al. (2018) underscore the importance of social learning and spatial spillovers in the adoption of environmentally friendly farming practices, showing that neighboring organic farms and social learning networks can significantly influence the diffusion of sustainable agricultural technologies. Li et al.

(2019) and Pegels and Altenburg (2020) extend this discussion to broader economic and policy frameworks, arguing that green development and transformation can lead to economic co-benefits, but require strategic planning and policy support to balance short-term economic needs with long-term sustainability goals. Barbier (2020) and Cui et al. (2019) further elaborate on the structural and systemic changes needed to support green transformation, such as improving resource efficiency, reducing deforestation, and enhancing the diffusion of green technologies through effective policies and economic incentives. The common thread across these studies is.

3.2.5. Bibliographic coupling cluster 5: Low-Carbon agriculture

This fifth collection of papers presents a cohesive narrative centered on the dynamic between environmental sustainability and technological innovation in agricultural and coastal ecosystems. A prevalent theme across the studies is the critical role of innovative approaches in mitigating greenhouse gas (GHG) emissions and adapting to climate change impacts. Kuenzer and Renaud (2012) emphasize the vulnerabilities of river deltas to societal and climate-induced pressures, underscoring the need for multi-faceted mitigation and adaptation strategies. Sommer et al. (2009) explore the reduction of GHG emissions through advanced manure management practices in livestock farming, highlighting the variability in effectiveness across different climatic and management conditions. Le Gal et al. (2010) introduce a modeling framework to evaluate farm-level innovations, illustrating the importance of stakeholder involvement in designing effective agricultural systems. Balezentis et al. (2016) employ an environmental performance index to assess the Lithuanian economy, identifying high and low-performing sectors in terms of GHG emissions, thus pinpointing areas for targeted sustainability strategies. Luo et al. (2023) discuss the collaborative efforts required among agricultural enterprises, universities, and the government to advance low-carbon agricultural technologies in China, providing a game-theoretical perspective on innovation dynamics. Kaspersen et al. (2016) demonstrate the potential of bioenergy solutions in Denmark to link climate change mitigation with water quality improvement, showcasing the integrative benefits of anaerobic co-digestion processes. He et al. (2021) address the economic and technological dimensions of reducing agricultural GHG emissions in China, advocating for region-specific strategies to enhance cost-effectiveness. Finally, Coleman et al. (2022) evaluate the economic feasibility of kelp-based carbon dioxide removal technologies, revealing significant cost reductions through process optimization and supply chain decarbonization.

3.2.6. Bibliographic coupling cluster 6: Green strategies

The studies collected in cluster 6 highlight the challenges and strategies pertinent to advancing green technologies. Kemp et al. (1998) emphasize the lock-in effect of existing technological regimes and the potential of strategic niche management (SNM) to foster sustainable technological transitions by creating protected spaces for new innovations. This theme resonates with Caniëls and Romijn (2008), who further explore SNM’s role in enabling socio-technical transitions through societal experiments in various sustainable fields, stressing the necessity of evolving these experiments into viable market niches. Kostoff et al. (2003) introduce the concept of disruptive technologies, which can revolutionize industries by offering cheaper, better, and more convenient solutions, yet often face resistance due to existing strategic planning processes favoring sustaining technologies. This idea is echoed by Hall et al. (2011) and Hall et al. (2019), who discuss the multifaceted uncertainties—technological, commercial, and social—that accompany innovations, using Brazilian biofuels and green entrepreneurship as case studies to illustrate the importance of managing these uncertainties through strategic frameworks and institutional work. The notion of utilizing waste as a resource is explored by Alibardi et al. (2020) and Yadav et al. (2022), who both highlight the potential of biorefineries to convert organic waste into valuable products, thereby contributing to sustainable waste management and resource recovery. Frare et al. (2022) and Morone et al. (2015) investigate the specific challenges and opportunities within the bioplastics sector and agri-tech startups respectively, focusing on the network structures and green process innovations that can drive environmental performance and market development.

3.2.7. Clusters interrelationship and development

The six classifications identified through bibliographic coupling analysis represent distinct but interrelated themes in the broader landscape of green technologies in agriculture. These clusters have developed in response to the growing need for sustainable solutions in agriculture, driven by climate change, resource scarcity, and environmental degradation. Each cluster addresses specific challenges, but their strength lies in how they complement and reinforce each other.

Cluster 1: Biogas and Cluster 2: Biochar both focus on renewable energy production and waste management, which are key priorities in reducing agriculture’s environmental footprint. Biogas production uses organic waste to generate clean energy, while biochar sequesters carbon and improves soil health. These technologies have developed as part of a larger global effort to transition to low-emission agricultural systems. They address the need to reduce dependence on fossil fuels and mitigate climate change impacts, while also providing practical solutions for waste management. Cluster 5: Low-Carbon Agriculture is intricately linked to biogas and biochar, as all three focus on reducing greenhouse gas emissions. Low-carbon agriculture integrates these energy and soil improvement technologies into broader farming practices aimed at reducing the sector’s overall carbon footprint. This cluster developed in response to global climate agreements, such as the Paris Agreement, which emphasize the need for agriculture to contribute to decarbonization. The use of renewable energy, carbon sequestration, and sustainable land management practices all work together to make agricultural systems more resilient and environmentally friendly. Cluster 3: Biotech Remediation addresses soil contamination and pollution, critical issues that degrade agricultural land and reduce its productivity. This cluster developed out of the necessity to rehabilitate degraded ecosystems and ensure that farmland remains viable in the long term. As biotechnological innovations in soil remediation—such as bioremediation and phytoremediation—have advanced, this cluster has become essential in supporting the broader Cluster 4: Sustainable Agriculture Transition. Biotech remediation allows for the restoration of contaminated land, enabling a smoother transition toward sustainable farming practices by making previously unusable land productive again. Cluster 6: Green Strategies functions as a unifying framework for the other clusters, focusing on strategic planning, policy support, and the managerial aspects necessary for implementing green technologies. The development of this cluster reflects the recognition that technological advancements alone are insufficient to achieve widespread adoption. Green strategies have emerged as critical to overcoming the economic, regulatory, and operational barriers that often prevent the implementation of sustainable practices. They emphasize the importance of policy frameworks, financial incentives, and market-based mechanisms that can help scale innovations like biogas, biochar, low-carbon agriculture, and biotech remediation.

These clusters have developed in response to the evolving demands of modern agriculture, which must balance the need for increased productivity with the imperative to reduce environmental impacts. The interconnected nature of these clusters highlights the need for an integrated approach to sustainable agriculture, where technological innovation is supported by strategic planning and policy frameworks. By working together, these clusters offer a comprehensive pathway toward achieving a more sustainable and resilient agricultural sector.

3.3. The author's keyword co-occurrence analysis

The bibliometric analysis of the author's keywords co-occurrence network reveals several distinct clusters that highlight the integration of green technologies within business strategies and models in the agricultural sector, each characterized by unique thematic focuses. Core to this analysis is the concept of "betweenness centrality" (BC): BC is a metric used in bibliometric analysis to assess the significance of a node within a network. In the context of a co-occurrence network, where nodes represent entities such as the author's keywords, and edges represent their co-occurrences or relationships, BC measures how frequently a node serves as a bridge on the shortest path between other nodes. This indicates the node's role in connecting disparate parts of the network, highlighting its importance in the flow and dissemination of knowledge within the academic field (Rossa-Roccor et al., 2020). In this case, our study, filtering for the author's keywords with a minimum number of edges equal to 2, identified 42 keywords, divided into 8 unique clusters in a network, each representing interconnected themes based on keyword co-occurrence analysis (Aria and Cuccurullo, 2017), as represented in **Figure 4**. Cluster 1 (green), with the highest BC (413.87), centers on strategic and managerial aspects, innovation, and policymaking. Keywords such as "strategies," "management," and "innovation" underscore the critical importance of developing and adopting effective policies and overcoming challenges through innovative approaches and conservation efforts in sustainable agriculture. Cluster 2 (blue), with a significant BC of 392.96, emphasizes energy-related topics, as evidenced by keywords like "energy," "sustainability," and "growth". This cluster highlights the centrality of energy efficiency and environmental impact in the discourse on sustainable agricultural practices. Cluster 3 (orange), with a BC of 291.41, focuses on agricultural performance metrics, efficiency, and water management, indicating the importance of optimizing resource use and enhancing productivity. Cluster 4 (purple), with a BC of 218.00, addresses soil and plant-related issues, particularly contamination and remediation, as indicated by keywords like "heavy-metals" and "phytoremediation". This cluster underscores the necessity of improving soil health for sustainable agricultural practices. Cluster 5 (red), with a BC of 108.06, highlights environmental impact assessments and waste management, with "emissions" playing a crucial role in reducing greenhouse gas emissions and promoting sustainable waste treatment methods. Cluster 6 (brown), with a BC of 101.05, focuses on the impacts of climate change on agriculture, emphasizing "food security" and "vulnerability". The keywords reflect concerns about the resilience of agricultural systems to climatic variability. Cluster 7 (pink), with a BC of 73.65, emphasizes renewable energy sources, particularly "biomass," indicating a shift towards eco-friendly energy alternatives in agriculture. Lastly, cluster 8 (grey), although smaller and disconnected from the others, with a BC of 0.00, highlights "degradation" and "biodegradation" processes, reflecting their relevance in understanding and managing sustainable agricultural practices.

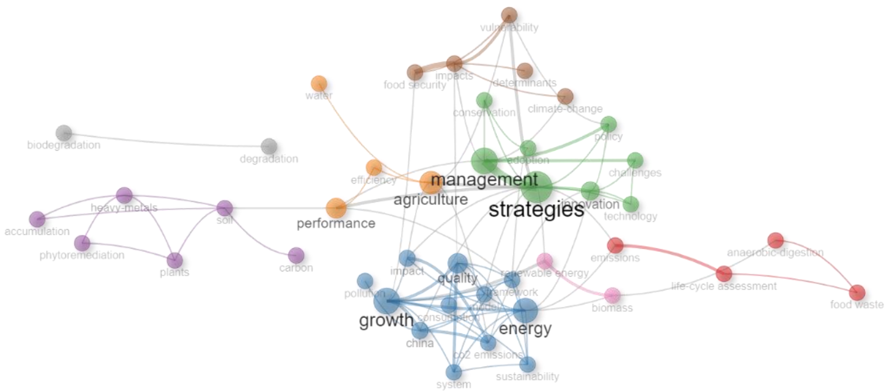

Figure 4. Author's keywords co-occurrence network.

4. Discussion

The results of our study reveal a compelling evolution in the research focus and methodologies surrounding green technologies and sustainable business strategies in the agricultural sector. This progression reflects both advancements in the field and shifting priorities towards more applied, innovative, and interdisciplinary approaches.

The descriptive analysis highlighted a growing trend in publications, especially post-2015. This surge aligns with significant global milestones such as the UN's 2030 Agenda for Sustainable Development and the Paris Agreement, indicating a heightened scholarly interest in sustainable agricultural practices. These international agreements have catalysed a worldwide commitment to sustainability, urging scholars and practitioners to explore and implement green technologies. The notable increase in publications post-2018 suggests that global events and policies have significantly influenced research directions, underscoring the urgency of adopting sustainable agriculture practices. This period also saw a re-evaluation of global food systems' resilience due to the COVID-19 pandemic, which further highlighted the need for robust and sustainable agricultural practices. The increasing frequency of extreme weather events has driven a scholarly focus on sustainable innovations, recognizing the vulnerability of agriculture to climate change. Examining the top journals and highly cited papers reveals the interdisciplinary nature of this research area. Journals like "Journal of Cleaner Production" and "Sustainability" focus on technical innovations and their practical implementation, highlighting the importance of technological solutions in achieving sustainability. Meanwhile, journals such as "Energy Policy," "Technology Analysis and Strategic Management," and "Journal of Environmental Management" emphasize policy and strategic frameworks, reflecting the need for comprehensive approaches that encompass environmental, social, and economic perspectives. This diversity underscores the need for a comprehensive approach to integrating green technologies in agriculture, combining technical, environmental, social, and economic perspectives. The convergence of different disciplinary insights suggests that effective integration of green technologies requires collaboration across various fields to address complex sustainability challenges holistically. The analysis of academic contributions by country highlights China's leading role, with a significant increase in publications peaking at 126 articles in 2023. This trend reflects China's strong emphasis and substantial investment in sustainable practices and green technology research, driven by national policies and international commitments. China's leadership in this area underscores the impact of national policies and global agreements on research orientations. India's growing contributions and the consistent outputs from the USA, the UK, and Italy indicate a robust international interest and collaboration in this field. However, the limited contributions from other countries point to potential barriers such as economic constraints, differing policy priorities, and lack of infrastructure or expertise. Addressing these disparities through international cooperation and capacity-building initiatives could enhance global efforts towards sustainable agriculture, fostering a more inclusive approach to global sustainability goals.

The bibliographic coupling network analysis reveals several key clusters of focus within the field of sustainable agriculture and green technologies. The identification of these clusters highlights the multifaceted nature of current research and its alignment with global sustainability goals. The prominence of these clusters in the network analysis is not coincidental. Each represents a critical component of the broader effort to develop sustainable agricultural practices and technologies. Their relevance is underscored by interdisciplinary integration, as they reflect a convergence of diverse research disciplines. This convergence indicates that sustainable agricultural solutions require an integrated approach. For instance, the biogas and biochar clusters emphasize the need for both technological innovation and supportive policy frameworks, demonstrating that technical advancements alone are insufficient without the right regulatory environment. Environmental and economic synergy is another key factor that underscores the relevance of these clusters. Research areas such as biochar and low-carbon agriculture highlight the dual focus on environmental benefits and economic viability. This dual focus is crucial for the adoption and implementation of sustainable practices. By addressing both ecological and economic aspects, these research areas provide practical solutions that can be realistically adopted by farmers and policymakers alike. The emphasis on localized and tailored approaches, as seen in the biochar and biotech remediation clusters, highlights the importance of adapting sustainable agricultural practices to specific contexts. This growing recognition suggests that one-size-fits-all solutions are ineffective, and tailored approaches to local conditions enhance the effectiveness and acceptance of sustainable technologies. Furthermore, the clusters focused on the transition to sustainable agriculture and strategic niche management point to the need for comprehensive strategies that encompass technological, social, and economic dimensions. This holistic view is critical for understanding the complex interactions within agricultural systems and for designing interventions that promote long-term sustainability. The focus on these clusters provides valuable insights into the current state of research in sustainable agriculture: the identification of biogas, biochar, and low-carbon agriculture clusters highlights the ongoing innovation in green technologies. These technologies are essential for reducing the environmental impact of agricultural practices and for developing new, sustainable sources of energy and soil improvement methods. The role of strategic planning, policy support, and government incentives in the biogas cluster underscores the importance of governance in facilitating the adoption of sustainable technologies. Effective policy frameworks are essential for overcoming barriers and incentivizing sustainable practices. The emphasis on transition and niche management clusters reflects a growing interest in understanding and managing the complex process of transitioning to sustainable agricultural systems. This involves not only technological changes but also shifts in social norms, economic structures, and institutional frameworks. The analysis of the bibliographic coupling network also reveals emerging trends that are shaping the future of sustainable agriculture research. A prominent emphasis on renewable energy and waste management solutions, particularly biogas and biochar, illustrates the sector's increasing commitment to reducing greenhouse gas emissions and fostering circular economy practices. In parallel, advancements in soil remediation technologies, such as bioremediation and phytoremediation, are addressing the pressing need to rehabilitate degraded land and sustain agricultural productivity. Furthermore, the adoption of low-carbon agricultural practices signals the sector's proactive stance toward meeting global climate objectives through innovative and efficient farming techniques. Another key trend is the growing recognition of the role of policy frameworks and government incentives, which are crucial for overcoming implementation barriers and driving the widespread adoption of green technologies. Together, these trends highlight the convergence of technology, policy, and market forces in promoting agricultural sustainability. Additionally, the identified clusters highlight potential research gaps. While significant progress has been made in biogas and biochar technologies, there may be a need for more research into their long-term impacts and scalability. Furthermore, the integration of biotech remediation with traditional methods suggests a need for further exploration of combined approaches to soil health restoration. Eventually, the keyword co-occurrence analysis further identifies key themes central to this field, such as innovation, energy efficiency, agricultural performance, soil health, emissions reduction, climate change impacts, and renewable energy sources. These themes reflect the interconnected nature of technological, environmental, and economic aspects in developing sustainable agricultural business models. Understanding these interconnected themes is crucial for developing holistic strategies that address multiple sustainability dimensions simultaneously.

5. Conclusions

This study presents a comprehensive bibliometric analysis of sustainable technologies and business strategies in the agricultural sector, highlighting key trends, influential authors, prominent journals, and significant research clusters. Our findings underscore the growing interest and scholarly attention to integrating green technologies within agricultural business models, driven by global sustainability initiatives and the increasing urgency of addressing environmental challenges.

The integration of green technologies within agribusiness requires coordinated policy frameworks that align technological advancements with practical, scalable solutions. As highlighted in the clusters, biogas, biochar, low-carbon agriculture, biotech remediation, and green strategies all require tailored policy support to ensure effective adoption and implementation. Policymakers should focus on creating enabling environments by addressing financial, technical, and regulatory barriers. Government incentives, such as subsidies and tax credits, as shown by Kothari et al. (2020), can reduce the financial burden and promote widespread adoption of technologies like biogas and biochar. Furthermore, coordinated national and regional strategies that promote soil health restoration and sustainable agricultural practices are essential. Elahi et al. (2022) emphasize the need for disaster preparedness and proactive adaptation measures, especially in vulnerable regions. Strengthening institutional cooperation and creating protected spaces for innovation, as highlighted by Hall et al. (2011) and Kemp et al. (1998), will ensure that technological innovations are supported by effective policy frameworks and collaboration across sectors.

Despite the insights provided, this study has several limitations. Firstly, the reliance on the Web of Science Core Collection may exclude relevant publications indexed in other databases. Secondly, the analysis is constrained by the available bibliometric tools, which may not capture the full complexity of the research landscape; notwithstanding that this study provides a comprehensive bibliometric analysis through bibliographic coupling, offering insights into current trends and thematic clusters, it is important to acknowledge the inherent limitations of this method in providing a fully forward-looking perspective. While bibliographic coupling connects documents through shared references, providing an understanding of ongoing research, it may not completely capture the most groundbreaking or disruptive innovations that have yet to generate significant citations. As such, this method tends to focus on established areas of research and may not adequately predict future paradigm shifts or novel cross-disciplinary innovations. Additionally, bibliographic coupling can overlook nascent trends that might be underrepresented in citation networks but are critical to the future of sustainable agriculture. Lastly, while bibliometric methods provide valuable quantitative insights, they do not fully account for the qualitative nuances of the research themes and their practical implications. To offer a more comprehensive view of the future evolution of green technologies, combining bibliometric methods with qualitative foresight approaches, such as expert opinion or scenario analysis, would be beneficial, as well as aiming to include a broader range of databases. Further studies could also explore the impact of emerging technologies and policies on the evolution of sustainable agriculture practices, offering a more dynamic and forward-looking perspective.

Author contributions: Conceptualization, LO and RP; methodology, LO and RP; software, RP; validation, LO, RP and LZ; formal analysis, RP; investigation, RP; resources, RP; data curation, RP; writing—original draft preparation, RP, LO and LZ; writing—review and editing, RP and LO; visualization, RP; supervision, LO and LZ; project administration, LZ; funding acquisition, LZ. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out within the Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)–MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4–D.D. 1032 17/06/2022, grant number [CN00000022]. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Acknowledgments: I would like to express my sincere gratitude to the editor, the journal's editorial board, and the anonymous reviewers for their valuable feedback and constructive suggestions, which have greatly contributed to improving the quality of this manuscript.

Conflict of interest: The authors declare no conflict of interest.

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