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Steering the Green Transition: Business Models and Innovation Dynamics in the Agri-Tech Sector

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Rocco Pavesi
Supervisor: Prof. Luigi Orsi
Co-Supervisor: Prof. Stefanella Stranieri

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STEERING THE GREEN TRANSITION: BUSINESS MODELS AND INNOVATION DYNAMICS IN THE AGRI-TECH SECTOR

ECON-07A

ROCCO PAVESI
Matr. R14068
ORCID n. 0009-0006-7667-2497

TUTOR
PROF. LUIGI ORSI

COORDINATORICE DEL DOTTORATO
PROF.SSA MARCELLA GUARINO

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INTRODUCTION

From National Strategy to a Research Imperative

The global agri-food sector stands at a crucial, yet precarious, crossroads. For decades, the dominant paradigm prioritized productivity and intensification above all else, a model that, while successful in feeding a rapidly growing population, has exacted a significant and unsustainable toll on the planet's ecological systems. Today, the sector is confronted by the profound and complex consequences of this legacy. It is tasked with the monumental challenge of ensuring food security and nutrition for a projected global population of ten billion by 2050, yet it must do so within the tightening constraints of a changing climate and degrading natural resources. Agriculture is both a primary driver of environmental stress, contributing significantly to greenhouse gas emissions, biodiversity loss, soil degradation, and water scarcity, and one of the sectors most vulnerable to the disruptive impacts of these very changes. This dual reality, a feedback loop of cause and consequence, has rendered traditional, linear models of agricultural production untenable. A systemic paradigm shift is no longer a choice, but an urgent and unavoidable imperative for global resilience.

In response to this global urgency, the European Union has positioned itself at the forefront of a transformative agenda, launching the landmark *NextGenerationEU* recovery plan. Articulated in Italy through the National Recovery and Resilience Plan (NRRP), this initiative transcends the scope of a conventional post-pandemic economic stimulus. It represents a strategic blueprint for a systemic transition towards a more sustainable, resilient, and technologically advanced future. Central to this vision are two interconnected strategic pillars: fostering a profound green transition to ensure environmental sustainability and driving a comprehensive digital transformation to enhance competitiveness and efficiency. This forward-looking industrial policy creates a framework where technological innovation is seen as a primary enabler for sustainability goals, while the quest for sustainability, in turn, can become a powerful driver for new technological development.

Within this ambitious European framework, the agricultural sector has been identified as a critical domain for intervention and innovation. To facilitate this transformation in Italy, the NRRP has catalyzed the creation of several National Research Centers, among which the National Research Center for Agricultural Technologies (AGRITECH) stands as the flagship initiative for the agri-food domain. Representing a cornerstone of the national strategy, AGRITECH has been established through a major investment to unite Italy's leading scientific and industrial expertise. Its clear and ambitious mandate is to develop and deploy cutting-edge technologies that can make the national agri-food industry more sustainable, competitive, and resilient in the face of 21st-century challenges. The Center's mission is formally articulated around five core strategic pillars: enhancing resilience to climate change; promoting low-impact production systems; fostering circularity through waste valorization; enabling the recovery of marginal lands; and ensuring the traceability and safety of food supply chains.

To operationalize this national strategy and foster a truly integrated innovation ecosystem, AGRITECH is structured according to a robust Hub & Spoke model. A central Hub, managed by the University of Naples Federico II, provides strategic coordination, administrative oversight, and manages the crucial activities of knowledge dissemination and technology transfer. The core research and development agenda, however, is executed by nine thematic Spokes. Each Spoke is led by a top-tier Italian university or research institution and functions as a specialized node of excellence.

This organizational logic is designed to cultivate deep expertise in specific vertical domains, from genetic resources and crop health to smart farming systems and supply chain management, while ensuring that these specialized efforts are continuously integrated and aligned with the overarching national objectives defined by the Hub.

This dissertation is situated within the scientific and strategic purview of Spoke 8: “New models of circular economy in agriculture through waste valorization and recycling”. This Spoke addresses one of the most fundamental challenges of the green transition: the systemic inefficiency and environmental burden of the linear “take-make-dispose” economic model. Its core objective is to develop the scientific and technological foundations to re-imagine agricultural and agro-industrial residues, transforming them from a costly liability into a valuable resource. The research within Spoke 8 is therefore dedicated to creating high-value products from diverse waste streams, including bioenergy, biofuels, biopolymers, and advanced bio-fertilizers—thereby closing resource loops, reducing pollution, and creating novel, sustainable value chains. Within the intricate structure of Spoke 8, the research is further organized into specific Work Packages.

This Ph.D. project is formally embedded in Work Package 8.4: “Evaluation and assessment of new circular technologies in agriculture”. The mission of this WP is of critical importance, as it serves as a bridge between scientific discovery and real-world impact. Its focus moves beyond pure technological development to address the complex and often-overlooked question of viability. It seeks to build and apply a rigorous, multidimensional framework for evaluating whether the innovative green technologies emerging from the other research tasks are not only technically sound but also economically, socially, and environmentally sustainable in the long run. This WP addresses the so-called “valley of death”, where promising inventions often fail for lack of a clear path to market.

This brings us to the specific locus of the present research, which contributes directly to Task 8.4.1: “Economical-financial and cost/benefit measures of the technologies proposed”. While traditional financial and cost-benefit analyses provide a crucial, yet ultimately static, assessment of a technology’s potential profitability, they often fail to capture the dynamic and strategic architecture required to bring an innovation to market successfully. A technology does not exist in a vacuum; its ultimate success or failure is contingent on the business model designed to deploy it, scale it, and capture value from it. Therefore, this doctoral research is conceived as the strategic and applied culmination of Task 8.4.1’s mandate. It posits that the true measure of a green technology’s value lies not in its technical efficiency alone, but in its ability to be embedded within a viable, scalable, and sustainable business model.

This thesis aims to bridge the critical gap between technological invention and market innovation. By leveraging advanced strategic management frameworks and applying them to the cutting-edge green technologies emerging from the national research agenda, this dissertation seeks to design and validate the very business models that can translate the scientific potential generated by AGRITECH into tangible, durable, and sustainable competitive advantage for the agricultural enterprises of the future. Specifically, the core thesis defended in this dissertation is that technological invention alone is insufficient for the green transition. It posits that a durable competitive advantage in the agri-tech sector can only be achieved through a strategic architectural reconfiguration of the firm, where green innovations are not adopted in isolation but are synergistically integrated with digital capabilities (Twin Transition) and embedded within circular business models that explicitly account for economic, environmental, and social value layers. This work, therefore, intends to provide not just an academic contribution to the field of sustainable business strategy but also a concrete and practical framework for practitioners and policymakers dedicated to realizing the ambitious vision of the NRRP.

The Research Journey: Structure of the Dissertation

This dissertation unfolds as a structured intellectual inquiry, designed to address the complex, multi-faceted nature of the green transition in agriculture through a deliberate, multi-scalar research design. The thesis is not conceived as a single, monolithic study but as a cumulative and coherent argument built across four distinct, yet deeply interconnected, chapters. Each chapter functions as a standalone research paper that employs a specific methodological lens—bibliometric, case-based, patentometric, and econometric—to examine the central research question from a different and necessary vantage point. This progression allows the investigation to build upon itself, moving systematically from the foundational theories that govern the field, to the practical realities of strategic implementation, to the global landscape of technological invention, and culminating in a rigorous test of economic impact. This architectural choice ensures that the final conclusions are robust, nuanced, and grounded in a rich, triangulated body of evidence.

The investigation commences in the first chapter with a systematic mapping of the literature. To build new knowledge, one must first possess a precise map of the existing world. This chapter, therefore, moves beyond a conventional literature review to conduct a comprehensive bibliometric analysis of the scholarly domain where green technology, sustainability, and business strategy converge. This data-driven approach allows for a quantitative and visual rendering of the intellectual architecture of the field, revealing its foundational pillars, its most influential streams of thought, and the conceptual bridges that connect disparate areas of research. The primary purpose of this initial step is twofold: first, to establish a rigorous theoretical point of departure for the dissertation, and second, to identify with precision the uncharted territories, the critical gaps in understanding, and the unresolved questions that demand new empirical investigation. This chapter thus answers the foundational question: “What is the intellectual structure of this field, and where does the frontier of knowledge currently lie?”. It represents a synthesis of two peer-reviewed articles: “Green Light for Business Sustainability: a Bibliometric Analysis on the Integration of Green Technologies within Business Strategy”, published in *Sustainable Futures*, and “Seeds of Change: a Bibliometric Study on Sustainable Technologies and Business Strategies in Agriculture”, published in the *Journal of Infrastructure, Policy and Development*.

From this broad cartographic survey, the second chapter executes a strategic deep-dive, plunging from the high altitude of academic theory into the strategic empirical setting. It addresses the critical challenge of translating elegant concepts into workable instruments. Taking the principles of circularity and sustainable value creation identified in the first chapter, this section subjects them to the pressures of practical business model design. Through an intensive, explorative case study of a specific circular innovation, this chapter serves as a microcosm for the broader challenges of the green transition. Its core contribution is the development and application of a novel, multidimensional framework for strategic analysis, forged specifically to capture the unique economic, environmental, and social dynamics of circular ventures. This chapter provides the bridge between abstract knowledge and practical strategy, answering the question: “How can the theoretical imperatives of sustainability and circularity be forged into a robust, coherent, and viable business model?”. This chapter is a revised and extended version of the author’s peer-reviewed article, “Enhancing Circularity in Urban Waste Management: A Case Study on Biochar from Urban Pruning”, published in the journal *Environments*.

Having stress-tested a strategic design at the micro-level, the third chapter expands the aperture dramatically to conduct a panoramic survey of the inventive landscape at a global scale. If the previous chapter explored how a single sustainable enterprise could be designed, this chapter asks a different, larger question: what green agricultural technologies are actually being created across the world? Employing a large-scale analysis of patent data, this section functions as an empirical census of technological output. It moves beyond corporate pronouncements and policy ambitions to reveal the de facto innovation strategies of nations and firms as reflected in their codified inventions. This macro-level analysis charts the dominant technological trajectories, identifies the epicenters of inventive activity, and uncovers crucial patterns in the strategic protection and abandonment of intellectual property. It provides a data-driven answer to the question: “What is the tangible, inventive output of the global green agricultural engine, and what does it reveal about the true direction and momentum of the transition?”. The analysis presented here draws upon two distinct research efforts: it is primarily based on the manuscript titled “Green Patenting in Agriculture: China’s Rise and the Global Patent Landscape”, currently under the second round of review at *Innovation and Green Development*, and is further informed by a work in progress titled “Twin Transition in Agriculture: a Global Patent Analysis”.

The fourth and final chapter represents the culminating empirical test of the entire dissertation, addressing the ultimate “so what?” question that motivates the research. The preceding chapters established the theory, tested the practice, and mapped the inventive output. This final stage moves to the highest level of strategic inquiry: evaluation. It addresses the decisive question of whether these new technological paradigms create durable economic value. Shifting its methodology to the econometric analysis of a large, longitudinal panel of innovative European firms, this chapter rigorously measures the impact of different innovation strategies on firm performance. It is here that the central hypothesis of the work is formally tested: that a synergistic integration of green and digital technologies within a “Twin Transition” framework provides a source of competitive advantage that is not only superior but also more sustained over time. This chapter seeks to deliver a conclusive, data-driven verdict, moving beyond correlation to assess the economic returns of a strategy, thereby answering the question: “In the competitive reality of the market, which innovation pathway pays?”. The empirical work in this chapter is based on the working paper titled “Twin Transition as Driver of Firms’ Competitiveness: Evidence from the European Agricultural Sector”, which is currently in preparation for submission to a peer-reviewed journal.

Finally, regarding the dissemination of this research, the journals selected for the publication of the initial chapters were strategically chosen to align with the specific focus of each study. Sustainable Futures (Elsevier) was selected for the theoretical framework in Chapter 1 because of its emphasis on forward-looking sustainability research and interdisciplinary business strategies. The Journal of Infrastructure, Policy and Development (EnPress) was chosen for the agricultural insights within Chapter 1 due to its focus on the intersection of development policy and sector-specific infrastructure. Environments (MDPI) was selected for the applied case study in Chapter 2 to align with its technical scope on environmental systems and circular economy applications. The remaining chapters represent ongoing research currently prepared as working papers for submission to specialized venues in innovation economics.

Together, this deliberate progression, from intellectual cartography to strategic design, from a panoramic survey of technology to a definitive test of its economic value, constructs a comprehensive and escalating argument. It is through this multi-layered inquiry that the dissertation aims to provide a rich and robust answer to the overarching challenge of how to effectively understand, strategize for, and steer the green transition in the modern agri-food sector.

CHAPTER 1 – SUSTAINABLE BUSINESS MODEL THEORETICAL FRAMEWORK

The transition to a sustainable agri-tech sector is not a linear path but is shaped by the convergence of technological innovation, strategic business decisions, and shifting policy landscapes. To navigate this complexity, any investigation must first build on a solid theoretical foundation. Before examining specific technologies or market dynamics, it is therefore essential to map the existing academic terrain. The following chapter begins this journey by charting the intellectual structure of the field, providing a comprehensive framework that will ground the empirical analyses to come.

Abstract

This chapter addresses the growing need to integrate green technologies into business strategies by mapping the intellectual structure of the research field. Through a comprehensive bibliometric analysis of 951 academic articles from the Web of Science database, the study employs co-citation, bibliographic coupling, and keyword co-occurrence analyses. The results highlight a clear evolution of the field, shifting from foundational theoretical frameworks, such as Porter's Hypothesis, towards more applied, interdisciplinary, and policy-oriented research. A significant surge in publications is observed after 2015, driven largely by China's scientific output. The analysis also reveals a disconnect between established theoretical pillars and emerging research frontiers, suggesting a field in full transition. This "intellectual cartography" establishes a rigorous point of departure for the thesis, identifying key knowledge gaps and confirming the need to investigate the practical feasibility and economic impact of sustainable business models.

1.1. Introduction

Amidst escalating climate challenges, the imperative for businesses to transition towards sustainable practices has never been more critical. Drawing upon recent studies, such as the exploration of corporate green competitive advantage through green technology adoption and dynamic capabilities (Zhu et al., 2023), the role of corporate social responsibility in fostering green technology innovation (Chen & Jin., 2023), and the delineation of emerging green technologies and business models for sustainability (Islam, 2023), our study underscores the profound impact of green technologies on business innovation, offering a compelling narrative for the integration of sustainable processes into core business strategies.

Green technologies and business strategy are crucial components in driving sustainability and innovation within organizations. Green technologies encompass practices such as energy efficiency and sustainable site planning, aimed at reducing environmental impact and fostering economic growth Qiu et al. (2021). Integrating green technologies into business strategies not only promotes environmental sustainability but also influences competitive advantage and value creation (Zhao & Pan, 2021). Recent studies have investigated the characteristics and evolution of business models for green buildings, emphasizing the importance of incentives and economics in driving green initiatives (Lindgren et al., 2021). Furthermore, the concept of green business model innovation has gained traction, highlighting the need for dynamic measurement tools to assess green practices in real time (Bocken et al., 2018). The impact of green innovation on business sustainability has been a focal point, with research indicating the positive correlation between green practices and economic viability, particularly in energy-intensive industries (Li et al., 2020). Additionally, the role of green intellectual capital and absorptive capacity in shaping green business strategies has been explored, emphasizing the importance of structural equation modeling and moderated mediation in understanding these dynamics (Islam, 2023). The evolving landscape of green strategy research underscores the increasing social awareness and support for sustainable practices, indicating a shift towards greener business models and operations (Şener & Artar, 2024). These recent studies collectively emphasize the significance of integrating green technologies into business strategies to achieve sustainable success, competitive advantage, and environmental responsibility in the modern business environment.

Although bibliometric analyses abound in the fields of environmental science and business management separately, e.g. focusing in the first case on green energy (Qin et al., 2022; Tan et al., 2021), as well as green technologies innovation considered under multiple contexts and regulators (Li et al., 2022; Niknejad et al., 2023), and instead, on the economic side, concentrating on key concepts such as the business model (Belussi et al., 2019) and its implementation of sustainability (Pan et al., 2023; Goyal et al. 2021), To the best of our knowledge, few studies have synthesized this comprehensive body of work into a unified academic framework, analyzing the interaction between these fields.

This paper distinguishes itself by offering a comprehensive bibliometric analysis that bridges a critical gap in understanding the intersection of sustainability and business strategy through green technologies. While Dewi et al. (2022) attempted a bibliometric analysis regarding the relationship between “green technologies” (et similia) and “business”, their focus remained limited to the analysis and trends of mere keywords, without exploring additional aspects that could have provided a more rounded and complete bibliometric analysis. In contrast, what sets this study apart is its integration of numerical bibliometric measures with qualitative insights, offering a holistic view of how sustainability and business strategy intersect. Moreover, the research extends beyond academic discourse to provide insights for policymakers and business leaders, making it a critical resource for aligning environmental sustainability with economic growth. This multidimensional approach, spanning three decades of research, is unprecedented in existing literature and fills a critical gap in understanding the transformative role of green technologies in business innovation. To enrich this broad analysis, this chapter will also draw upon insights from a parallel, focused bibliometric study on the agricultural sector (Pavesi et al., 2024). This “sector spotlight” will serve to illustrate how general trends and strategic frameworks manifest within a critical real-world context. Accordingly, this study aims to explore the intersection of sustainability with strategic business practices, offering recommendations for aligning environmental sustainability with economic growth.

In the next section, we detail the methodologies applied for data analysis. Following this, we present our key findings, providing a detailed review of the examined articles, their references, and a visual representation of co-citation, bibliographic coupling, and keyword co-occurrence analyses. Subsequent discussions focus on the significant results of our study. The concluding part highlights the implications of our findings, outlines the limitations of our research, and suggests directions for future investigation into sustainable green technologies in the context of business models and strategies.

1.2. Literature Review

The integration of green technologies within business strategies has been extensively analyzed from multiple perspectives, with scholars investigating regulatory influences, economic drivers, and innovation dynamics.

One of the earliest discussions on the intersection of environmental regulation and business competitiveness was introduced by Porter (1991), who argued that well-designed environmental policies could enhance innovation and improve firms' long-term competitiveness. This perspective, later refined by Porter and van der Linde (1995), challenged the conventional view that environmental regulations impose a cost burden on businesses. Subsequent empirical studies have provided mixed evidence, with some confirming the innovation-stimulating effects of regulation (Ambec & Lanoie, 2008) while others highlight sectoral differences in regulatory impact (Jaffe et al., 1995). The role of green innovation in shaping business performance has been another focal point of research. Rennings (2000) introduced the concept of eco-innovation, distinguishing between regulatory-driven and market-driven sustainability transformations. Later studies, such as Horbach et al. (2012), emphasized the influence of firm-specific capabilities in successfully integrating green technologies into business models. More recently, research has examined the strategic implications of circular economy principles, demonstrating that companies adopting resource-efficient practices often achieve cost reductions and competitive advantages (Geissdoerfer et al., 2017). Economic and policy drivers play a crucial role in facilitating the adoption of green technologies. Market-based incentives, including carbon pricing and green subsidies, have been widely studied for their effectiveness in promoting sustainable investments (Borghesi et al., 2015). Public-private partnerships have also emerged as a critical mechanism in advancing green R&D and scaling up sustainable innovations (Carley & Konisky, 2020). However, several studies highlight persistent barriers to green technology adoption, including high initial costs, consumer resistance, and regulatory uncertainty (Kiefer et al., 2019).

Another emerging area of interest is the role of knowledge management in green business models. Research on green intellectual capital has demonstrated how firms leveraging sustainability-oriented knowledge assets tend to outperform competitors in innovation efficiency and environmental impact mitigation (Chen, 2008). The concept of absorptive capacity, originally introduced by Cohen and Levinthal (1990), has also been applied to sustainability research, emphasizing how firms' ability to integrate external green knowledge directly influences their technological transformation (Del Río González, 2009). As the digital economy advances, scholars have begun exploring the interplay between artificial intelligence, big data, and green technology adoption, identifying new frontiers for sustainable business strategy (Wang et al., 2022). From a business management perspective, strategic tools have also evolved to accommodate sustainability-driven innovation. Amit and Zott (2010) laid the foundation for business model theory, focusing on value creation through inter-firm networks and strategic resources. Over time, business model frameworks have expanded to incorporate environmental and social dimensions, with scholars developing approaches like the Triple Layered Business Model Canvas (Joyce & Paquin, 2016), the Eco-Canvas (Daou et al., 2020), and the Circular Triple Layered Business Model Canvas (Pavesi et al., 2024). These tools integrate economic, environmental, and social considerations, allowing firms to design more sustainable business models. The shift towards such frameworks reflects the growing recognition that long-term competitiveness increasingly depends on sustainable value creation rather than short-term financial gains.

In summary, the existing literature highlights a dynamic and evolving relationship between green technologies and business strategy, shaped by regulatory frameworks, economic incentives, and organizational capabilities. However, despite the extensive body of research, a comprehensive, data-driven perspective on how these elements interact over time remains limited.

This study builds upon these foundations by offering a bibliometric analysis that systematically maps global research trends, thematic developments, and collaborative networks within this interdisciplinary field. By leveraging bibliometric techniques, this study systematically maps global research trends, thematic developments, and collaborative networks within this interdisciplinary field. This approach allows for the identification of key knowledge clusters, research gaps, and emerging trajectories, offering both scholars and practitioners a structured understanding of how green technologies integrate into business strategies over time.

1.3. Methodology

1.3.1. Search Strategy

Selecting an appropriate database is crucial for conducting dependable bibliographic analysis. Clarivate Web of Science (WoS), considered the “gold standard”, has been widely used for evaluating academic performance and ranking universities (Harzing & Alakangas, 2016). Elsevier’s Scopus and Google Scholar (GS) have gained popularity as alternatives, with Scopus being a well-established competitor since 2004 (ibid.). Although Scopus offers broader coverage in terms of absolute document counts, Web of Science was maintained as the primary database because it has been widely recognized as a superior tool for rigorous bibliometric analysis. It represents the oldest scholarly database (Birkle et al. 2020), hosting more than 74.8 million records and 1.5 billion references across 254 subject disciplines (Singh et al. 2021). Crucially for this study, WoS is proven to be more precise in uniforming references compared to other databases (Aria & Cuccurullo, 2017). In addition to that, the citation analysis offered by Web of Science provides superior visuals and more in-depth details compared to that of Scopus (Falagas, Pitsouni, et al. 2008). Furthermore, WoS employs a more rigorous selection process for its indexed journals, ensuring the high quality of the publications included in the analysis (Leydesdorff et al., 2013). In contrast, alternatives like Google Scholar, while having a broader coverage, cannot filter out low-quality publications and grey literature, which can potentially skew the results of a bibliometric analysis (Delgado-López-Cózar et al., 2014). Therefore, for a more comprehensive, accurate, and quality-controlled bibliometric analysis, WoS was eventually adopted.

To maintain the quality of the publication sample, articles were retrieved from the Wos “Core Collection” spanning the period 1990 to 2023. WoS has been widely employed in scientometrics research, and the primary bibliometric analysis software is designed for its use (e.g. Fiala & Tutoky, 2017; Gurzki & Woisetschläger, 2017). The chosen time frame for this research, traversing from the 1990s to the present, is justified by the emergence of green growth and the convergence between green technologies and businesses during this period. As Hart (1997) emphasizes, the 1990s marked the beginning of businesses incorporating sustainability into their strategies, moving beyond mere compliance, and adopting innovative practices for long-term sustainability. Examining this period allows the research to capture the critical juncture at which the prioritization of green growth and the evolution of green technologies unfolded, offering valuable insights into the dynamics and impact of this transformative era.

The keywords used for the search through the WoS “Core Collection” were (“green* tech*” OR “clean* tech*” OR “sustain* tech*”) AND (“strateg*” OR “business* model*”) in the topic (title, abstract, and keywords). The selected keywords were deliberate in their choice, aiming to encompass the broader landscape of emerging sustainable technologies. On the technology side, by incorporating variations of these terms (green, clean, and sustainable), the search sought to encompass a comprehensive body of literature, since, as pointed out by Ebrahim (2020), while different terminology is utilized, each refers to innovative technological solutions for environmental issues. Furthermore, the keywords were specifically chosen to link the technology side with the business side of green technologies: the choice of "business model" and "strategy" as keywords for our analysis stems from the understanding that, as Mignol & Bankel (2022) highlighted, integrating sustainable technologies into businesses is fundamentally a strategic innovation challenge. This approach acknowledges that achieving sustainability is not just about adopting new technologies but about redefining how businesses operate and compete. The interrelation between business models and strategic planning is crucial for firms aiming to embed sustainability into their core operations. Eventually, this focused approach facilitated the retrieval of pertinent academic literature that focuses on the interconnection between sustainable technologies, business models, and strategies, thereby furnishing valuable insights for scholarly inquiry. To strengthen a specific emphasis, the research was limited to the "Web of Science Categories" of "Economics", "Management", "Business", and "Environmental Sciences", as concentrating the search within these domains ensures a targeted exploration of scholarly literature directly relevant to the scope of the study. Finally, as already mentioned, the selected time frame ranged from 01-01-1990 to 31-12-2023, resulting in a final sample of 951 papers, authored by 3053 distinct scholars. These papers were disseminated across a broad array of 250 unique academic journals or sources. For co-citation analysis, it is critical to underscore that the referenced literature is not strictly confined to the time frame of 1990-2023 but can draw from publications of any year. The chosen sample only includes academic papers that are written in English, as it is often argued that focusing solely on English-written papers is crucial for the effectiveness of bibliometric analysis (Kabil et al., 2021; Guo, 2022; Pranckutė, 2021).

1.3.2. Data Analysis

In conducting our thorough bibliometric study, the utilization of R and RStudio proved to be crucial. R, a widely used software environment for statistical computing and graphics, provided a robust set of techniques and graphical methods essential for data analysis and visualization (Hevner et al., 2004). Complementing R, RStudio served as an integrated development environment (IDE) that enhanced the user experience by offering features like syntax highlighting, debugging tools, and workspace management, thereby streamlining the coding process and improving workflow efficiency (Aria & Cuccurullo, 2017). For the specific needs of the bibliometric study, the researchers employed the Bibliometrix R package within RStudio. Bibliometrix, designed for comprehensive science mapping analysis, equipped the researchers with a suite of functions tailored for quantitatively analyzing bibliometric data (Linnenluecke et al., 2019). This integration of R's computational capabilities and RStudio's user-friendly interface facilitated the efficient execution of the bibliometric study, enabling in-depth analysis and visualization of the data. By leveraging these tools within the R environment, the researchers were able to navigate into the intricacies of bibliometric analysis, benefiting from the advanced statistical computing features of R and the enhanced coding environment provided by RStudio. This approach not only streamlined the data manipulation and calculation processes but also facilitated the graphical representation of the findings, contributing to a more thorough and insightful bibliometric study.

A notable enhancement in our analysis process was facilitated by Biblioshiny, a user-friendly web interface for the Bibliometrix R-package. This tool significantly streamlined the data cleaning phase, allowing for an efficient exclusion of documents that did not meet our quality criteria. Specifically, Biblioshiny enabled the removal of 26 documents due to missing DOIs and an additional 3 for lack of abstracts. This cleansing ensured the final dataset, now composed of 922 papers, was robust and reliable for further analysis (Aria & Cuccurullo, 2017). Beyond data cleaning, Biblioshiny was extensively used for the descriptive analysis of the sample, providing insights into publication trends, most prolific authors, institutions, and countries, thereby setting a solid foundation for the detailed examination of the bibliometric landscape. Specifically, for the network visualization in VOSviewer, the parameters were set to ensure clarity and relevance. We applied the Association Strength method for normalization to accurately reflect the relatedness of items. To filter out less significant connections and ensure a readable map, a minimum cluster size of 5 items was established. Furthermore, the network layout was optimized using the LinLog/modularity normalization settings to clearly distinguish between the identified thematic clusters.

Simultaneously, VOSviewer plays a crucial role in the construction and visualization of bibliometric maps. This software specializes in the visualization of bibliometric networks, and clustering papers based on measures such as bibliographic coupling, co-citation counts, and keyword co-occurrence. These methods are in line with the established methodology for bibliometric analysis and offer a deeper understanding of the thematic structures within the dataset (Boyack & Klavans, 2010). The use of VOSviewer for the creation and visualization of bibliographic coupling, co-citation, and keyword co-occurrence networks further enriches our study by illuminating the interconnectedness and thematic focus of the research landscape.

1.3.3. Method of Analysis

Bibliometric tools offer a quantitative analysis of academic literature, presenting a map of discipline-specific trends and relationships (Appio et al., 2014; Holton, 2000). Three main techniques are used: direct citations, co-citation analysis, and bibliographic coupling, each offering different views of document relationships (Boyack & Klavans, 2010; Sandström, 2009). Bibliographic coupling and co-citation analysis, which focus on joint citations and commonly cited references respectively, are believed to be more accurate than direct citations (Garfield, 1988). While co-citation analysis helps to identify the discipline's key concepts, methods, and experiments (Small, 1999), bibliographic coupling is increasingly used for its utility in studying emerging fields (Boyack & Klavans, 2010; Vogel & Güttel, 2013). In contrast to co-citation's retrospective view, bibliographic coupling offers a more forward-looking perspective. The study also incorporated a co-occurrence analysis of keywords, as described by Sedighi (2016), to better understand the thematic structure of a research field and identify interconnected concepts or trends (Van Eck & Waltman, 2010). In addition to this broad-spectrum analysis, a targeted bibliometric review of the agricultural sector was conducted using a similar methodology (Pavesi et al., 2024). The findings from this sector-specific study will be integrated as illustrative examples in the Results and Discussion sections to provide practical depth and context to the broader findings. Figure 1.1 provides a graphical representation and summary of the methodology and criteria used in the preparation of the study

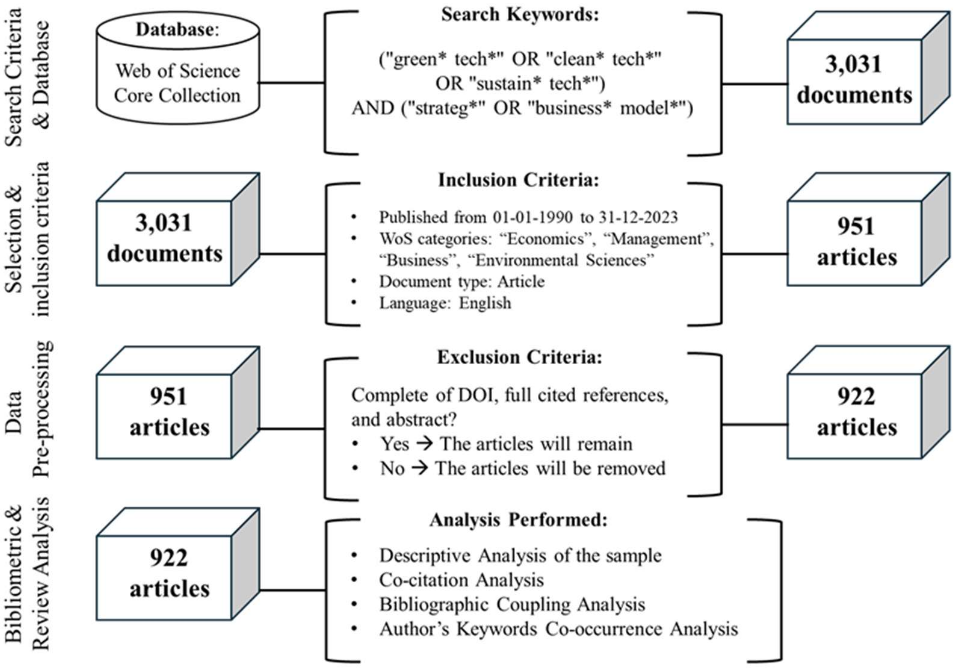

Figure 1.1 Methodological flowchart. Source: Author's elaboration.

1.4. Results

1.4.1. Descriptive Analysis of the Sample

The provided data indicates a growing trend in the number of publications over the years on the topics of green, clean, and sustainable technologies with business models or strategies. Figure 1.2 elucidates a notable uptick in interest beginning between 2015 and 2017, coinciding with the United Nations' ratification of the 2030 Agenda and its accompanying Sustainable Development Goals in 2015, as well as the enactment of the Paris Agreement in 2016. However, it is post-2018 that the publication trajectory markedly steepens, with each successive year outpacing the last, culminating in a zenith of 257 papers in 2023. The steep increase in the later years might be attributed to the intersection of multiple global developments: the 2030 Agenda invigorated the integration of business practices with sustainable development objectives (Walsh et al., 2022); and the Paris Agreement reinforced the urgency of decarbonization and climate action (Jakučionytė-Skodienė & Liobikienė, 2022); most relevantly, eventually, the COVID-19 pandemic prompted a re-evaluation of global economic resilience and sustainability (McNeely, 2021); Together, these factors have not only elevated the discourse on environmental and social responsibility but have also necessitated a profound scholarly focus on how green technologies can be woven into the fabric of business strategy, reflecting a paradigm shift towards prioritizing sustainability in the face of rapid environmental changes and societal expectations. Given this trend, we can anticipate that the focus on the intersection of sustainability and business strategy will continue to increase, driving further research and publications in the years to come.

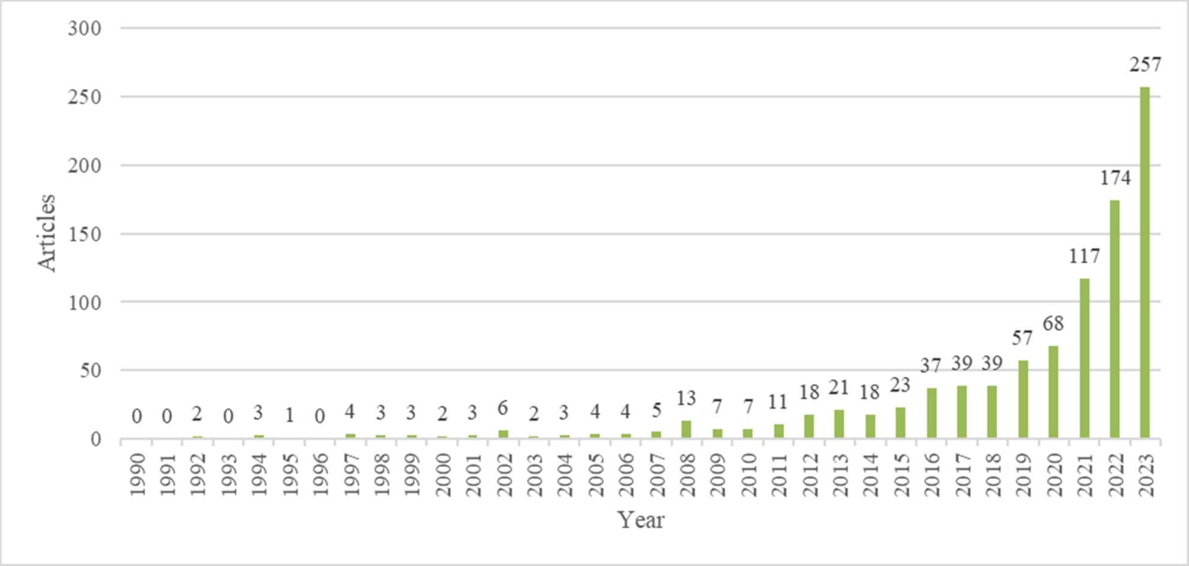

Figure 1.2 Annual Scientific Production. Source: Author's elaboration.

Table 1.1, on the other hand, displays the top 10 journals for the papers considered as the sample in this analysis. The landscape of academic journals pertaining to the integration of green technologies in business strategies showcases a remarkable scenario of interdisciplinary focus, underlined by a collective high-impact scholarly contribution. The Western-centrism of this ranking, merely based on the country of origin of the publisher, should not overcome the high internationality profile that characterizes each one of them. The diverse focus areas of these journals reflect the multifaceted nature of sustainability research, pointing to the importance of a holistic approach that integrates environmental, technological, social, and health perspectives. By taking a deeper look at these journals' aims and scopes, it is then possible to identify three main clusters:

1) Technical and Applied Sciences: Journals like "Sustainability", "Science of the Total Environment", and "Journal of Cleaner Production" focus on technical solutions and innovations in sustainability;

2) Environmental and Ecological Research: Journals such as "Environmental Science and Pollution Research" and "Frontiers in Environmental Science" emphasize ecological research and the study of environmental changes;

3) Business and Environmental Strategies: journals like "Journal of Environmental Management", "Environment Development and Sustainabilty", and "Business Strategy and the Environment" focus on the implementation of environmental sustainability practices, strategies, and policies within business operations and management;

Distinguished within this top ten list, two journals—"Technological Forecasting and Social Change" and the "International Journal of Environmental Research and Public Health", ranked 5th and 10th respectively—stand out for adding remarkable depth of interdisciplinarity and diversity to the field. As the former is dedicated to exploring the interrelations between social, environmental, and technological factors through the lens of technological forecasting and future studies, the latter is a transdisciplinary journal that focuses on health promotion and disease prevention within the context of environmental research. Their prominent standings, despite their distinct focuses, underscore their critical contributions and relevance to the field, particularly for what concerns the unique contribution of "Technological Forecasting and Social Change" lies in its forward-looking perspective, focusing on predicting and planning for future technological developments and their societal and environmental implications. This approach is crucial for integrating green technologies into business strategies, as it emphasises foresight and the anticipation of future trends.

Journals	Country	Publisher	IF 2022	Articles
Sustainability	CH	MDPI	3.9	138
Journal of Cleaner Production	NL	Elsevier	11.1	131
Environmental Science and Pollution Research	USA	Springer	5.8	74
Journal of Environmental Management	NL	Elsevier	8.7	24
Technological Forecasting and Social Change	NL	Elsevier	12	22
Business Strategy and The Environment	USA	Wiley	14.88	21
Frontiers in Environmental Science	CH	Frontiers	10.3	21
Science of the Total Environment	NL	Elsevier	9.8	19
Environment Development and Sustainability	USA	Springer	4.9	18
International Journal of Environmental Research and Public Health	CH	MDPI	4.53	17

Table 1.1 List of the top 10 Journals. Source: Author's elaboration.

Citations are often employed as a measure of the impact of works within a particular research domain. Table 1.2 provides a list of the ten most cited papers of the sample within the sample itself, ranked by their local citation count. The value of global citations, i.e. citations from the whole academic world, are reported as a contextual reference. The collection of the most cited papers on the integration of green technologies within business strategy spans a rich array of insights, theoretical frameworks, and empirical analyses, published across prestigious journals. The most recurring one is the "Journal of Cleaner Production", a leading international journal that focuses on sustainable development and environmental management practices. Nevertheless, it's important to emphasise that the top and bottom positions in this ranking are held by prestigious journals with a focus on business and strategy, namely "Technology Analysis & Strategic Management" and "Harvard Business Review". This underscores the critical role of strategic considerations in the successful integration of green technologies into business operations. By analysing these papers, it is possible to identify three main recurring thematics. The first one is the foundational theme that emerges through the theoretical and strategic frameworks proposed in seminal works by Kemp et al. (1998), Hart (1997), and Bohnsack et al. (2014). Kemp's introduction of strategic niche management offers a nuanced approach to managing the transitions towards sustainable technologies, highlighting the importance of protective spaces for innovation. Hart expands on this by delineating a comprehensive framework for sustainable development, charting the stages of environmental strategy, and

pinpointing business opportunities that arise from sustainable practices. Meanwhile, Bobhnsack concentrates on the evolution of business models within the electric vehicle sector, showcasing how path-dependent behaviors of firms significantly shape the trajectory of sustainable technology integration. If this first one focuses on strategy, the papers by Deng et al. (2019), Mishra et al. (2020), and Montalvo (2008) go deep into the nuanced relationship between policy, governance, and the economic ramifications of embracing green technologies. Deng's work utilizes game theory to dissect how political competition influences strategies for green technology innovation, presenting a unique intersection of politics and business strategy. Mishra's study sheds light on the effectiveness of carbon tax and cap policies, underlining their significant role in steering investments toward green technologies and reducing carbon emissions. Montalvo provides a comprehensive survey on the myriad factors that affect the adoption and diffusion of cleaner technologies, with a special focus on policy and its implications for economic growth. Eventually, the papers from Fernando et al. (2019), Luo et al. (2019), Sun et al. (2017), and Ma et al. (2021a) all collectively illustrate the importance of innovation in driving market dynamics and enhancing sustainability, explaining their high citation rates as essential resources for both researchers and practitioners aiming to leverage green technologies for sustainable business outcomes, particularly in Fernando's research which illuminates how service innovation serves as a crucial mediator between eco-innovation and business
governance, and the economic ramifications of embracing green technologies. Deng's work utilizes game theory to dissect how political competition influences strategies for green technology innovation, presenting a unique intersection of politics and business strategy. Mishra's study sheds light on the effectiveness of carbon tax and cap policies, underlining their significant role in steering investments toward green technologies and reducing carbon emissions. Montalvo provides a comprehensive survey on the myriad factors that affect the adoption and diffusion of cleaner technologies, with a special focus on policy and its implications for economic growth. Eventually, the papers from Fernando et al. (2019), Luo et al. (2019), Sun et al. (2017), and Ma et al. (2021a) all collectively illustrate the importance of innovation in driving market dynamics and enhancing sustainability, explaining their high citation rates as essential resources for both researchers and practitioners aiming to leverage green technologies for sustainable business outcomes, particularly in Fernando's research which illuminates how service innovation serves as a crucial mediator between eco-innovation and business
sustainability, suggesting that the integration of environmental considerations into service offerings can enhance corporate sustainability.

Title	Author(s)	Journal	Year	Local Citations	Global Citations
Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management	Kemp, R., Schot, J. & Hoogma, R.	Technology Analysis & Strategic Management	1998	18	1543
Optimal strategy for enterprises' green technology innovation from the perspective of political competition	Deng, Y., You, D., & Wang, J.	Journal of Cleaner Production	2019	15	74
Pursuing green growth in technology firms through the connections between environmental innovation and sustainable business performance: Does service capability matter?	Fernando, Y., Chiappetta Jabbour, C. J., & Wah, W.	Resources, Conservation and Recycling	2019	14	317
Efficiency evaluation of green technology innovation of China's strategic emerging industries: An empirical analysis based on Malmquist-data envelopment analysis index	Luo, Q., Miao, C., Sun, L., Meng, X., & Duan, M.	Journal of Cleaner Production	2019	12	147
Business models for sustainable technologies: Exploring business model evolution in the case of electric vehicles	Bohnsack, R., Pinkse, J., & Kolk, A.	Research Policy	2014	11	329
General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007	Montalvo, C.	Journal of Cleaner Production	2008	10	165
Ecological-economic efficiency evaluation of green technology innovation in strategic emerging industries based on entropy weighted TOPSIS method	Sun, L., Miao, C., & Yang, L.	Ecological Indicators	2017	10	196
A sustainable production-inventory model for a controllable carbon emissions rate under shortages	Mishra, U., Wu, J., & Sarkar, B.	Journal of Cleaner Production	2020	10	135
Top management team faultlines, green technology innovation and firm financial performance	Ma, Y., Zhang, Q., & Yin, Q.	Journal of Environmental Management	2021	10	75
Beyond Greening: Strategies for a Sustainable World	Hart, S. L.	Harvard Business Review	1997	9	788

Table 1.2 Top 10 Cited Papers. Source: Author's elaboration.

In concluding our descriptive analysis, a nuanced examination of the geographical spread within this rapidly evolving research domain reveals significant insights. The country collaboration map presented in Figure 1.3 delineates the extent of scholarly interactions across nations. Countries are shaded in progressively darker tones of blue to denote the frequency of their international collaborations, connected by red lines. A striking observation from this visual representation is the prominent position of China, indicated by its dark blue hue and extensive network of red lines signifying numerous partnerships. Notably, while a global discourse is evident, with participation from the majority of the world, certain regions such as South America, Greenland, some Eastern countries, and large swathes of the African continent, appear less engaged. This suggests a concentration of academic efforts and partnerships within specific areas of the world, as corroborated by the bilateral interactions concerning the integration of green technologies in business strategy. Predominantly, China emerges as a central node in this network, engaging with a diverse set of countries including the UK, USA, India, Korea, Pakistan, Australia, Malaysia, and Denmark. It is particularly noteworthy that China's sphere of influence extends beyond the traditional Western academic powerhouses, resonating also with Eastern nations: collaboration among such countries extends beyond simple geographic closeness, as it is underpinned by a complex dynamic of factors including shared economic goals, strategic regional initiatives like the "Belt and Road", similar environmental challenges, and the pursuit of sustainable development. Coherent policy directives among these nations further catalyze partnerships, indicating a collective prioritization of green technology within their economic strategies. Such partnerships suggest a deliberate regional approach to leverage combined expertise and innovation in advancing sustainable practices. This trend is emphatically reflected in the trajectory of research outputs as illustrated in Figure 1.4. Post-2020, China has witnessed an exponential surge in scholarly publications within this field, a testament to its central role and a clear indicator of its ascendance to a position of global leadership in green technology research, well aligned with its strategic objectives as outlined in the nation's 14th Five-Year Plan. Such a meteoric rise in academic productivity is a sign of a shifting paradigm, where China is not only actively shaping the field but also setting the pace and direction for future developments.

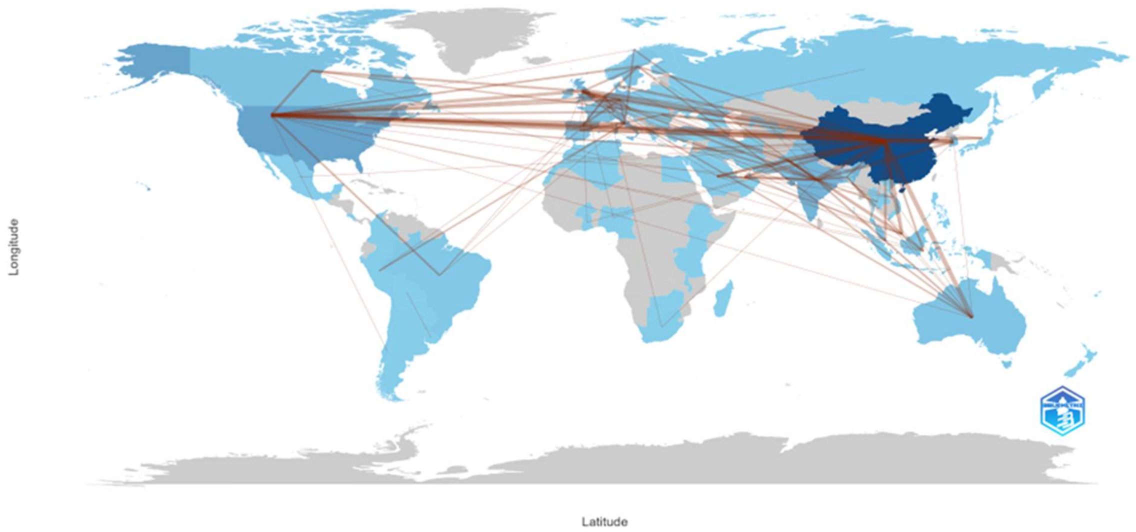

Figure 1.3 Country Collaboration Map. Source: Bibliometrix.

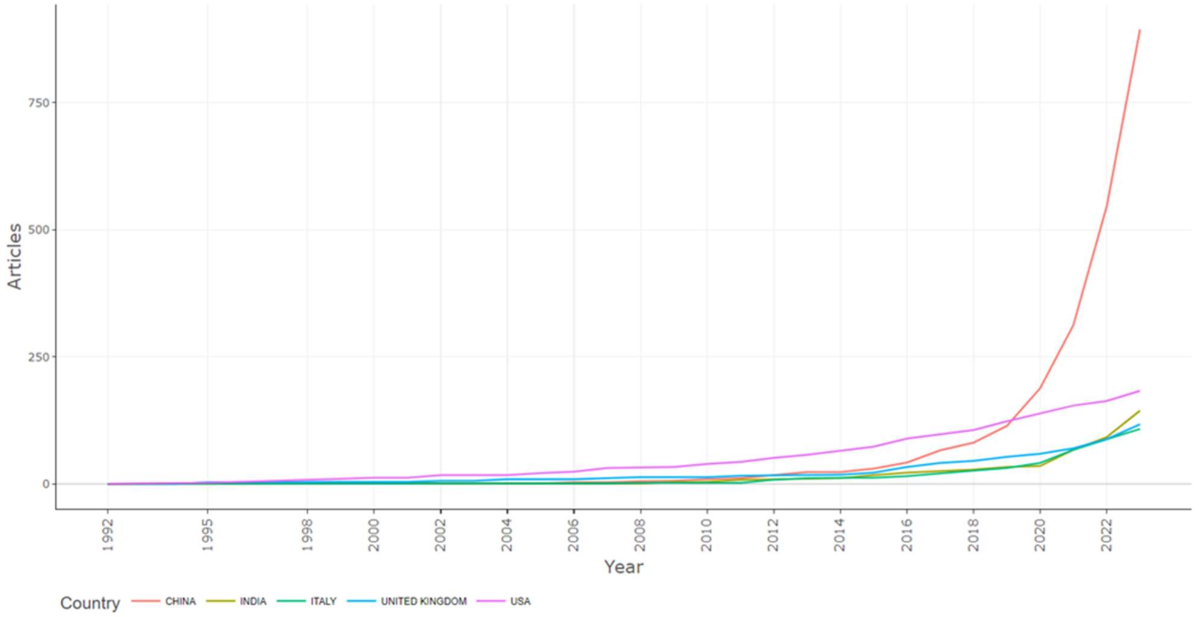

Figure 1.4 Top Countries' Production Over Time. Source: Bibliometrix.

1.4.2. The Co-Citation Network Analysis

As previously discussed, the utilization of co-citations, which refers to the pairing of two publications that are both cited by another paper and listed in the paper's references (Chen, 2006), can contribute to the comprehension of the fundamental concepts, methodologies, or the current state of advancement in a particular field. The examination of co-citations involves identifying the occurrences of joint references, in this work, within the collection of papers relevant to green technologies and business strategies, thereby enabling the identification and categorization of documents that may not have a direct connection to the field. This approach adopts a retrospective perspective and is commonly employed to ascertain the seminal works within a specific research domain. This study performs a document co-citation analysis of 51,383 valid references that have been cited by the 922 publications in this sample. Given the substantial number of references connected to the concept of the integration of green technologies within business strategies, the objective was to enhance the network's interpretability and concentrate on the core publications. Thus, to achieve a sample consisting of 138 valid references, we established a threshold that only includes papers with a minimum of 10 citations. This threshold represents an equitable citation count in consideration of the "greenness" of this subject matter and symbolises a just equilibrium between the contraction of information attributable to an excessive threshold. After further refinements of the sample, including the exclusion of 3 cited references for lack of data, and of 1 other for not having any connections within the network, the final sample consisted of 134 valid cited references.

The analysis of the co-citation network reveals the structural properties of both the network and the clusters. At the structural network level, the key network measures are density and modularity. Density is calculated as the ratio of existing links to all possible links within a subgroup, therefore, a maximum density is obtained when all nodes in a subgroup are linked to all other nodes in that group. As a bibliometric indicator, density reflects the extent to which various streams within a subfield of research pursue their agendas on common grounds. The network has a density of 0.27, which indicates that the network is moderately dense, with present connections among the documents (Vogel & Güttel, 2013). Determined by using an algorithm for community detection, the modularity index measures how well the network can be clustered into groups (Waltman & Van Eck, 2013). Within the network, the analysis identifies five main clusters: the modularity value obtained for the network stands at 0.46, signifying considerable interlinkages among all the documents included in the analysis (Wu et al., 2019). This value also underscores the substantial overlap among the five identified clusters. The moderate modularity score attests to the presence of noteworthy interconnectedness across all document clusters, rather than sharply distinct divisions.

Table 1.3 enumerates the association strength, label, size, and average publication year for each document cluster. Regarding the association strength, it is used for normalising the strength of the links between items; apart from a multiplicative constant, this method is identical to Eq. (6) in Van Eck and Waltman (2009). Subsequently, a comprehensive qualitative assessment of the content within these four distinct clusters is presented. To illustrate the evolution of the understudied research field, clusters are arranged chronologically, guided by the average publication year of the documents within each cluster. For length restrictions, only the first author will be reported.

Co-citation Cluster 1: Sustainable Supply Chains

This collection of studies converges on the critical examination of how collaborative strategies and innovative contract designs can promote environmental sustainability within supply chains, underscoring the complexity of aligning economic incentives with environmental objectives through strategic supply chain management. Krass et al. (2013) sets a foundational context by investigating the role of environmental taxes, fixed cost subsidies, and consumer rebates in motivating firms towards green technologies, highlighting the significant influence of regulatory policies on corporate sustainability decisions. This backdrop is crucial for understanding the dynamics that drive supply chain entities towards collaborative and innovative contractual arrangements. For instance, Hong & Guo (2019) and Ghosh & Shah (2015) explore the nuances of contract designs, such as green-marketing cost-sharing and two-part tariff contracts, and their potential to drive or deter the adoption of environmentally friendly practices. These studies highlight the centric role of contractual agreements in fostering cooperation among supply chain partners, thereby enhancing the environmental performance of the entire chain. Moreover, the interaction between consumer demand for green products and the effectiveness of supply chain coordination emerges as a significant theme. Liu et al. (2012) and Ghosh & Shaha (2012) provide insights into how increased consumer environmental consciousness not only influences the strategic decisions of individual firms but also catalyzes collaboration between manufacturers and retailers. This consumer-driven demand acts as a linchpin in encouraging supply chain entities to adopt greener operations, underscoring the importance of understanding market dynamics in the design of environmental strategies. The emphasis on collaboration extends to policy implications, where the interchange between governmental incentives and private sector strategies is scrutinized. Studies like those by Bi et al. (2017) and Cohen et al. (2016) investigate how government subsidies and regulations can be structured to complement supply chain initiatives, suggesting a synergistic approach to achieving sustainability goals.

Co-citation Cluster 2: Porter’s Hypothesis

Porter & Van der Linde (1995) lay the foundation by challenging the presumed trade-off between environmental regulation and competitiveness, advocating for environmental standards that spur innovation and enhance resource productivity. This premise is echoed and expanded upon by Rennings (2000), who introduces eco-innovation as a multifaceted concept encompassing technological, social, and institutional changes, driven in part by regulatory mechanisms. The notion of regulatory influence is further substantiated by Xie et al. (2019) and Du et al. (2021), who explore the positive dynamics between green technology innovation and financial performance within firms, highlighting the role of environmental regulation as a significant driver. Moreover, publications in this cluster highlight the critical role of financial and institutional frameworks in supporting eco-innovation. Lv et al. (2021) identify the nuanced effects of financial development on green technology innovation, emphasizing the mediating and moderating roles of environmental regulation and innovation output. This complexity is further illustrated by Cai (2020), who observes the significant incentive effect of direct environmental regulations on green technology innovations within heavily polluting industries, suggesting a nuanced interaction between policy, ownership, and industry type. Du et al. (2019) fits here by expanding the discussion on how the impact of green technology innovations on CO2 emissions varies across economies with different income levels, adding a crucial layer to understanding the environmental and economic interplay of green technology. The empirical investigations by Jaffe & Palmer (1997) and Horbach (2008) provide evidence supporting the positive impact of environmental regulation on R&D expenditures and the encouragement of environmental innovations, aligning with the Porter hypothesis. Acemoglu et al. (2012) introduce a theoretical model to demonstrate how directed technical change towards “clean” inputs, facilitated by policy interventions, can achieve sustainable growth, which is a critical consideration for achieving long-term environmental and economic objectives.

Co-citation Cluster 3: Strategic Green Integration

A common theme across this third cluster is the recognition of the complexity and diverse nature of driving sustainable innovation within and across industries. Boons & Lüdeke-Freund (2013) and Bocken (2014) both emphasize the necessity of integrating sustainable business models that encompass a triple-bottom-line approach, addressing environmental, social, and economic dimensions. This perspective is reinforced by Hockerts & Wüstenhagen (2010) who discuss the interaction between new entrants and incumbents in fostering industry-wide sustainability transformation, highlighting the roles of both ‘Emerging Davids’ and ‘Greening Goliaths’. Cohen & Levinthal (1990) introduce the concept of absorptive capacity, which is critical for firms’ innovative capabilities and their ability to adapt and apply new, external information for commercial ends. This idea of absorptive capacity is echoed in the discussions by Schaltegger et al. (2012) and Teece (2010) about the importance of business model innovation and the architecture of value creation, delivery, and capture in supporting sustainable practices and innovations. The challenge of transitioning to sustainable technologies and overcoming market penetration barriers is a focal point in the work by Bohnsack et al. (2014) and Kemp et al. (1998), who both address the need for strategic approaches in managing technological regimes and niches to expedite sustainable development. Similarly, Hekkert et al. (2007) propose a framework focusing on the functions of innovation systems to better understand and facilitate technological change towards sustainability.

Co-citation Cluster 4: Holistic Sustainability

Hart (1995) lays the foundational premise by introducing a natural-resource-based view of the firm, emphasizing pollution prevention, product stewardship, and sustainable development as key strategies for leveraging the natural environment for competitive advantage. This view is echoed by Chen et al. (2006), who find a positive correlation between green innovation (both product and process) and competitive advantage, arguing for the strategic importance of green innovation investment. Sharma & Vredenburg (1998) extend this discussion to the impact of green marketing orientations on SME performance, highlighting the importance of both tactical and strategic approaches to green marketing in enhancing firm and environmental performance. Barney (1991) and Teece et al. (1997) contribute to this discourse by examining the role of firm resources and dynamic capabilities, respectively, in sustaining competitive advantage, suggesting that environmental sustainability can be a strategic resource or capability in rapidly changing technological environments. Fornell & Larcker (1981) and Podsakoff et al. (2003) provide methodological insights, the former cautioning against the pitfalls of common statistical tests in structural equation modeling, and the latter discussing the influence of method biases in behavioral research, indirectly underscoring the complexity of measuring and interpreting the impacts of green strategies on firm performance. Porter & Van der Linde (1995a) introduces a paradigm shift, arguing that environmental regulation, contrary to being a hindrance, can spur innovation and enhance competitiveness. Berrone et al. (2013) and Russo & Fotus (1997) both highlight the positive linkage between environmental performance and economic performance, with the former emphasizing the role of regulatory and normative pressures in fostering environmental innovation, particularly in firms with significant pollution relative to their peers.

Documents in cluster and association strength (in parentheses)	Label	Description	Cluster number	Size	Year (avg.)
Krass (2013), (127); Xu (2017), (73); Drake (2016), (70); Hong (2019), (64); Liu (2012), (64); Ghosh (2015), (63); Bi (2017), (60); Cohen (2016), (60); Ghosh (2012), (58); Benjaafar (2013), (56); Swami (2013), (56); Yang (2021), (56); Dong (2016), (53); Yalabik (2011), (51); Chen (2019), (48); Bian (2020), (47); Chen (2001), (47); Xu (2016), (44); Zhu (2017), (42); Toptal (2014), (41); Yang (2018), (34); Mishra (2020), (33)	Sustainable Supply Chains	Cluster 1 explores the impact of collaborative strategies and contract designs on enhancing environmental sustainability within green supply chains.	1	22	2015
Porter (1995), (305); Rennings (2000), (180); Xie (2019), (144); Du (2021), (134); Lv (2021), (115); Baron (1986), (109); Jaffe (1997), (108); Acemoglu (2012), (104); Cai (2020), (103); Horbach (2008), (93); Fernando (2019), (84); Du (2019), (80); Li (2017), (80); Zhang (2019), (77); Ambec (2013), (75); Porter (1991), (75); Singh (2020), (75); Horbach (2012), (72); Rubashkina (2015), (72); Jaffe (2005), (71); Popp (2006), (71); Deng (2019), (69); De Marchi (2012), (67); Cai (2018), (65); Kraus (2020), (62); Brunnermeier (2003), (60); Kunapatarawong (2016), (60); Song (2020), (58); Du (2019), (57); Miao (2017), (57); Ma (2021), (53); Sun (2017), (51); Xu (2021), (51); Hambrick (1984), (50); Bai (2019), (48); Yu (2021), (48); Jaffe (2002), (46); Acemoglu (2016), (45); Li (2018), (45); Yuan (2018), (45); Luo (2021), (42); Luo (2019), (41); Wang (2019), (40); Braun (1994), (38); Wang (2021), (36); Arellano (1991), (30); Wu (2020), (27); Cao (2021), (26); Charnes (1978), (14); Field (2014), (11); Grossman (1995), (5)	Porter's Hypothesis	Cluster 2 investigates the dynamic relationship between environmental regulation, eco-innovation, and economic performance, highlighting the critical role of policy in fostering sustainable development and green technology advancements.	2	51	2012
Boons (2013), (108); Cohen (1990), (101); Hockerts (2010), (99); Schaltegger (2012), (89); Eisenhardt (1989), (87); Teece (1986), (84); Bocken (2014), (83); Teece (2010), (82); Geels (2002), (78); Bohnsack (2014), (77); Kemp (1998), (75); Schaltegger (2016), (74); Stubbs (2008), (74); Boons (2013), (72); Chesbrough (2002), (71); Eisenhardt (2007), (70); Geels (2007), (70); Zott (2011), (70); Christensen (2013), (65); Chesbrough (2010), (61); Nelson (1982), (53); Gioia (2013), (51); Hekkert (2007), (50); Markard (2012), (50); Schot (2008), (50); Bergek (2008), (49); Unruh (2000), (41); Cohen (2007), (35); Stern (2008), (8); Pesaran (2001), (4); Hoel (2010), (3)	Strategic Green Integration	Cluster 3 studies the interplay between business model innovation, organizational absorptive capacity, and strategic management for sustainable technological transitions.	3	31	2006
Hart (1995), (186); Chen (2006), (144); Sharma (1998), (137); Barney (1991), (136); Fornell (1981), (122); Porter (1995), (109); Berrone (2013), (103); Russo (1997), (100); Podsakoff (2003), (98); Teece (1997), (98); Chen (2008), (89); Aragón-Correa (2003), (83); Klassen (1999), (82); Shrivastava (1995), (82); Hair (2010), (81); Podsakoff (1986), (74); Teece (2007), (74); Chiou (2011), (72); Hart (2011), (71); Schiederig (2012), (69); Wernerfelt (1984), (68); Hart (2003), (67); Pujari (2006), (64); Dangelico (2016), (60); Armstrong (1977), (52); Hart (1996), (51); Dimaggio (2000), (42); Montalvo (2008), (41); Suchman (1995), (32); Ajzen (1991), (22)	Holistic Sustainability	Cluster 4 highlights the shift in strategic management from treating environmental sustainability as an external factor to a core component of competitive advantage.	4	30	2000

Table 1.3 Overview of Co-citation Clusters. Source: Author's elaboration.

1.4.3. Bibliographic Coupling Network Analysis

Diverging from co-citation analysis, bibliographic coupling employs a prospective viewpoint, concentrating on emerging trends and research areas within the literature, selected by authors with similar bibliographies. In this method, documents are interconnected through their mutual citations. Notably, bibliographic coupling's focus lies not on the cited papers themselves, but on the nascent sub-fields within the broader scholarly discourse. This investigation utilizes a bibliographic analysis of 922 documents that are referenced by the green technologies in companies' strategies publications included in this sample, facilitating the identification of salient publications and the assembly of articles into distinguished clusters. Considering the extensive array of documents associated with the field under study, criteria were established to enhance network interpretability and highlight key publications, thus stipulating a minimum of 30 citations per paper. This approach yielded 224 applicable publications. Like the methodology employed in co-citation analysis, a threshold of 30 citations represents an optimal equilibrium between information reduction due to an excessively high cut-off and a steep decline in the modularity index for a cut-off of less than 30. Following further refinements, i.e. excluding the documents that did not show any connections within the network, the final sample consisted of 198 papers. Table 4 delineates the documents within each cluster, alongside their coupling association strength, labels, and descriptive factors such as cluster size and average publication year. The bibliographic network provided by VOSviewer exhibits a density of 0.1, which denotes a lower-than-moderate degree of interconnection within the network (Vogel & Güttel, 2013) whereas the modularity index of the 11 clusters that the bibliometric software identified is 0.42, indicating relatively considerable interlinkages among all the documents included in the analysis (Wu et al., 2019). Out of the ten clusters that emerged from VosViewer, however, two will not be considered in the following discussion due to their relative significance within the sample, being both are composed of fewer than 10 papers each, which appeared to be poorly related to a first abstract screening. Eventually, one last cluster, composed of 2 papers only, rather than being excluded, was merged with another one having the same focus (cluster 5). The remaining 7 remained clusters are arranged in a time-sequential manner, dictated by the average publication year of the documents contained within each cluster. The reference to individual cluster members can be found in Table 1.4. For length restrictions, only the first author will be reported.

Bibliographic Coupling Cluster 1: China's Leading Role

A common theme across these studies is exploring how green technology innovation, environmental regulation, and the role of cultural and societal factors can help drive economic growth while mitigating environmental impact. Xie & Teo (2022) addresses the role of green technology innovation in facilitating cleaner industrial upgrading within China, highlighting the complex effects of environmental regulation on such processes. Similarly, Yang et al. (2021) and Li et al. (2023) study the dynamics of green innovation ecosystems and the positive effects of new media and environmental regulations on corporate green technology innovation. Costantini et al. (2017) and Fernandes et al. (2021) broaden the scope by examining the diffusion pathways of green technologies and their impacts on sectoral environmental performance and green growth's contribution to economic growth, respectively. These studies underscore the interconnectedness of eco-innovations along the supply value chain and the central role of sustainable technology transfer in promoting economic sustainability. Orlando et al. (2022) and Lian (2022) offer insights into the cultural and policy dimensions influencing green technology management and innovation, with the former highlighting the significance of societal culture and government investments in eco-innovation, and the latter examining the nuanced effects of environmental regulation on substantive versus symbolic green innovation.

Tang et al. (2021), Zhou & Wang (2022), and Zhou & Du (2021) present analyses of the infrastructure and policy mechanisms that foster green technology innovation, including telecommunications infrastructure, carbon emissions trading schemes, and the interplay between financial development and environmental regulations. These studies collectively suggest that strategic investments in green technology and supportive policy frameworks are essential for enhancing environmental and economic outcomes. Xu et al. (2023) and Ikram et al. (2022) focus on the role of green finance policies and strategic planning in advancing green technology innovation, with Xu evaluating the action points of China's Green Finance Pilot Policy. Lastly, Yang (2022) explores the impact of manufacturing intelligence on green innovation performance, indicating the potential of digital transformation to bolster environmental sustainability efforts.

Bibliographic Coupling Cluster 2: Reducing CO2 emission

This second cluster revolves around the exploration of strategies for reducing carbon emissions through the adoption of green technologies and the implementation of carbon tax, cap-and-trade policies, and other regulatory mechanisms. Notably, the research emphasizes the significance of co-opetition (Luo et al., 2016), sustainable economic production models (Mishra et al., 2020; Mishra et al., 2021a), and strategic investments in green technologies (Mashud et al., 2021a; Mashud et al., 2021b; Ma et al., 2021b; Lu et al., 2020) as essential elements in enhancing both environmental sustainability and economic profitability. The papers highlight the importance of integrating emission-sensitive demand considerations into the operational and strategic decision-making processes of firms (Chen et al., 2017). This integration is showcased as a critical factor in achieving low-carbon manufacturing and sustainable supply chain management. Moreover, the studies highlight the role of governmental policies in influencing corporate behaviors towards more environmentally friendly practices (Yang et al., 2020; Wang et al., 2020; Dou & Choi, 2021; Zhang et al., 2021b). The research underlines that while investments in green technologies can lead to improved environmental and economic outcomes, the specific impacts depend on various factors including market structure, competition, and the design of regulatory frameworks. Through game theory analysis, mathematical modeling, and system dynamics, these papers offer insights into how different market power structures and policy interventions can influence the optimal pricing, technology investment, and cooperative strategies among firms, leading to varied implications for carbon emissions reduction and profitability (Chen et al., 2017; Lu et al., 2020; Yang et al., 2020; Ma et al., 2021b). Additionally, the significance of supply chain collaboration and the strategic role of inventory management in green supply chains are explored (Mishra et al., 2021A; Mashud et al., 2021B), revealing that the adoption of green technologies not only enhances firms' environmental performance but also their economic viability.

Bibliographic Coupling Cluster 3: Green Knowledge Management

Within the publications of this cluster, significant emphasis is placed on Green Knowledge Management (GKM) as a critical factor in advancing sustainable development and environmental innovation. This focus is particularly evident in the works of Abbas & Sağsan (2019), Wang et al. (2022B), and Sahoo et al. (2023), which collectively underscore the role of GKM in fostering green innovation and contributing to Corporate Sustainable Development (CSD) activities. The former lays the groundwork by examining how knowledge management processes, specifically knowledge creation, acquisition, sharing, and application, significantly impact green technology and management innovation. This study provides a comprehensive view of the instrumental role of KM in enhancing the environmental, social, and economic facets of sustainability, highlighting the crucial dynamic between KM processes and green innovation outcomes. Building on this, Wang and coauthors introduce the concept of Green Knowledge Management (GKM) and investigate its influence on organizational capabilities to achieve Sustainable Development Goals (SDGs). This study further explores how an organizational green culture (OGC) can amplify the effectiveness of GKM in promoting green innovation. Wang's findings reveal that GKM not only strengthens an organization's ability to innovate sustainably but also asserts that a supportive green culture enhances this relationship, thereby facilitating the achievement of SDGs. Sahoo and coauthors, eventually, extend the discourse by focusing on green knowledge acquisition's role within the framework of GKM. This research elucidates how green knowledge acquisition is instrumental in improving GKM and green technology innovation, ultimately leading to better corporate environmental performance. The study introduces the concept of resource commitment as a moderating factor, suggesting that the allocation and budgeting of resources towards green practices are critical for leveraging the benefits of GKM.

Bibliographic Coupling Cluster 4: Green Capabilities

Recent literature underscores the importance of integrating cleaner technology strategies and green process innovations within firm operations to enhance competitive positioning and respond to increasing environmental concerns (Bhupendra & Sangle, 2016; Bhupendra & Sangle, 2015; Khan et al., 2021). These studies highlight the necessity for firms to adopt proactive environmental strategies, focusing on innovative capabilities, top management's risk-taking abilities, and the adaptation to regulatory uncertainties (Bhupendra & Sangle, 2015; De Stefano et al., 2016). Furthermore, the role of green technology in facilitating eco-innovation and its impact on business sustainability, mediated by service innovation capability, is increasingly recognized as a significant driver for long-term competitive advantage (Fernando et al., 2019). Yacob et al. (2019) and Qi et al. (2020) explore the adoption of green initiatives and green innovation, respectively, within the manufacturing sector, emphasizing the mediating effects of managerial intention towards green and the moderating effects of green technology adoption on environmental sustainability. Wu et al. (2022) adds to this discussion by analyzing compliance strategies in family businesses, showing a blend of substantial environmental improvements and impression management tactics influenced by public pressure and business-government relationships, highlighting the complexity of strategic environmental responses in varying organizational contexts. These contributions suggest that a firm's strategic response to environmental challenges is not only a function of internal capabilities but is also influenced by external pressures from regulators, competitors, and other stakeholders (Weigelt & Shittu, 2015; Dangelico et al., 2013; Kim, 2013). Moreover, the intersection of patented environmental innovations with non-environmental innovations, as discussed by Aragon-Correa & Leyva-de la Hiz (2016), and the exploration of partnership diversity in green-technology ventures (Meyskens & Carsrud, 2013), provide insights into how firms can leverage external collaborations and technological innovations to achieve environmental sustainability goals.

Bibliographic Coupling Cluster 5: Green Tech Adoption

Common themes in this fifth cluster include the identification and overcoming of barriers to technology adoption, the importance of sustainability assessments, and the development of frameworks for decision-making in the context of green technologies and cleaner production methods. Xia et al. (2019), Bhandari et al. (2019), and Xia et al. (2017) discuss the challenges and frameworks for green technology adoption, emphasizing the importance of overcoming operational, psychological, and financial barriers through comprehensive methodologies like FAHP and AHP. These studies underscore the critical role of aligning technological solutions with organizational competencies and sustainability goals. Ren et al. (2017), Hrovatin et al. (2016), and An et al. (2017) delve into the assessment of sustainable technologies in wastewater treatment, energy efficiency, and groundwater remediation, respectively, highlighting the use of multi-criteria decision-making (MCDM) methods to evaluate alternatives based on economic, environmental, social, and technological criteria. Tseng et al. (2013) and Vanapalli et al. (2021) address broader sustainability issues within supply chains and waste management during the COVID-19 pandemic, focusing on green supply chain management, circular economy principles, and the need for sustainable consumption and production patterns. Sun et al. (2017) and Belhadi et al. (2020) explore the impact of green technology innovation on industry efficiency and waste management strategies, presenting models to evaluate technological solutions' ecological and economic benefits. Cruz & Katz-Gerro (2016) and Tarei et al. (2021) discuss the behavioral and policy aspects of adopting green technologies, emphasizing the gap between values and practices and the interdependencies among barriers to technology adoption, such as infrastructure and consumer awareness.

Bibliographic Coupling Cluster 6: Systemic Innovation

The matter of contention across these papers is the investigation of the dynamics between innovation systems, policy frameworks, and the strategic management of knowledge and resources to foster the development and diffusion of sustainable technologies. Orsatti et al. (2020) highlight the significance of inventor teams' capacity to creatively recombine knowledge in the context of green technology innovation, underscoring the role of experience and policy environments in enhancing innovation outcomes. This notion is echoed in Coenen et al. (2010), which digs into theoretical frameworks like sectoral systems of innovation (SSI), technological innovation systems (TIS), and socio-technical systems (ST-Systems), suggesting a systems approach to understanding innovation and its policy implications. Further, the papers collectively emphasize the importance of governance, policy, and institutional frameworks in facilitating or hindering the adoption of sustainable technologies. For instance, Browne et al. (2012) and Mignon & Bergek (2016) discuss the barriers to market penetration and diffusion of alternative fuels and renewable energy technologies, respectively, pointing to the need for frameworks that can address these barriers. This is complemented by the work of Musiolik et al. (2012) and Soderholm et al. (2019), who examine the role of formal networks and policies in supporting technological innovation systems and sustainable transitions. Moreover, several studies focus on the commercialization challenges and business model innovations necessary for the widespread adoption of sustainable technologies. Hall et al. (2018) discuss the downstream commercialization challenges, including regulatory hurdles, while Wadin et al. (2017) and Bohnsack et al. (2014) explore the dynamics of business model innovation in the context of sustainability, highlighting the differing approaches of incumbent and entrepreneurial firms. Lubik & Garnsey (2016) further examine the unique challenges faced by university spin-outs in commercializing advanced material technologies, emphasizing the trial-and-error nature of business model development.

Bibliographic Coupling Cluster 7: Urban Sustainability

Central to this final cluster is instead the recognition of urban areas as critical arenas for implementing circular economy (CE) principles and sustainability innovations. Desing et al. (2020) introduce a resource-based approach to CE that is pertinent to urban contexts, emphasizing the need for a paradigm shift in environmental management that aligns with sustainable urban development. This notion is echoed by Lam et al. (2009), who identify key factors for the successful specification of green construction, an essential component of sustainable urban development. These factors include stakeholder involvement and the integration of green technology, highlighting the collective effort required for urban sustainability. The work of Phdungsilp (2011) on the Göteborg 2050 project exemplifies the effective use of backcasting methodologies in urban planning to envision and actualize a sustainable city. This approach fosters a long-term perspective that is crucial for addressing the multifaceted challenges of urban sustainability, suggesting that visionary planning can significantly accelerate the transition towards sustainable urban environments. Similarly, Green & Vergragt (2002) address the necessity of combining technological and social innovations within urban settings to achieve a high factor of environmental efficiency, pointing to the indispensable role of cultural and lifestyle shifts alongside urban technological transformations. Moreover, Almeida et al. (2015) highlight the urgent need for sustainable urban patterns, pointing out the role of improved corporate management and policy integration in promoting cleaner technologies within urban areas.

Insight Box 1: A Sector Spotlight on Sustainable Agriculture

As anticipated in the Methodology section, to contextualize these general thematic clusters, we can now examine how these dynamics translate into a specific sector like agriculture. These findings show the practical application of the wider "green strategy" and "innovation" concepts. Key agricultural clusters identified in the study by Pavesi et al. (2024) include:

- Biogas and Biochar: these clusters focus on renewable energy production from organic waste and carbon sequestration in soil, representing tangible pathways toward a low-emission agricultural system;
- Biotech Remediation: this research area concentrates on using biological methods like phytoremediation to restore contaminated land, a critical step for ensuring long-term farmland viability;
- Low-Carbon Agriculture: this theme integrates technologies like biogas and biochar into wider farming practices to reduce the sector's overall carbon footprint, directly responding to global climate agreements;
- Sustainable Agriculture Transition: this cluster examines the complex process of shifting entire farming systems, encompassing not just technology but also social learning and policy support.

These specific clusters demonstrate how the general principles of green innovation are being translated into tailored solutions to address the unique environmental and economic challenges of the agribusiness sector.

Documents in cluster and association strength (in parentheses)	Label	Description	Cluster number	Size	Year (avg.)
Xie (2022), (148); Yang (2021), (103); Costantini (2017), (89); Fernandes (2021), (86); Li (2023), (76); Orlando (2022), (75); Lian (2022), (73); Tang (2021), (71); Zhou (2022), (71); Zhou (2021), (69); Xu (2023), (66); Ikram (2022), (63); Hottenrott (2016), (61); Zeng (2022), (61); Liu (2021), (61); Zhang (2022A), (58); Wang (2021B), (54); Shahzad (2022), (54); Yang (2022), (53); Guo (2020), (43); Sun (2020), (43); Kivimaa (2006), (41); Deng (2019), (40); Chien (2022), (34); Feng (2021), (31); Zhu (2021), (29); Zhang (2022B), (29); Li (2021), (29); Du (2022), (29); Zeng (2021), (25); Li (2022), (23); Wang (2022A), (23); Peng (2020A), (17); Luo (2019), (17); Gao (2021), (16); Aldieri (2019), (12); Zhang (2020), (11); Huang (2023), (10); Li (2019), (9); Ali (2021), (8); Shen (2020), (6); Jin (2018), (4); Yu (2020), (4)	China's Leading Role	Cluster 1 investigates the impact of green technology and environmental policies on sustainable economic growth, with a focus on China's industrial upgrading.	1	43	2021
Luo (2016), (68); Mishra (2020), (54); Chen (2017), (50); Mishra (2021A), (49); Mashud (2021A), (41); Mashud (2021B), (39); Ma (2021B), (34); Lu (2020), (32); Yang (2020), (31); Wang (2020), (29); Dou (2021), (27); Zhang (2021B), (26); Taleizadeh (2021), (25); Nielsen (2019), (25); Hussain (2020), (24); Chemama (2019), (22); Ding (2018), (21); Yu (2021), (18); Alizamir (2016), (16); Bhardwaj (2016), (16); Niu (2019), (15); Chalmardi (2019), (11); Puller (2006), (9); Li (2020), (8); Gong (2013), (6); Usmani (2021), (2); Fadda (2022), (1)	Reducing CO2 Emissions	Cluster 2 studies strategies for reducing carbon emissions through green technology investments and policy-driven corporate cooperation.	2	27	2019
Abbas (2019), (62); Wang (2022B), (51); Sahoo (2023), (41); Abbas (2022), (35); Sang (2015), (33); Mohiuddin (2018), (30); Zhang (2018), (17); Bilal (2022), (16); Yang (2016), (15); Shobande (2022), (9); Bibri (2020), (9); Batool (2019), (8); Zhang (2015), (6); Jim (2013), (2); Zhang (2011), (1)	Green Knowledge Management	Cluster 3 emphasizes the critical role of GKM in enhancing green innovation and achieving sustainability goals.	3	15	2018
Bhupendra (2016), (177); Bhupendra (2015), (168); Khan (2021), (141); Cristina De Stefano (2016), (121); Fernando (2019), (111); Yacob (2019), (100); Qi (2020), (99); Weigelt (2015), (88); Dangelico (2013), (87); Kim (2013), (81); Aragon-Correa (2016), (74); Meyskens (2013), (70); Rauer (2015), (63); Mrkajic (2019), (55); Ma (2021A), (49); Wu (2022), (48); Xia (2015), (39); Mcknight (2018), (38); Yin (2018), (38); Sadovnikova (2017), (32); Kishna (2017), (26); Niesten (2017), (21); Cohen (2014), (20); Mishra (2021B), (20); Malek (2014), (18); Islam (2018), (16); Hargadon (2012), (14)	Green Capabilities	Cluster 4 examines how firms adopt cleaner technologies and green innovations for sustainability and competitive advantage.	4	28	2016
Xia (2019), (47); Bhandari (2019), (36); Xia (2017), (29); Tseng (2013), (11); Ren (2017), (11); Hrovatin (2016), (10); Sun (2017), (9); Cruz (2016), (8); Belhadi (2020), (8); Tarei (2021), (8); An (2017), (6); Vanapalli (2021), (3); Fiorentino (2017), (2); Nissim (2018), (2); Maxim (2014), (2); Juwarkar (2009), (1); Sangle (2011), (10); Montalvo (2008), (10)	Green Tech Adoption	Cluster 5 highlights the adoption and challenges, and of green technologies across multiple sectors.	5	18	2016
Orsatti (2020), (131); Coenen (2010), (114); Browne (2012), (80); Musiolik (2012), (80); Hall (2018), (71); Soderholm (2019), (70); Foxon (2008), (65); Wadin (2017), (63); Hillman (2011), (62); Mignon (2016), (57); Bohnsack (2014), (56); Lubik (2016), (56); Wicki (2019), (54); Bolton (2016), (51); Sushandoyo (2014), (48); Heiskanen (2015B), (44); Caniels (2008B), (38); Schmidt (2016), (32); Kemp (1998), (31); Huenteler (2016), (21)	Systemic Innovation	Cluster 6 focuses on the interplay between innovation, policy frameworks, and strategic management in fostering sustainable technologies.	6	30	2014
Desing (2020), (33); Partidario (2002), (21); Lam (2009), (18); Tan (2010), (12); Moors (2005), (11); Robèrt (2002), (9); Wang (2021C), (9); Phdungsilp (2011), (8); Green (2002), (8); Almeida (2015), (8); Nwankwegu (2022), (7); Pitt (2011), (7); Lee (2018), (7); David (2022), (6); Oyetibo (2017), (5); Jansen (2003), (5); Pandey (2021), (5); Maes (2017), (3); Fernandez (2018), (2); Mcgee (2009), (2)	Urban Sustainability	Cluster 7 centers on sustainable urban development through clean technologies, innovative planning, and systemic change.	7	22	2013

Table 1.4 Overview of Bibliographic Coupling Clusters. Source: Author's elaboration.

1.4.4. The Author’s Keyword Co-occurrence Analysis

Bibliometric analysis is a valuable tool for understanding the structure and dynamics of scientific research within a field by examining the co-occurrence of keywords in literature. This analysis involves mapping out relationships between different concepts, often represented as nodes in a network where connections indicate co-occurrences. Through this approach, clusters of closely associated nodes emerge, reflecting coherent sub-themes or topics within the field (Aria & Cuccurullo, 2017). Centrality measures like betweenness and closeness are commonly used in bibliometrics to assess the significance of keywords in the network. Betweenness centrality highlights a keyword’s potential to bridge different research areas, while closeness centrality indicates the accessibility and relevance of a keyword within the network (Rossa-Roccor et al., 2020). Researchers can utilize tools like Bibliometrix to conduct comprehensive science mapping analyses focusing on the author’s keywords to uncover the research landscape’s structure. This method can reveal interconnected themes represented by clusters based on keyword co-occurrence, providing insights into the main topics under investigation and their interconnections. Such analyses are crucial for tracking research trends, understanding the evolution of fields, and identifying opportunities for interdisciplinary collaboration (Aria & Cuccurullo, 2017). This approach not only sheds light on the main topics but also reveals how these topics are related, offering valuable insights into research trends and potential interdisciplinary collaboration opportunities (Aria & Cuccurullo, 2017). In this case, our study, filtering for the author’s keywords with a minimum number of edges equal to 2, identified 40 keywords, divided into 8 unique clusters in a network, each representing interconnected themes based on keyword co-occurrence, as represented in Figure 1.5.

Cluster 1 (blue) is dominated by “green technology” with a betweenness centrality of 221.21, signaling its central role in connecting different concepts, as well as suggesting a strong focus on technology-specific discussions. “Supply chain” has a betweenness of 36.00, and “innovation” follows with 10.48, indicating their importance but more niche focus compared to “green technology”. The inclusion of “covid-19” may suggest a recent focus on the pandemic’s impact on green technology adoption. Cluster 2 (red) is instead led by “green technology innovation” with a betweenness of 214.70, highlighting its significance in bridging various themes. “China” shows a betweenness of 14.16, indicating a significant amount of research focused on Chinese practices or policies related to green technology, while “environmental performance” has a notable value of 36.60, and “eco-innovation” follows with 22.89, pointing to a focus on practical outcomes and new environmental initiatives. Cluster 3 (green) centers around “sustainability” with the highest betweenness of 263.62, underscoring its critical importance. “Sustainable development” has a betweenness of 195.29, with “green innovation” at 77.30, showing a strong engagement with the development and implementation of sustainable technologies. Cluster 4 (purple) features “game theory” with a betweenness of 47.77, suggesting a strategic approach within this cluster. “Clean technology” has a betweenness of 36.00 and “climate change” comes in with 27.91, pointing to a focus on analytical and policy-driven research. Cluster 5 (orange) is built around “renewable energy” with a betweenness of 36.00, highlighting the focus on energy sources as a significant aspect of green technology integration. Cluster 6 (brown) discusses “barriers” with a betweenness centrality of 36.00, which may reflect on the obstacles encountered in transitioning to greener production methods, while cluster 7 (pink) includes “recycling” with a betweenness centrality of 36.00, indicating its role in the discussion about waste management and resource use within the circular economy. Eventually, cluster 8 (grey) consists of two author’s keywords, “heavy metals” and “pollution”, that, uniquely, show a closeness centrality of 1.0000, although their betweenness is 0.00, suggesting they are highly specific topics that are directly connected to all other terms within their cluster.

Figure 1.5 Author's Keywords Co-Occurrence Network. Source: VosViewer.

Additionally, through Bibliometrix, a thematic evolution map was developed, as displayed in Figure 1.6, to grasp the dynamics of keywords over time. In delineating temporal segments within the presented analysis, deliberate choices were made to align with the availability of data to render a factual representation of the evolutionary scholarly discourse. The initial span, 1992-2008, was selected to embody the array of papers that surfaced in the co-citation analysis, while also reflecting the average publication years of the most significant works considered. The ensuing segment, 2009-2018, adheres to a similar logic, yet pivots on bibliographic coupling methodology, mapping the intellectual structure of the field through interconnected publications. The final slice, 2019-2023, was determined to capture current trends, considering the latest socio-economic and health-related vicissitudes that have indubitably influenced academic focus and discourse. In the context of our paper focusing on the integration of green technologies within business strategies, these time frames serve to illustrate shifts in focus on various facets of sustainability and green innovation:

- 1992-2008: During this era, there appears to have been an initial drive toward the comprehension and incorporation of cleaner and more sustainable practices within businesses, signaled by the emphasis on broad concepts such as "environmental management", "cleaner production", "clean technology", "environmental policy", "sustainability", and "innovation".

- 2009-2018: This period witnesses the ascent of terms like "pollution", "environmental regulation", "eco-innovation", "sustainable development", "heavy metals", "alliances" and "green technologies". This suggests an evolution toward more precise environmental regulation and an understanding of eco-sustainability within innovation, as well as the initiation of strategic collaborations or alliances.

- 2019-2023: The recent years have shown a robust interest in "sustainability", "green technology innovation", "phytoremediation", "technological innovation", and "environmental sustainability". This denotes a significant push toward innovation and the application of green technologies in corporate strategies, with terms like "phytoremediation" gaining prominence, possibly reflecting a growing interest in more advanced and specific environmental sustainability solutions.

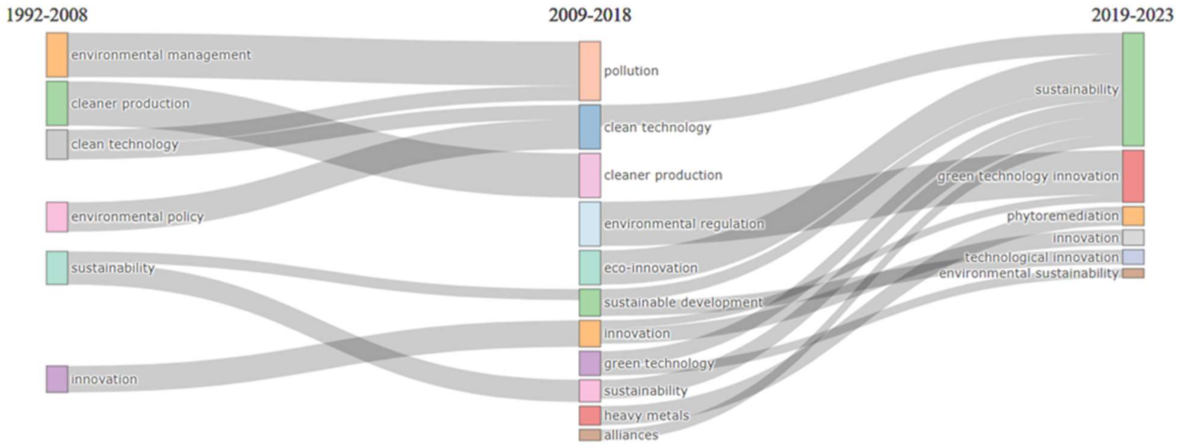

Figure 1.6 Thematic Evolution of Author's Keywords. Source: Bibliometrix.

1.5. Discussion

What emerged from the results of our study is an intriguing evolution of research focus and methodology within the field of green technologies and sustainable business strategies. This shift not only reflects the changing priorities and advancements in the field but also suggests a progression from foundational theoretical frameworks to more applied, innovative, and interdisciplinary approaches.

At first, the co-citation analysis primarily highlighted seminal works and foundational theories that have shaped the understanding of sustainability within business practices. These clusters tend to emphasize established concepts such as sustainable supply chains, Porter's Hypothesis, holistic sustainability, and strategic green integration, reflecting a focus on the underpinning theories and methodologies that guide sustainable business research. The bibliographic coupling clusters, on the other hand, demonstrate a shift towards applied innovations, policy analysis, and the exploration of green technology's role within specific contexts, such as China's leadership in green technology innovation and strategies for CO2 emission reduction. The role of China as a prominent player in these clusters, underscored by the descriptive analysis, reflects not just a geographic focus but also the impact of national policies and global agreements on research orientations. China's aggressive push towards green technologies, influenced by its commitments under the Paris Agreement and its own national development goals, exemplifies how geopolitical and economic ambitions drive the focus of current research. This is further illustrated by the international collaborations and the regional approach to sustainability, indicating a shift towards more localized and policy-driven research within the bibliographic coupling clusters. This suggests a move from theoretical exploration to practical application and the testing of concepts in real-world scenarios.

Such ongoing transformation, moreover, indicates a growing emphasis on geographical specificity and policy impacts. While foundational research provides a broad theoretical base, applied research seen in the coupling clusters often focuses on specific national or regional contexts, highlighting the importance of local policies, economic conditions, and cultural factors in shaping sustainable business practices. The progression reflects an increasingly interdisciplinary and cross-sectoral approach to research. Early co-citation clusters may have focused more on business and environmental science perspectives. Still, bibliographic coupling clusters reveal a broader integration of disciplines, including technology innovation, public health, and even media studies, showcasing the multifaceted nature of sustainability challenges and solutions.

The bibliographic coupling analysis also shows a dynamic response to global challenges, such as the COVID-19 pandemic, which may not be as prominent in the co-citation analysis. This suggests that recent research is rapidly evolving to address immediate global challenges, integrating sustainability with resilience and adaptation strategies.

The descriptive analysis highlighted a significant uptick in publications related to green and sustainable technologies, particularly from 2015 onwards, which aligns with the global ratification of the Sustainable Development Goals and the Paris Agreement. This growing scholarly attention suggests a broader academic and practical interest in translating foundational sustainability concepts into operational business strategies. The surge in publications post-2018, especially, reflects an intensified focus on innovative solutions and interdisciplinary approaches to sustainability, corroborating the shift observed from co-citation to bibliographic coupling clusters. Citation patterns from the descriptive analysis revealed the significant influence of certain key works, as emerged from the co-occurrence analysis, that bridge theoretical frameworks and practical applications, aligning with the shift from co-citation to bibliographic coupling clusters. Papers that focus on strategic niche management, the impact of policy and governance on green technology adoption, and the role of innovation in enhancing sustainability underscore the evolving research agenda. The prominence of works that not only conceptualize but also empirically examine the integration of green technologies into business models confirms a maturation of the field towards practical implications and strategies.

1.5.1. Implications for Scholars

The diversity of journals identified in the descriptive analysis, ranging from technical and applied sciences to environmental and ecological research, and business and environmental strategies, supports the observed transition to a more interdisciplinary and applied research focus. This diverse publishing landscape highlights the multifaceted nature of sustainability challenges and the necessity of cross-sectoral knowledge to address them. Nevertheless, the relatively sparse representation of business-focused journals in the green technology domain suggests a nascent, yet potentially explosive, domain ripe for scholarly exploration. This gives scholars a dual opportunity: to pioneer in a relatively untapped space and bridge the evident gap where newer publications seem disjointed from their predecessors.

As both the co-citation analysis and the bibliographic coupling were completed, providing a backward and forward perspective on the field of the integration of green, clean, and sustainable technologies within businesses' strategies respectively, it was interesting to look for possible linkages between the two of them. Therefore, as in Anwar (2023), the next step was to further analyze which co-citation clusters were cited by the coupling clusters to recognize the theoretical roots of each bibliographic coupling cluster. The results, reported in Table 5, nevertheless, were not particularly enlightening. It emerged that, out of the four co-citation clusters, the publications from cluster 3 “Strategic Green Integration” were the relatively most cited by the majority of the papers from the bibliographic coupling clusters, particularly from cluster 6 “Systemic Innovation”. Clusters 2 “Porter's Hypothesis” and 4 “Holistic Sustainability” of the co-citation analysis follow with even more modest figures, except for the link between the latter and the fourth bibliographic cluster “Green Capabilities”. Lastly, for what concerns the first co-citation cluster, “Sustainable Supply Chains”, the only connection that was found out is with the publications pertaining to the second bibliographic cluster “Reducing CO2 Emissions”, although again not very significative. Overall, the resulting percentages score relatively low figures across the board: this suggests that, given the ongoing evolution of scientific and academic contributions in this field, there is currently no well-established foundation. Instead, technological advancements predominantly shape the trajectory, underscoring their significant role in driving progress. These disconnects hint at an evolving academic landscape. Scholars are presented with both a challenge and an opportunity here, i.e. to weave these disparate threads into a unified synthesis of understanding. Furthermore, the potential for interdisciplinary collaboration could not be overemphasized. By melding insights from technology, environment, and business domains, scholars can lead a holistic and enriched academic discourse.

	CC Cluster 1	CC Cluster 2	CC Cluster 3	CC Cluster 4
BC Cluster 1	0	0	6 (0.7%)	0
BC Cluster 2	54 (4.2%)	2 (0.1%)	0	4 (0.3%)
BC Cluster 3	0	10 (1%)	2 (0.2%)	11 (1.1%)
BC Cluster 4	0	21 (1.3%)	17 (1%)	82 (5%)
BC Cluster 5	0	1 (0.1%)	2 (0.3%)	2 (0.3%)
BC Cluster 6	0	14 (1%)	80 (6.1%)	9 (0.7%)
BC Cluster 7	0	0	6 (0.7%)	0

Table 1.5. Co-Cited Reference Cross-Checking Coupling Cluster. Source: Author's elaboration.

1.5.2. Implications for Managers

The observed shift in the research landscape towards the practical application of green technologies and sustainable business strategies underscores several critical areas for managerial action and strategic consideration in today's rapidly evolving business environment. Firstly, the prominence of China in leading green technology innovation suggests an emerging paradigm where managers, particularly those in multinational corporations or businesses looking to expand, should consider engaging more deeply with Chinese markets, partners, and innovation ecosystems. China's aggressive advancement in green technologies, backed by supportive government policies, offers a fertile ground for collaborative projects, joint ventures, or for sourcing cutting-edge sustainable technologies. Managers should stay updated on the developments in this space, seeking opportunities to integrate such innovations into their business models to drive sustainability and competitive advantage. Given the emphasis on geographical specificity and policy orientation, managers should consider localized strategies that align with regional environmental policies, market conditions, and consumer preferences. Simultaneously, fostering international collaborations can provide access to a wider pool of knowledge, technologies, and best practices in sustainability, enhancing the firm's ability to navigate the complexities of global markets while advancing its sustainability agenda. Moreover, the focus on reducing CO2 emissions and leveraging green knowledge management within bibliographic coupling clusters highlights the importance of integrating sustainability deeply within business strategies. Managers are advised to move beyond viewing sustainability as a compliance requirement or a CSR initiative, treating it as a core strategic pillar. This involves embedding sustainability into the product lifecycle, from design through to production and end-of-life, to drive not only environmental benefits but also operational efficiencies and potential cost savings. Strategic investments in R&D for green technologies and fostering a culture of sustainability within the organization can enhance brand reputation, customer loyalty, and open new market opportunities. Acknowledging the dynamic response to global challenges, such as the COVID-19 pandemic, managers must cultivate organizational agility to adapt to sudden market changes and global disruptions. This involves not only investing in resilient supply chains and flexible business operations but also in the capability to pivot quickly towards new business opportunities that such disruptions may present, particularly in the domain of sustainable practices and green technologies. Eventually, the interdisciplinary nature of current research on green technologies and sustainable practices highlights the value of cross-disciplinary innovation within organizations. Managers should foster collaborative environments where insights from diverse fields—engineering, environmental science, business strategy, and even public health—can intersect to spur innovation. This approach can lead to the development of novel solutions that address sustainability challenges in holistic and effective ways, potentially unlocking new business models or market niches.

Therefore, the insights derived from our analysis point towards a strategic imperative for managers to actively engage with the latest developments in green technology and sustainability research. By embracing innovation, fostering interdisciplinary collaboration, aligning with global trends, and leveraging strategic partnerships, businesses can navigate the uncertainties of the modern business landscape while contributing positively to environmental sustainability.

Insight Box 2: Strategic Interrelationships in Agribusiness Innovation

The implications of these findings become even more evident when observed through the lens of a specific sector. The analysis of agribusiness, for example, not only confirms these trends but also reveals their complex strategic interdependencies. The sector-specific analysis of agriculture does not merely identify distinct research clusters but also reveals their deep interconnection, offering a model for how holistic green strategies should be structured. It clearly emerges that technological solutions and managerial strategies are inseparable: progress in areas like Biogas and Biochar can only reach its full potential when supported by adequate policy frameworks, financial incentives, and new business models, as explored in the Green Strategies cluster. Similarly, the goal of a Sustainable Agriculture Transition proves achievable only if foundational issues like land remediation are addressed, which is the focus of the Biotech Remediation cluster. This demonstrates that for a successful green transition in a sector like agriculture, strategies must integrate technology, policy, and ecological realities in a systemic and coordinated approach, rather than relying on isolated solutions.

1.6. Conclusions

Our study highlights a significant shift in green technologies and sustainable business strategies, moving from theoretical foundations to practical, interdisciplinary approaches. Initially focused on seminal works on sustainable supply chains and the Porter's Hypothesis, recent research pivots toward innovative applications, with a notable emphasis on China's green technology advancements and CO2 reduction strategies. This reflects a broader trend toward applied research influenced by geographical, policy, and economic considerations. The transition signifies a move from theoretical models to real-world applications, integrating diverse disciplines such as technology innovation and public health. This is echoed in the increase of publications post-2015, aligning with global sustainability efforts. Despite a varied journal landscape, the scarcity of business-focused publications suggests an emerging field ripe for exploration. The analysis reveals both challenges and opportunities for scholars and practitioners to bridge gaps in current research, emphasizing technological advancements and the need for interdisciplinary collaboration. For managers, this evolution underscores the strategic importance of aligning with sustainability trends, engaging in international partnerships, and adopting localized, innovative strategies to navigate the complexities of sustainability and green technology in a global business environment.

Nevertheless, this study, while contributing to new insights, possesses indeed some limitations. Methodologically, the reliance on the Web of Science Core Collection as the exclusive source may have induced biases, and the broad scope of the keywords might have excluded pertinent publications. Furthermore, while bibliometric analyses provide a valuable map of a research field, they often remain at a high level of abstraction. The analysis so far suggests that future research should investigate deeper into how government policies, innovation ecosystems, and corporate strategies can be synergistically aligned. A promising approach to overcome the limitations of a broad analysis is to adopt a multi-level research design, moving from a wide cross-sectoral view to a more granular, context-specific investigation. A recent example of such an effort is Pavesi et al. (2024), which applies a similar bibliometric approach specifically to the primary sector. By narrowing the focus to sector-specific green technology adoption in agriculture, this research demonstrates how a more targeted analysis can yield deeper insights into strategic sustainability transformations. The identification of concrete research clusters like ‘biogas,’ ‘biochar,’ and ‘biotech remediation’ within agriculture shows how broad concepts of “green innovation” translate into tangible technological pathways. This nested approach points towards a clear direction for future academic fellows: to focus on how businesses can proactively engage with specific green technologies, integrating sustainability into the core of their operations. Future studies could further drill down, moving from the sector-level to the technology-level, to analyze the specific business models and value chains emerging around innovations like biochar. This not only ensures their long-term viability but also contributes to the broader goal of sustainable development, setting a course towards a more resilient and environmentally conscious global economy.

CHAPTER II – AN EXPLORATIVE CASE STUDY FOR CIRCULAR BUSINESS MODELS VIABILITY

The initial chapter has mapped the broad theoretical landscape of sustainable business models and green technologies, leaving the analysis at a conceptual level. To translate theory into practice, the investigation must now move from the abstract to the tangible. This subsequent chapter, therefore, anchors the discussion in a real-world context, assessing a specific circular innovation, biochar from urban pruning waste, with a dedicated business model framework. This shift in scale is crucial to test the practical viability of the concepts previously explored.

Abstract

This chapter moves from theory to practice by addressing the challenge of sustainable urban green waste management. It introduces the Circular Triple-Layered Business Model Canvas (CTLBMC), an innovative framework that integrates economic, environmental, and social dimensions to evaluate circular economy initiatives. The objective is to demonstrate the tool's utility through an explorative case study on the production of biochar from urban pruning waste in Milan. By populating the CTLBMC's three layers, the analysis illustrates the initiative's multidimensional value proposition. The economic layer demonstrates profitability through biochar sales and avoided disposal costs; the environmental layer quantifies benefits such as carbon sequestration; and the social layer highlights opportunities for community engagement and job creation. The chapter concludes that the CTLBMC is an effective tool for designing and assessing circular business models, building a crucial bridge between abstract circular economy principles and a tangible, operational business strategy.

2.1. Introduction

As urban populations expand, so does the volume of green waste generated through routine pruning and landscaping activities (Yigitcanlar & Kamruzzaman, 2015; Finco & Nijkamp, 2001). Traditionally, this organic waste is either left to decompose or sent to landfills, both unsustainable and environmentally taxing processes that contribute to greenhouse gas emissions and strain landfill capacity (Muscas et al., 2024; Araujo et al., 2024; Araújo et al., 2018): conventional disposal methods of pruning residues lead to methane emissions through anaerobic decomposition, further intensifying urban greenhouse gas outputs. Additionally, discarding nutrient-rich organic matter wastes valuable resources and disrupts nutrient cycles, depriving urban soils of potential enhancements that could improve soil quality and resilience. Without sustainable waste management practices, municipal systems face increased pressure, and valuable organic materials remain underutilized. While composting represents a step toward circularity by recycling organic matter back into the soil (Vaverková et al., 2020; Bekchanov & Mirzabaev, 2018; Benito et al., 2006), it does not fully capitalize on the potential of such waste, as it primarily addresses nutrient cycling without leveraging the additional benefits of carbon sequestration or multifunctional material creation (Oldfield et al., 2018; Sánchez-Monedero et al., 2019).

Given these environmental and resource challenges, there is an urgent need to rethink green waste management. Traditional disposal methods do not capitalize on the potential of organic waste to contribute positively to urban ecosystems, highlighting the need for more sustainable, resource-efficient approaches (Araujo et al., 2024; Adami & Schiavon, 2021; Duque-Acevedo et al., 2020). This is where the circular economy (CE) model, promoted by the Ellen MacArthur Foundation (2013), presents a promising alternative. Unlike the conventional linear "take, make, dispose" model, CE promotes a transformative shift towards systems where materials continuously circulate within closed loops. As Kirchherr et al. (2016) define, CE encompasses reducing, reusing, recycling, and recovering materials across multiple levels—individual products, regional industrial networks, and national frameworks—aiming to achieve sustainable development. This approach not only maximizes material utility while reducing waste but also prioritizes environmental quality, economic vitality, and social equity. By applying CE principles to urban green waste, cities can transform pruning residues from a disposal issue into a valuable resource, fostering resilient ecosystems and a regenerative economy.

Applying CE principles to urban green waste not only shifts waste management from a linear to a regenerative model but also unlocks new opportunities for waste valorization (Paes et al., 2019; Bottausci et al., 2022; Ddiba et al., 2022). Biochar, a carbon-rich material produced through the pyrolysis of organic waste, embodies the circular economy in practice by transforming green waste into a multifunctional resource (Kurniawan et al., 2023; Schmidt et al., 2021; Weber & Quicker, 2018). Through the pyrolysis process, organic materials such as pruning residues are thermally decomposed in an oxygen-limited environment, producing biochar, a material that sequesters carbon and can enhance soil properties over the long term (Pavesi et al., 2024; Li et al., 2018). As a product of urban green waste, biochar aligns with circular economy goals by offering a sustainable outlet for organic waste, reducing landfill dependency, and capturing carbon that would otherwise contribute to greenhouse gas emissions (Singh et al., 2022; Ayaz et al., 2021). Beyond waste diversion, biochar's benefits include improvements to soil structure, nutrient retention, and water-holding capacity, making it a valuable resource for urban and agricultural applications. Nevertheless, it must be noted that biochar application also presents potential risks, such as the accumulation of heavy metals during pyrolysis, which can pose environmental hazards, particularly in urban contexts (Zheng et al., 2020). Additionally, impacts on soil pH and nutrient dynamics have been observed, where high application rates may disrupt microbial communities and nutrient availability (Regmi et al., 2022; Yaashikaa et al., 2020). These challenges necessitate careful consideration of feedstock quality and application strategies to maximize biochar's potential benefits while mitigating associated risks. Despite these complexities, biochar offers significant promise for fostering resilient ecosystems and advancing circular economy goals, since, by converting pruning waste into biochar, cities can close the waste loop and support ecosystem resilience, all while tapping into biochar's potential to mitigate climate change (Novotný et al., 2023; Azzi et al., 2022; Ariluoma et al., 2021).

Biochar serves as a prime example of a resource that embodies circular economy principles, converting organic waste into a sustainable and valuable product. Effectively evaluating such innovations requires advanced business models that integrate economic, environmental, and social dimensions. Historically, business models have provided frameworks for structuring value creation and economic activities (Belussi et al., 2019; Zott & Amit, 2010; Chesbrough & Rosenbloom, 2002). However, traditional approaches, such as Osterwalder and Pigneur's (2010) Business Model Canvas, primarily emphasize financial viability while often neglecting explicit sustainability considerations. As sustainability has become a central focus (Falkner, 2016; Meuleman & Niestroy, 2015; Boons et al., 2013; Barkemeyer et al., 2014; Daou et al., 2020), newer business models, including the Triple-Layered Business Model Canvas (TLBMC) by Joyce and Paquin (2016) and the circular business model framework proposed by Lewandowsky (2016), have been developed. These models explicitly incorporate circular economy principles, enabling organizations to align their strategies holistically with economic, environmental, and social objectives.

This study aims to explore the potential of biochar produced from urban pruning waste as a circular solution within urban waste management. While biochar's environmental and agricultural benefits are well-documented, existing research lacks a comprehensive framework that integrates its economic, environmental, and social impacts in a circular economy context. To address this gap, we combine the TLBMC with the circular business model framework to create the *Circular Triple Layered Business Model Canvas* (CTLBMC). This approach enables a holistic evaluation of biochar's role within circular economy principles, examining its potential to transform urban green waste management and provide multidimensional value. To our knowledge, this is the first case study to apply such an integrated model to biochar, offering valuable insights for policymakers, urban planners, and sustainability-focused stakeholders.

2.2. Methodological Framework and Contextual Background

2.2.1. Introducing the Circular Triple-Layered Business Model Canvas

As sustainability and circular economy principles become integral to business strategies, existing frameworks, such as the TLBMC and the CBM, have provided valuable tools for integrating these elements into organizational planning. However, while these models offer significant insights, they often independently emphasize certain aspects—such as sustainability or circularity—rather than through a cohesive lens that balances economic, environmental, and social dimensions within a circular economy context. For instance, the TLBMC focuses on triple-bottom-line impact, yet it does not inherently align with circularity principles, while Lewandowsky's circular business model primarily addresses resource efficiency and closed-loop systems but lacks an explicit social dimension. Building on the foundational insights of the TLBMC for sustainability and Lewandowsky's focus on circularity, the *Circular Triple-Layered Business Model Canvas* integrates these frameworks for a comprehensive assessment across dimensions. The CTLBMC enables a more thorough evaluation of value creation, supporting a holistic analysis of how circular economy practices impact financial sustainability, ecological resilience, and societal well-being. This combined approach provides a nuanced perspective that aligns with the growing complexity of sustainability challenges and the need for multi-faceted solutions in business practices.

To achieve its goal of being a practical as well as adaptable tool that avoids overcomplication, the CTLBMC emphasizes circularity within the economic layer while allowing its effects to influence the environmental and social layers indirectly. The transition to a circular economy requires companies to reconceptualize traditional business practices, emphasizing innovation in the economic structure of their models (Suchek et al., 2021). Perey et al. (2018) highlight how businesses achieve greater sustainability by redefining waste as a resource within their products and services, reinforcing the importance of economic adjustments in adopting circular principles. Rattalino (2018) further emphasizes that a shift toward circularity relies on five core practices, including business model innovation, management support, sustainability performance tracking, customer willingness to support sustainable products, and stakeholder collaboration: these practices underscore the central role of the economic layer in integrating circularity, as it directly influences operational strategies and market alignment. This structure keeps the framework clear and accessible, enabling users to assess circularity's impacts across dimensions without necessitating additional, specific blocks.

The CTLBMC builds on the foundational elements of Joyce and Paquin's TLBMC and Lewandowsky's circular business model by combining their key layers into a single, adaptable framework. This integration enables the assessment of circular and sustainable business practices across three interconnected dimensions:

- Economic Layer: Adapted from Lewandowsky's circular business model, this layer evaluates economic viability within a circular economy framework. It focuses on metrics such as resource efficiency, closed-loop production, cost savings, and revenue generation associated with circular practices. This economic focus is essential for assessing how sustainable practices can align with and support profitability goals, particularly in resource-intensive sectors.
- Environmental Layer: Derived from the environmental focus of the TLBMC, this layer examines ecological impacts, including emissions reduction, resource conservation, and waste minimization. By retaining the environmental layer from the TLBMC, the CTLBMC can capture the ecological value generated through circular practices, reinforcing the environmental benefits of transitioning away from linear models.
- Social Layer: Borrowing from the TLBMC's social layer, this component addresses the societal implications of business activities. It evaluates aspects such as community engagement, social equity, and workforce well-being, capturing how circular practices can contribute positively to societal goals. This social dimension ensures that business models do not solely focus on environmental and economic gains but also consider their impact on social structures and community welfare.

The horizontal and vertical coherence of the CTLBMC allows each layer to operate as an independent dimension, enabling users to assess economic, environmental, and social impacts separately. At the same time, it facilitates a vertically integrated view of value creation, highlighting the interconnections between these dimensions to support more informed decision-making. The theoretical integration of these layers is grounded in General Systems Theory (Von Bertalanffy, 1968), which postulates that economic value creation cannot be structurally decoupled from its environmental material flows and social implications. Unlike traditional business model frameworks that treat sustainability as an externality, the CTLBMC operationalizes a systems-thinking approach by mandating a "horizontal coherence" check. This ensures that value captured in the economic layer is explicitly cross-referenced with its resource inventory in the environmental layer and its stakeholder impact in the social layer, thereby validating the circularity of the entire system.

2.2.2. Explorative Application: Biochar as a Case Study for the CTLBMC

This research adopts a single exploratory case study methodology, following the guidelines established by Yin (2015) for investigating contemporary phenomena within their real-life context. The biochar initiative within the AGRITECH framework serves as a critical case to test the theoretical viability of the CTLBMC. To ensure robustness, data triangulation was achieved by combining secondary quantitative data from the municipality of Milan (Ferla et al., 2020) with technical specifications of pyrolysis processes to populate the three layers of the canvas. This study applies the *Circular Triple-Layered Business Model Canvas* to the case of biochar production from urban pruning waste within the AGRITECH project, which currently funds this research. Biochar's production and use as a carbon-sequestering soil amendment align closely with circular economy principles by transforming waste into a resource, reducing landfill dependency, and providing environmental benefits. Thus, biochar presents a fitting example to illustrate the CTLBMC's application within a circular economy context. Although the biochar initiative is still in its pilot phase within AGRITECH, and comprehensive empirical data are not yet available, this study uses the CTLBMC to demonstrate the model's functionality, applicability, and flexibility. By populating the CTLBMC's economic, environmental, and social layers with hypothetical or secondary data, this case study serves as a conceptual exercise to showcase how the framework can capture the multidimensional value of biochar in future studies with empirical data. This illustrative application not only highlights the CTLBMC's adaptability but also provides a foundation for future research and practical use cases. As the biochar pilot matures and data becomes available, the model can be revisited and empirically validated, offering deeper insights for policymakers, businesses, and researchers evaluating circular innovations. Ultimately, the biochar case demonstrates how the CTLBMC can guide diverse stakeholders in assessing and implementing circular economy initiatives across various sectors.

Case Study Context: Milan as a Pilot City for Biochar Production

This study applies the Circular Triple-Layered Business Model Canvas (CTLBMC) to assess the potential of biochar production from urban pruning waste within the context of Milan, Italy. Milan, the most densely populated city in northern Italy, with approximately 1.3 million residents and a density of 7,150 inhabitants per square kilometer (as of 2020), exemplifies an urban environment where circular economy principles can address green waste challenges. As the hub for AGRITECH's Spoke 8, which explores economic analyses of green technologies, Milan provides an ideal pilot city for demonstrating biochar's potential in a structured and data-rich context.

Data Sources and Case Study Justification

The data for this case study draws extensively from Ferla et al. (2020), which provides detailed insights into Milan's urban greenery management:

- Milan has approximately 24 million m^2 of public green spaces, encompassing parks, gardens, roadside greenery, and public building open spaces.
- These areas include an estimated 270,000 trees, with 60% located in parks and gardens, 29% along roads, and 11% within public building spaces.
- Maintenance of 75% of these green areas is managed by a consortium company in cooperation with municipal offices. This system includes an advanced computerized framework for monitoring and recording activities, ensuring efficient management.
- Current practices for green waste involve composting (using 14 local plants with a total capacity of 23,438 tons/year) or disposal, which incurs significant public costs and misses opportunities for enhanced resource recovery.

This comprehensive data underscores Milan's suitability as a pilot city for exploring biochar production. Biochar production, as proposed by AGRITECH, potentially offers an advanced method to reduce greenhouse gas emissions, create long-term carbon storage, and maximize resource efficiency.

Furthermore, the application assumes a public-private partnership (PPP) framework to integrate biochar production into Milan's existing green waste management system. In this model:

- The municipality provides access to pruning waste feedstock and regulatory support, aligning with its sustainability goals.

- Private entities manage biochar production and explore revenue opportunities through biochar sales and carbon credits, leveraging technical expertise and market connections.

This PPP structure exemplifies how circular economy initiatives can align municipal objectives with private sector capabilities to advance sustainable urban waste management systems.

2.3. Results

2.3.1. CTLBMC: the Economic Layer

The economic layer of the CTLBMC, as displayed in Figure 2.1, demonstrates the biochar initiative's potential to generate economic value while supporting circular principles. Studies such as those by Nematian et al. (2021) and Wang et al. (2020) highlight how converting biomass into biochar through Public-Private Partnerships (PPP) can foster economic growth and sustainability, aligning with policy goals while creating cost-effective solutions in waste management. Similarly, Ferla et al. (2020) and Mazzocchi et al. (2019) insights into urban biomass management underscore the potential to convert green waste into profitable outputs, reinforcing our case study's approach to leveraging Milan's pruning waste. Supported by Pieroni et al. (2019) and Lewandowsky's (2016) work on circular business model innovation, this economic layer illustrates that circular models can simultaneously deliver value across financial, social, and environmental dimensions, positioning the biochar initiative as a practical example of sustainable economic restructuring.

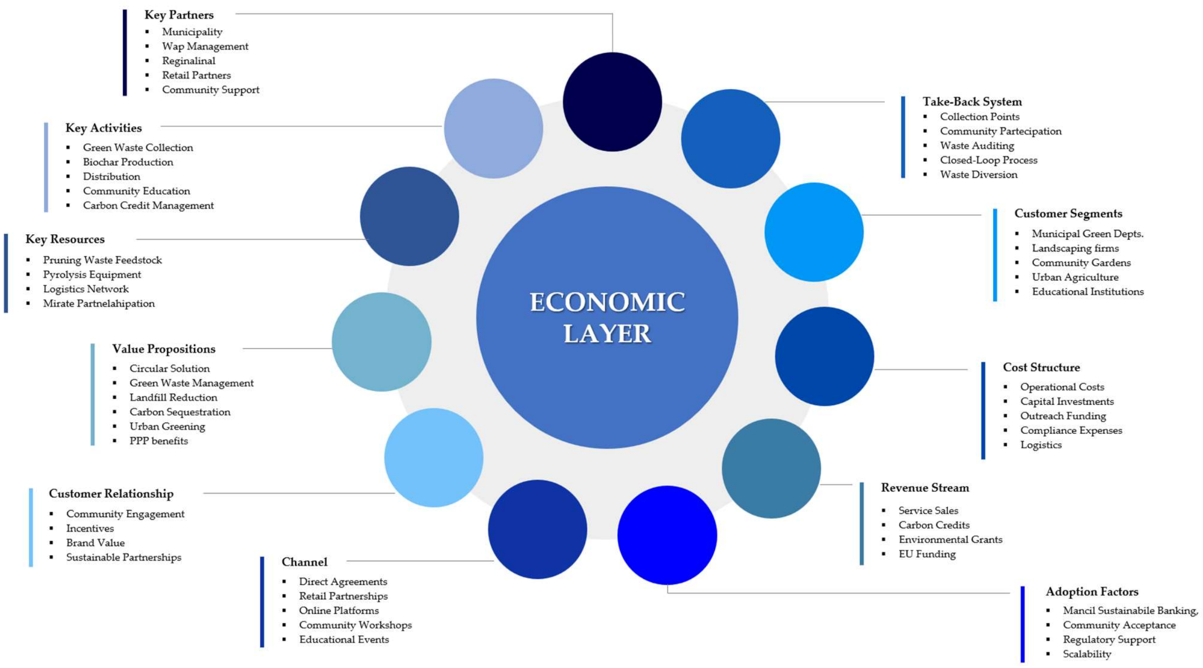

Figure 2.1 The Economic Layer of the CTLBMC. Source: Author's elaboration.

Value Proposition

The biochar initiative offers a multifaceted value proposition. For Milan, biochar presents a circular solution to managing green waste, reducing landfill use, and generating an environmentally beneficial product. The biochar produced can improve soil phytotoxicity, contribute to carbon sequestration, and create a local, circular economy product for urban greening projects. In this PPP structure, the municipality benefits from reduced disposal costs, enhanced sustainability metrics, and potential revenue from carbon credits, while the private partner gains a new product line with demand in municipal, commercial, and community segments.

Customer Segment

The biochar initiative serves a diverse range of customer segments within Milan. Municipal green departments are the primary customers, managing the city's parks and public green spaces, where biochar is used to enhance soil phytotoxicity and reduce maintenance costs. Landscaping and gardening firms, catering to both public and private clients, can incorporate biochar into their sustainability offerings, adding value to their services and supporting environmentally conscious projects. Community gardens and urban agriculture initiatives also benefit from biochar, as it improves soil quality in community-led green spaces and aligns with local environmental values. Educational institutions, including schools and universities, show interest in integrating biochar into green programs, promoting sustainable practices and fostering awareness of carbon capture benefits.

Channel

The biochar will be distributed through a combination of public and private channels to maximize reach and accessibility. Direct supply agreements with municipal green departments and contracted landscaping firms ensure a steady application of biochar in public green spaces and urban landscaping projects. Retail partnerships with local gardening centers and agricultural suppliers make biochar readily available to individual consumers and community gardens, extending its use across various urban applications. Online platforms support broader outreach through direct sales and digital campaigns, providing residents with information on biochar's environmental and economic benefits. Additionally, workshops and educational events organized by the municipality promote public use and awareness, encouraging biochar adoption in community-led sustainability projects.

Customer Relationship

The partnership promotes collaboration and community engagement, fostering relationships based on environmental and economic value. For the municipality, biochar offers an efficient waste management solution aligned with Milan's sustainability goals. For the community, workshops and incentives encourage residents to contribute to pruning waste collection, offering discounts on biochar for local gardens or educational initiatives. Partnerships with landscaping companies allow them to add eco-friendly solutions to their portfolio, building brand value through sustainability.

Revenue Stream

This public-private partnership model generates revenue through multiple channels, creating a financially sustainable approach to biochar production. Sales of biochar to municipal clients, community gardens, and the general public contribute a primary revenue stream, while service fees charged to private landscaping companies and third-party providers for processing their green waste help offset operational costs. Additional income is derived from carbon credits, as the biochar's carbon sequestration properties benefit both municipal and private partners in meeting sustainability goals. Further financial support is sought through environmental grants and subsidies from governmental and EU-level programs, which prioritize projects that advance the circular economy and carbon capture initiatives. The potential revenue from biochar sales, estimated at approximately €2.34 million annually, is based on a market price of €500 per ton and an anticipated annual production of approximately 4,688 tons of biochar derived from Milan's pruning waste. This calculation reflects the pyrolysis conversion rate of green waste, typically yielding biochar at a rate of about 20% of the feedstock's weight. Milan's pruning waste, reported at approximately 23,438 tons annually (Ferla et al., 2020), serves as the feedstock, supporting these production figures. In addition to revenue generation, the initiative could significantly reduce municipal waste management costs. In Lombardy (the region of Milan), landfill taxes for municipal solid waste are €19 per ton (CEWEP, 2021). Redirecting 23,438 tons of pruning waste from landfills could save the municipality approximately €445,322 annually. These combined financial benefits demonstrate the economic viability of the biochar initiative, highlighting its potential to transform waste management into a value-generating circular economy model.

Key Resources

The initiative relies on several critical resources to ensure efficient biochar production and distribution within Milan. Milan's urban pruning waste, estimated at 25,000 tons annually, serves as the primary renewable feedstock, providing a continuous supply of green waste for conversion into biochar. Pyrolysis equipment and production facilities are essential for processing this waste, and these units must be strategically located to optimize both collection and production logistics. A well-coordinated logistics network is also required to facilitate the efficient collection and transport of pruning waste from various locations to processing sites. Additionally, strong partnership networks are vital, including municipal collaboration for secure feedstock access and private partnerships that provide the technological, logistical, and retail support needed to maximize the initiative's impact and reach.

Key Activities

Core activities within this initiative are centered on sustainable and efficient biochar production, ensuring each stage of the process contributes to the overall circular economy model. The collection and sorting of green waste, coordinated by the municipality, prioritize high-volume pruning areas to make the best use of available resources. Biochar production, managed by private partners, utilizes pyrolysis technology, with a strong emphasis on maintaining quality standards to ensure biochar's effectiveness as a soil amendment. Distribution and sales are handled through municipal agreements and partnerships with local retailers, creating a steady market flow and making biochar accessible to various customer segments. Community engagement and education programs, led by municipal authorities, actively inform residents about the environmental benefits of biochar, cultivating a broader customer base and enhancing public support. Additionally, both municipal and private partners work together to document and verify the carbon sequestration benefits of biochar, enabling them to pursue additional revenue through carbon credits and further aligning the initiative with sustainability goals.

Key Partners

Partnerships play a crucial role in ensuring the success and functionality of the biochar initiative. The Milan municipality and its green departments serve as primary feedstock providers and customers, granting access to pruning waste and applying biochar in city greening projects, thereby aligning municipal operations with sustainability goals. Waste management companies contribute essential logistical support, overseeing the collection and transport of green waste to processing facilities. Environmental organizations collaborate to raise public awareness, support grant applications, and conduct educational outreach, which broadens community engagement and fosters understanding of biochar's environmental benefits.

Retail partners, including gardening centers, extend the initiative's market reach by making biochar accessible to individual consumers and community-led initiatives, reinforcing the product's role in promoting urban sustainability

Cost Structure

The initiative incurs several primary costs essential to its operation and long-term sustainability. Operational costs encompass the collection, sorting, and processing of green waste, alongside ongoing maintenance for pyrolysis equipment and facility operation. Initial capital investments are necessary for purchasing pyrolysis units, upgrading facilities, and establishing logistical infrastructure, with these expenses potentially shared by both municipal and private partners. Educational and outreach costs cover funding for workshops, promotional campaigns, and public engagement programs to raise awareness and encourage community involvement. Compliance with regulatory requirements brings further expenses, including environmental assessments, health and safety certifications, and securing carbon credit verification. Finally, logistical expenses are involved in transporting green waste from various collection points to processing sites and in distributing the produced biochar to customer locations, ensuring accessibility and efficiency in the supply chain. The cost structure for Milan's biochar initiative reflects a total production cost of approximately €216 per ton, based on operational expenses, feedstock procurement, and transport logistics (Patel & Panwar, 2024). With an estimated annual production of ~4,688 tons, this translates to an overall expenditure of approximately €1.01 million. Operational costs, including labor, constitute a significant portion, while transport expenses remain relatively low due to Milan's compact urban geography. These costs are offset by potential revenues from biochar sales and municipal savings from waste diversion, underscoring the initiative's financial viability.

Take-Back System

The take-back system is essential for ensuring a steady supply of urban green waste and maintaining a streamlined, circular process from collection to biochar production. Coordinated efforts among Milan's municipality, private waste management companies, and local communities establish collection points in high-pruning areas to efficiently gather feedstock. Waste management companies oversee transportation to production facilities, ensuring a consistent supply chain. To encourage participation, residents and businesses involved in green maintenance are incentivized to contribute pruning waste. Partnerships with community organizations and educational institutions raise awareness of biochar's environmental benefits, fostering engagement and positioning citizens as active participants in the circular economy. Municipal green departments align waste collection schedules to minimize storage needs and ensure timely processing. Quality control is integrated through waste audits that monitor collection volumes, pruning sources, and contamination levels, ensuring suitable feedstock for pyrolysis. This take-back system establishes a closed-loop cycle, transforming urban green waste into biochar while contributing to environmental sustainability and community engagement.

Adoption Factors

The successful adoption of this biochar initiative relies on several key factors for integration into Milan’s urban systems and stakeholder acceptance. Strong municipal and private-sector backing lays a solid foundation, with Milan’s sustainability goals aligning with the private sector’s operational expertise.

Community engagement is equally crucial, achieved through educational outreach targeting schools, community gardens, and neighborhood groups to raise awareness of biochar’s benefits and promote a sense of local ownership. Financial sustainability is supported by diversified revenue streams, including biochar sales, carbon credits, and environmental grants, ensuring consistent funding and appealing to potential investors. Transparency in environmental and economic impact data further strengthens end-user buy-in. Regulatory support and favorable policies are also essential. Milan’s municipality works closely with environmental authorities to comply with regulations and secure carbon sequestration certifications, while EU recognition strengthens the initiative’s funding prospects. Scalability and adaptability are integral, enabling the initiative to process other organic waste types over time. These combined factors—community support, financial resilience, regulatory alignment, and scalability—create a robust framework for embedding biochar into Milan’s sustainability and waste management landscape.

2.3.2. CTLBMC: the Environmental Layer

The environmental layer of the CTLBMC, detailed in Figure 2.2, emphasizes biochar’s role in contributing to sustainability goals by reducing greenhouse gas emissions, improving soil phytotoxicity, and enhancing resource efficiency. Studies by Carvalho et al. (2022) and Osman et al. (2024) provide critical insights into biochar’s life cycle assessment (LCA), supporting its efficacy in mitigating climate change through carbon sequestration and its potential to remediate contaminated soils. Matuštík et al. (2020) further highlight the net positive environmental impact of biochar, particularly through pyrolysis, where syngas and bio-oil co-products provide energy to offset emissions from production. Complementing these findings, Mukherjee and Lal (2013) demonstrate biochar’s benefits for soil physical properties, noting its ability to enhance water retention and stabilize carbon. Additionally, Salvador and Doong’s (2024) research on municipal waste utilization underscores biochar as a carbon sequestration tool within urban waste management, revealing its broader applicability in sustainable city planning. Collectively, these references substantiate the environmental advantages of biochar, reinforcing the CTLBMC’s capacity to capture the multi-faceted ecological benefits inherent in circular economy practices

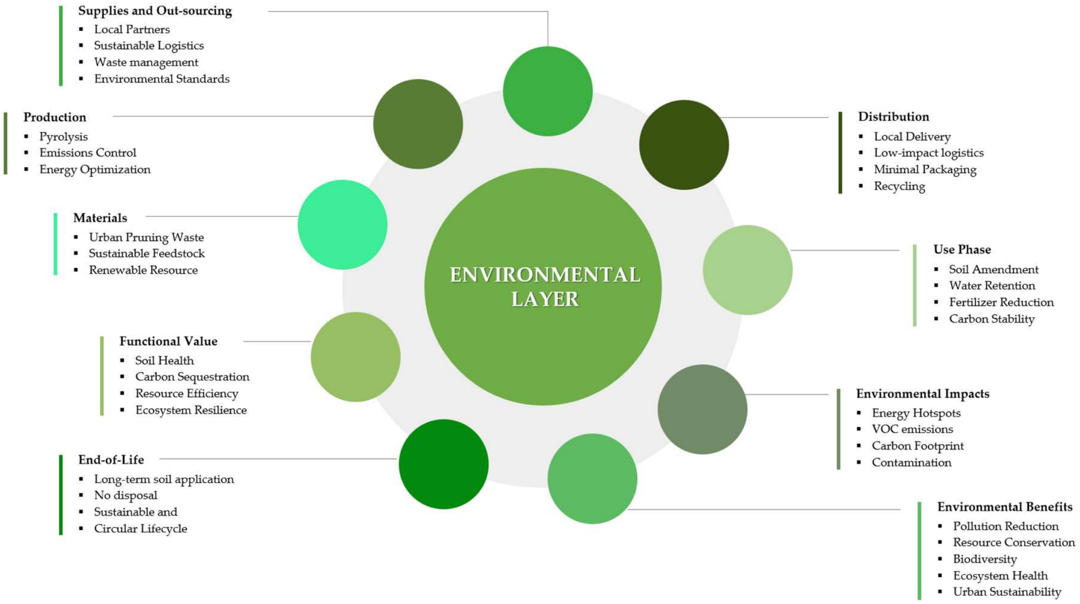

Figure 2.2 The Environmental Layer of the CTLBMC. Source: Author's elaboration.

Functional Value

The biochar initiative offers substantial environmental functional value by converting urban green waste into a beneficial soil amendment. Repurposing green waste supports sustainable urban waste management by reducing landfill needs and providing a local resource that improves soil quality and moisture retention. This functional benefit in urban areas like Milan addresses a critical need for resource-efficient waste solutions while fostering long-term ecosystem resilience.

Materials

The feedstock for biochar production in this study is derived entirely from Milan's annual pruning waste, which includes clippings from urban parks, roadside greenery, and public building spaces (Ferla et al., 2020). This renewable and locally available resource reduces the need for sourcing new raw materials, avoiding the environmental costs and carbon emissions associated with their extraction. Milan generates approximately 24 million m^2 of green waste annually, with pruning residues amounting to significant volumes suitable for biochar production (ibid.). By leveraging this existing waste stream, the initiative mitigates environmental impacts associated with transportation and reduces dependency on external feedstock supplies. Composting is currently the predominant method for managing Milan's green waste; however, transitioning to biochar production offers greater potential for long-term carbon sequestration and resource efficiency, enhancing the circularity of the city's waste management practices (Zheng et al., 2020).

Production

Biochar is produced through pyrolysis, a thermal process in which organic material is decomposed in a low-oxygen environment. This process stabilizes carbon, converting it into a solid form that can remain sequestered for decades to centuries (Carvalho et al., 2022). The pyrolysis process also generates co-products such as syngas and bio-oil, which can be harnessed for energy, further improving the circularity and efficiency of the system (Matuštík et al., 2020). Compared to traditional waste management methods like landfill disposal or open burning, pyrolysis significantly reduces methane emissions and contributes to greenhouse gas mitigation (Ramezanzadeh et al., 2023). However, it is important to note that energy input is required, particularly for processing large quantities of biomass, which can offset some of the environmental benefits if non-renewable energy sources are used (Gallego-Ramírez et al., 2023). To optimize the environmental performance of pyrolysis, integrating renewable energy sources or waste heat recovery systems could be explored in future iterations of the project. For readers seeking a deeper understanding of the technical aspects of pyrolysis and its associated environmental impacts, detailed analyses are available in recent studies (Carvalho et al., 2022; Osman et al., 2024). These works extensively examine biochar production systems, addressing factors such as feedstock variability, process efficiency, and lifecycle assessments.

Supplies and Outsourcing

Key suppliers and partners, such as waste management companies, are selected based on sustainable practices that align with Milan's environmental standards. By involving local partners in green waste collection and logistics, the initiative supports low-impact operations that reflect the city's ecological goals. Outsourcing certain activities may present challenges in scaling while maintaining environmental performance, so careful partner selection is essential to sustain positive outcomes throughout the supply chain.

Distribution

The distribution network for biochar in Milan prioritizes local delivery routes to reduce transport distances and associated emissions, aligning with circular economy principles. Biochar is delivered to municipal green departments, gardening centers, and community-led projects, supporting efficient resource use within the city (Ferla et al., 2020). Efforts to minimize packaging waste and use recyclable materials further reduce the environmental impact, ensuring that the distribution phase supports broader sustainability goals (Carvalho et al., 2022). Studies emphasize the importance of leveraging local networks to enhance logistical efficiency and reduce the carbon footprint of biochar applications (Osman et al., 2024).

Use Phase

During the use phase, biochar enhances soil phytotoxicity by improving water retention, nutrient cycling, and structure, which reduces the need for chemical fertilizers and pesticides and lowers pollution risks (Carvalho et al., 2022; Mukherjee & Lal, 2013). Its stable carbon form allows for long-term soil benefits and carbon sequestration, making it a key component in climate mitigation strategies (Osman et al., 2024). However, attention must be given to potential risks, such as heavy metal accumulation or shifts in microbial communities, which require careful monitoring and application strategies to maximize sustainability outcomes (Ramezanzadeh et al., 2023; Palansooriya et al., 2019).

End-of-Life

Biochar's end-of-life is inherently sustainable, as it remains in the soil, delivering environmental benefits without the need for disposal or recycling: this stability allows biochar to serve as a long-lasting soil amendment, providing continuous improvements to soil quality and promoting resilient green spaces (Supunsala Senadheera et al., 2024; Kong et al., 2021; Gross et al., 2021). Potential risks associated with biochar's end-of-life phase include alterations in soil chemistry, such as excessive increases in pH and salinity, overaccumulation of nutrients, and the potential release of harmful substances like heavy metals or polynuclear aromatic hydrocarbons. These challenges emphasize the importance of careful management and application strategies (Azzi et al., 2022; Li et al., 2020).

Environmental Impacts

The environmental impact of the biochar initiative is assessed throughout its life cycle, from waste collection to production and soil application. By diverting organic waste from landfills, the initiative reduces methane emissions and captures carbon in a stable form, yielding significant carbon sequestration benefits for Milan (Carvalho et al., 2022; Mukherjee & Lal, 2013). However, certain stages present environmental challenges. The pyrolysis process is energy-intensive, and its environmental benefits could be undermined if not powered by renewable energy sources (Osman et al., 2024). Emissions from pyrolysis, including volatile organic compounds and particulates, necessitate proper controls to minimize air pollution (Matuštík et al., 2020). Transportation for waste collection and distribution, though localized, contributes to the carbon footprint and requires optimized logistics to reduce emissions (Ferla et al., 2020).

Environmental Benefits

The environmental benefits of the biochar initiative include substantial resource conservation, pollution reduction, and ecosystem enhancement. By transforming pruning waste into biochar, the initiative reduces landfill dependency, mitigates greenhouse gas emissions, and contributes to carbon sequestration (Carvalho et al., 2022). Biochar application improves urban green spaces by enhancing soil resilience, nutrient retention, and water-holding capacity, reducing the reliance on chemical inputs that harm local biodiversity (Bekchanova et al., 2021; Mukherjee & Lal, 2013). These benefits strengthen Milan's commitment to sustainable urban development and highlight biochar's role as a key tool for climate mitigation (Osman et al., 2024). The initiative could sequester approximately 12,045 tons of CO_2-equivalents annually through the stable carbon content in biochar, leveraging the findings on carbon stability in biochar production systems (Osman et al., 2024; Carvalho et al., 2022). Furthermore, by diverting Milan's 23,438 tons of annual pruning waste toward biochar production, as outlined in Ferla et al. (Ferla et al., 2020), it is possible to avoid an additional 29,300 tons of CO_2-equivalents by reducing methane emissions from organic waste decomposition in landfills, in line with emission factors reported by the European Environment Agency (2019). This dual impact—carbon sequestration and methane emission avoidance—demonstrates the significant climate mitigation potential of integrating biochar into Milan's waste management system, complementing the broader insights on waste-to-carbon sequestration pathways discussed by Salvador and Doong (2024).

2.3.3. CTLBMC: the Social Layer

The social layer of the CTLBMC, supported by Figure 2.3, highlights the importance of integrating stakeholder engagement and community participation to achieve holistic sustainability in circular economy initiatives. Salvioni and Almici (2020) shed light on how transitioning to a circular economy demands a shift in corporate culture, emphasizing sustainability and fostering stronger relationships with stakeholders. Müller et al. (2019) further demonstrate the social implications of implementing biochar systems, emphasizing the need to address community-specific adaptation barriers and procedural processes such as participatory planning and farmer cooperatives, which can enhance community resilience and reduce vulnerabilities. The role of public-private partnerships in fostering social engagement is exemplified by Li et al. (2022), who illustrate how collaborative partnerships in urban development projects reconcile private sector interests with broader sustainability goals, advancing democratic ideals and public values. Similarly, Liu et al. (2020) emphasize the transformative potential of PPPs in smart city projects, highlighting emerging themes like citizen engagement and participatory governance. Together, these studies provide a robust foundation for assessing the social value of biochar initiatives, demonstrating how stakeholder involvement and community-centric approaches can strengthen the social fabric and drive the success of urban sustainability projects.

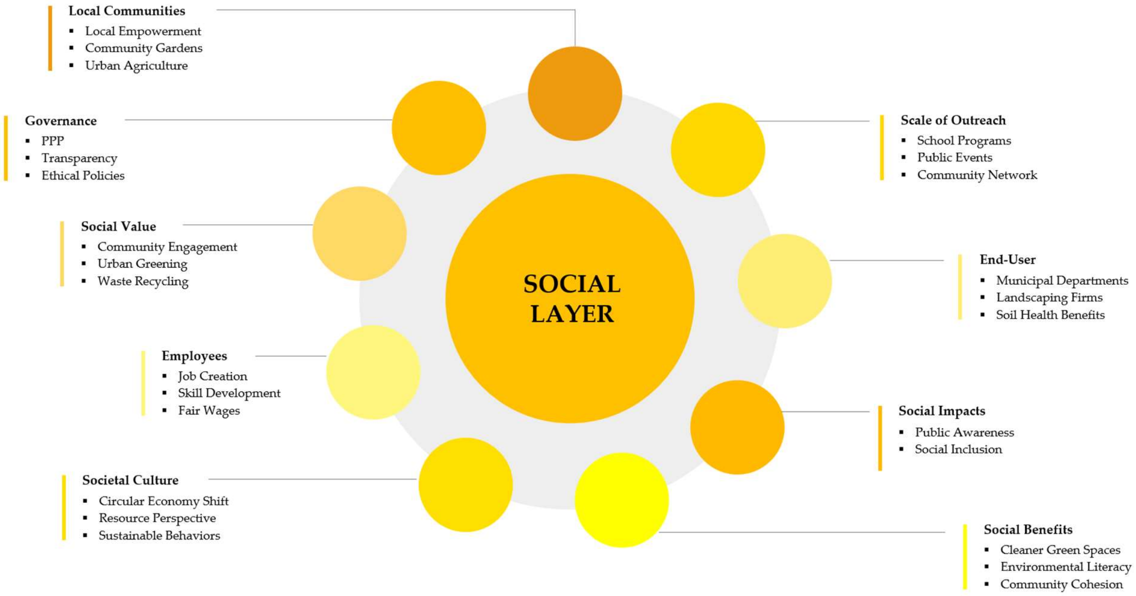

Figure 2.3 The Social Layer of the CTLBMC. Source: Author's elaboration.

Social Value

The biochar initiative offers meaningful social value by addressing Milan's waste management needs and contributing to local sustainability. By repurposing urban green waste into a product that enhances soil quality, it supports Milan's goals for a greener city, while offering tangible benefits to the community through cleaner, healthier urban spaces. This initiative fosters local engagement, encouraging residents to participate in waste collection efforts and educating them on the environmental benefits of sustainable waste management.

Employees

The initiative supports job creation within the biochar production and waste management sectors, providing stable employment opportunities in Milan. Employee well-being is prioritized through safe working conditions, fair wages, and training programs, especially around pyrolysis technology and environmental practices. Additionally, the initiative encourages skill development and provides opportunities for career growth within the green technology sector, enhancing job satisfaction and fostering a strong commitment to sustainability among employees. The production of biochar could generate ~4–5 direct jobs annually in Milan, based on industry benchmarks of employment per ton of processed biochar (Nematian et al., 2023). This reflects the initiative's potential to contribute to local economic development while promoting circular economy principles.

Governance

The biochar initiative operates under a public-private partnership governance structure, combining the regulatory guidance of the Milan municipality with private sector efficiency. Transparent policies govern waste collection, biochar production, and distribution, aligning the initiative with Milan's sustainability goals. The partnership prioritizes ethical governance, ensuring that each stage of production adheres to city regulations and EU environmental standards. Stakeholders, including local authorities and private partners, meet regularly to review the initiative's progress and ensure compliance with social and environmental objectives.

Communities

The initiative positively impacts local communities by creating greener, healthier urban environments. Community gardens and urban agriculture projects directly benefit from biochar, improving local soil quality and fostering more vibrant green spaces. Furthermore, the initiative promotes community participation through waste collection programs, educational workshops, and outreach events, helping residents understand the value of recycling urban green waste. Workshops and community engagement events could reach ~250 residents annually, fostering awareness about biochar's environmental and economic benefits. This participatory approach promotes local ownership of the initiative and aligns with Milan's commitment to community-driven sustainability efforts.

Societal Culture

By prioritizing sustainable waste management and environmental education, the biochar initiative supports a cultural shift in Milan towards circular economy principles. It encourages residents and businesses alike to adopt practices that view waste as a resource rather than a disposal issue. This change in perspective helps normalize sustainable behaviors and positions Milan as a forward-thinking city in terms of environmental stewardship, influencing societal norms and values around urban waste and resource efficiency.

Scale of Outreach

The initiative's outreach extends across various social segments in Milan, including municipal departments, local businesses, educational institutions, and community groups. Through workshops, school programs, and public events, the initiative raises awareness about biochar's benefits and sustainable practices in waste management. This outreach aims to build a robust community network and cultivate widespread support for biochar production as a beneficial practice, reaching diverse stakeholders and generating interest in urban sustainability initiatives.

End-Users

The end-users of biochar include Milan's municipal green departments, landscaping firms, and community gardens, all of whom benefit from enhanced soil phytotoxicity and reduced maintenance costs. Educational institutions also emerge as indirect end-users, incorporating biochar into programs that teach students about sustainable practices and carbon sequestration. By serving these end-users, the initiative promotes local engagement and demonstrates the practical benefits of biochar in real-world applications, enhancing its perceived value among stakeholders.

Social Impacts

The biochar initiative's social impacts span improved urban greening, enhanced public awareness, and increased community involvement in environmental practices. Positively, the initiative fosters social inclusion by engaging a broad spectrum of stakeholders, from municipal authorities to neighborhood groups. It creates educational opportunities, promoting environmental literacy and encouraging residents to view green waste as a valuable resource. On the downside, the initiative could potentially face challenges related to public acceptance, particularly if residents are not adequately informed about biochar's benefits. Effective outreach is essential to mitigate resistance and ensure broad social acceptance.

Social Benefits

The initiative contributes numerous social benefits to Milan's urban community, including cleaner, more sustainable green spaces, heightened environmental awareness, and enhanced community cohesion around sustainability goals. By improving the city's green spaces and reducing waste, the biochar initiative aligns with Milan's commitment to a sustainable urban environment, benefiting residents through cleaner air, healthier soils, and a more livable city. These benefits ultimately create a stronger sense of shared purpose among Milan's residents and strengthen the city's social fabric, making the biochar initiative a valuable contributor to Milan's long-term environmental and social well-being.

2.4. Discussion

This study explores the application of the *Circular Triple-Layered Business Model Canvas* to the case of biochar production from urban pruning waste in Milan. While the case study remains largely explorative, it provides a valuable demonstration of how the CTLBMC can align circular economy initiatives with sustainability goals, even in the absence of comprehensive empirical data. The findings underscore the framework's flexibility and capacity to integrate economic, environmental, and social dimensions into a cohesive evaluation of circular practices. The biochar case study highlights how the CTLBMC enables the identification of cascading effects across its three layers. For instance, the economic viability of the initiative, supported by revenue streams from biochar sales and potential carbon credits, directly funds community engagement programs and educational workshops. These activities build public acceptance and enhance participation in waste collection efforts, which in turn improve feedstock quality and ensure a consistent supply for biochar production. This interconnected value creation process exemplifies the CTLBMC's utility in mapping synergies across dimensions, providing a strategic roadmap for maximizing the impact of circular economy projects. Despite its exploratory nature, the case study sheds light on several practical insights specific to Milan's urban context. Milan's extensive green waste infrastructure, with approximately 23,438 tons of pruning waste generated annually, presents a significant opportunity for circular waste management. By converting this waste into biochar through pyrolysis, the initiative could sequester approximately 12,045 tons of CO_2-equivalents annually, while avoiding an additional 29,300 tons of CO_2-equivalents by reducing methane emissions from landfill decomposition. These figures reinforce the environmental potential of biochar as a tool for urban climate mitigation, aligning with Milan's sustainability objectives and broader circular economy principles. The case study also reveals potential trade-offs and challenges associated with biochar production. While the pyrolysis process contributes to greenhouse gas mitigation through carbon sequestration, it also requires significant energy inputs, which could offset some environmental benefits if non-renewable energy sources are used. Similarly, the social benefits of the initiative, such as job creation and community engagement, depend on sustained financial support and public participation. The CTLBMC facilitates the identification of these trade-offs, enabling stakeholders to prioritize interventions that maximize net benefits while mitigating potential risks. By structuring hypothetical and secondary data within the CTLBMC framework, this study provides a replicable template that can be refined with localized, empirical inputs in future iterations. The framework's adaptability enhances its relevance across diverse urban contexts, making it a valuable tool for stakeholders aiming to design and implement circular economy initiatives. For Milan, the biochar case study serves as a proof of concept that demonstrates how circular practices can transform urban waste management, offering strategic guidance for advancing sustainability in other cities with similar challenges. The key contribution of this study lies in its methodological innovation. While previous frameworks, such as the Triple-Layered Business Model Canvas and circular business models, address individual aspects of sustainability, the CTLBMC uniquely bridges these perspectives to enable a holistic analysis. By emphasizing cascading effects and interdependencies, the CTLBMC advances circular economy literature, offering a practical tool that integrates economic, environmental, and social dimensions into strategic decision-making.

2.4.1. Managerial Implications

The biochar case study offers critical insights for managers and decision-makers implementing circular economy initiatives, presenting the *Circular Triple-Layered Business Model Canvas* as both a structured and adaptive tool. This model's layered design integrates circular principles within economic activities, allowing managers to assess how these changes create cascading effects across environmental and social dimensions. This interconnected perspective enables managers to evaluate returns on circular investments beyond traditional financial metrics, capturing additional value in community engagement, waste reduction, and ecological resilience. By strategically leveraging revenue streams like carbon credits and biochar sales, managers can effectively align business goals with broader environmental objectives, building a model that simultaneously addresses municipal priorities and public support. The model also supports the formation of cross-sector partnerships, essential for urban circular economy projects. The biochar initiative demonstrates that by clearly outlining shared and individual benefits, managers can strengthen public-private partnerships. This transparency proves valuable for securing funding and community buy-in, providing stakeholders with a comprehensive understanding of each partner's contributions and benefits. Policymakers, too, can leverage this structure to assess the combined social and environmental value provided by potential collaborators, guiding partnership choices that align with public interests. From a policy perspective, the CTLBMC offers municipalities a robust structure to embed circularity into policy frameworks. As cities increasingly pursue sustainability, this model helps managers illustrate how circular initiatives meet regulatory standards, sustainability targets, and funding criteria. Aligning project objectives with policy priorities simplifies regulatory compliance, enhances the appeal of circular projects to local governments and funding agencies, and potentially expedites approval processes for such initiatives. The model's transparency in showing cascading effects across dimensions also enables managers to anticipate how decisions in one area influence others. By mapping these interdependencies, managers can develop strategies that are resilient and balanced across economic, environmental, and social factors. For instance, logistics adjustments that minimize environmental impacts can simultaneously foster greater community acceptance, as seen in the biochar initiative's localized approach to waste collection and processing. This interconnected perspective supports a comprehensive approach to decision-making, aligning with the multi-faceted goals of circular economy models while catering to both environmental science and managerial economics insights.

2.5. Conclusions

This study presents the *Circular Triple-Layered Business Model Canvas* as an innovative, adaptable tool for analyzing and implementing circular economy initiatives, using biochar production from Milan's urban pruning waste as a case study. The CTLBMC's layered structure facilitates an integrated approach, aligning economic, environmental, and social objectives in a cohesive framework that responds to the complex demands of urban sustainability. By capturing cascading effects initiated within the economic layer and observing their impact on the environmental and social dimensions, the model highlights the interconnected benefits of circular investments. This framework enables managers, policymakers, and stakeholders to align sustainable business objectives with community and municipal priorities, demonstrating its potential as a versatile tool in advancing circular economy practices in diverse urban contexts.

2.5.1. Limitations and Future Perspectives

While the CTLBMC showcases significant potential for supporting circular economy goals, this study remains conceptual, as the biochar case application is hypothetical and lacks comprehensive empirical validation. As such, real-world data on biochar's full economic, environmental, and social impacts in Milan is limited. Additionally, the CTLBMC's adaptability across other sectors and urban settings, while promising, would require further testing and adjustment to meet the specific needs and regulatory landscapes of different regions. The model's cascading impact across layers, while theoretically robust, may introduce challenges in isolating cause-and-effect relationships in dynamic urban systems. Future studies should build on this framework by incorporating empirical data to validate the CTLBMC's application in real-world contexts, such as biochar's quantitative impacts on waste reduction, carbon sequestration, and local community engagement. Applying the CTLBMC to other circular initiatives, such as water reclamation or sustainable construction, would further clarify its adaptability and scalability across urban sustainability projects. Integrating digital tools for tracking cascading effects across dimensions could also enhance its utility, offering a dynamic way to visualize and optimize sustainable practices. Ultimately, advancing the CTLBMC's design with empirical insights and digital integration could refine it as a foundational tool, bridging theory and practice in sustainable business model innovation.

CHAPTER III – MAPPING GREEN INNOVATION

While the in-depth case study demonstrated how a sustainable business model can be designed for a specific green technology, a single example cannot capture the dynamics of the entire sector. To understand the wider trends of the green transition, the focus must shift from the architecture of one business to the landscape of invention itself. The next chapter, therefore, takes a new empirical turn, analyzing the vast repository of patent data. This approach allows for a mapping of the dominant technological trajectories, the identification of key innovators, and an assessment of the strategic intent behind green innovation on a global scale.

Abstract

This chapter analyzes the global landscape of invention in agricultural climate technologies to understand the real dynamics of the green transition. Addressing the "innovation-policy disconnect", where patent volume often fails to translate into real-world impact, the study conducts a large-scale analysis of 13,727 patent families. The methodology is based on a targeted search in the Orbit Intelligence database to map temporal, geographical, technological, and assignee trends. Key findings reveal that the innovation landscape is overwhelmingly dominated by adaptation technologies rather than mitigation solutions. China emerges as the primary global actor in patent filings, with a peak after 2015, but this high volume is offset by a surprisingly high patent abandonment rate. This strategy contrasts with the long-term strategic retention of Western and Japanese firms. The analysis provides an empirical census of technological output, highlighting the profound differences between national innovation models and questioning the link between invention and on-the-ground climate action.

3.1. Introduction

Having explored the micro-level design of sustainable business models in the previous chapter, this dissertation now shifts its focus to the macro-level landscape of technological invention. While the case study demonstrated the theoretical viability of circular models, their practical scalability depends on the availability of specific technologies. Therefore, to understand the context in which firms operate, it is essential to map the global supply of innovation. This chapter provides that necessary context by analyzing the global patent landscape, identifying the dominant technological trajectories and the key actors driving the green transition.

Agriculture plays a dual role in the climate crisis, acting both as a significant contributor to greenhouse gas emissions and as one of the sectors most exposed to climate change risks. The sector accounts for a substantial share of global emissions, primarily through methane from livestock, nitrous oxide from fertilizers, and carbon dioxide from land-use changes (Balogh, 2020; Alvarado et al., 2021). Unsustainable practices further exacerbate soil degradation, biodiversity loss, and water overuse, intensifying environmental pressures (Ortiz et al., 2021; Adekoya et al., 2022). Simultaneously, agriculture faces increasing vulnerability to climate-induced stresses such as rising temperatures, shifting precipitation patterns, and extreme weather events, which threaten food security and rural livelihoods (Malhi et al., 2021; Habib-ur-Rahman et al., 2022; Bai et al., 2024). To address these challenges, climate-smart agricultural practices must enhance resilience while mitigating environmental impacts (Egerer et al., 2021; Ojo et al., 2021; Vizinho et al., 2021). However, their adoption is often constrained by financial, institutional, and behavioral barriers (Kreft et al., 2021; Fujimori et al., 2022). In this context, technological innovation emerges as a key driver of sustainable transformation, with advancements in precision farming, improved irrigation systems, and climate-resilient crop varieties offering potential solutions (Balasundram et al., 2023; Wakweya, 2023). Yet, its path from invention to real-world impact is fraught with challenges, many of which stem from a critical "innovation-policy disconnect". Current innovation policies, particularly in state-led systems, often incentivize patent filings as a primary metric of success (Wu et al., 2024; Cheng et al., 2024; Zhang et al., 2024; Zhu et al., 2024). This focus on quantity, however, can create an "illusion of progress", leading to a surge in patents that are never commercialized, strategically maintained, or translated into scalable climate solutions for farmers (Kang et al., 2025; Cao et al., 2024; Li & Lin, 2024). The result is a growing repository of promising-on-paper inventions that fail to deliver tangible environmental or economic benefits (Patel 2025; Ilić, 2024; Cefis et al., 2024). This paper argues that to design more effective policies, the focus must shift from simply counting inventions to understanding their entire lifecycle, from filing and retention to abandonment. Only by examining this full trajectory can we begin to bridge the gap between patented technology and genuine, on-the-ground climate action in agriculture.

The increasing role of digital agriculture further supports resource optimization, emissions reduction, and adaptation strategies (Maja & Ayano, 2021; Blakeney, 2022). Green patents provide a crucial lens for assessing technological progress in sustainability-driven innovation, reflecting both the intensity and direction of research efforts. Prior studies have investigated various dimensions of green patenting, including methodological approaches to tracking green technological innovation (Favot et al., 2023; Pavesi et al., 2024a), the role of policy and regulatory frameworks in stimulating green patent filings (Fabrizi et al., 2025; Nelson et al., 2022), and the relationship between firm-level characteristics and environmental innovation (Kim et al., 2021). Additionally, research has examined how green innovation is shaped by spatial and institutional factors, such as regional knowledge spillovers (Deng et al., 2022), global patenting trends across industries (Glaeser & Lang, 2024), and co-patenting collaborations in the agri-food sector (Ponta et al., 2022). Studies focusing on agriculture have explored specific technological advancements, such as biofuels (Nelson et al., 2022), administrative versus regulatory green technologies (Liu et al., 2023), and sustainability-oriented innovations within the food system (Ponta et al., 2022). Furthermore, broader analyses of climate change mitigation and adaptation emphasize the need for innovation to reduce environmental impact while ensuring resilience (Malhi et al., 2021; Grigorieva et al., 2023; Abbass et al., 2022). Despite this growing body of research, crucial questions and underexplored areas of inquiry persist. First, while green patent studies offer valuable insights into general technological trends, a limited understanding remains regarding the specific dynamics within the agricultural sector, particularly concerning the distinction between climate adaptation and mitigation technologies. Indeed, many studies incorporate agriculture into broader environmental innovation contexts without clearly examining its unique technological challenges and policy drivers. Secondly, the question arises as to how surges in patenting activity effectively align with national policy strategies and what the long-term trajectory of such innovations is, an aspect still little investigated (Deng et al., 2022; Liu et al., 2023). Thirdly, it is not yet clear to what extent green patents translate into commercially viable technologies or remain confined to institutional research systems, raising questions about their actual diffusion and impact (Glaeser & Lang, 2024; Yang et al., 2023). Finally, the legal status and lifecycle of agricultural climate patents, especially in terms of retention, abandonment, and their implications for the sustainability of innovation, constitute a critical yet still largely overlooked dimension in existing literature. These research gaps underscore a significant "innovation-policy disconnect": current innovation policies, while often incentivizing patent filings, frequently overlook their subsequent vitality, strategic maintenance, and effective translation into applied and disseminated climate solutions, especially in agriculture.

To address the research gaps and the policy disconnect previously outlined, this study conducts a large-scale patent analysis of agricultural climate technologies. The primary objective is to track temporal, geographical, and institutional trends across both adaptation and mitigation domains, assessing not only where green innovation is occurring, but also the extent to which it is sustained and strategically protected. Specifically, this paper makes three main contributions. First, it introduces a sector-specific patent analysis using a dual classification system (CPC + IPC). Second, it incorporates legal status and co-assignment data to assess the longevity and collaborative nature of innovation. Third, it evaluates how national innovation models, particularly China's state-led strategy, align with long-term climate resilience goals. By doing so, this research offers critical insights for policymakers and managers, informing the design of adaptation-focused innovation policies in regions highly vulnerable to climate change, where technology transfer and commercialization support are urgently needed to turn inventions into accessible, context-sensitive solutions.

The remainder of this paper is organized as follows. The next section provides a literature review, synthesizing key findings on green patents, climate innovation, and the role of policy in shaping agricultural technology trends. This is followed by the Methodology section, which outlines the data collection process, patent classification strategy, and analytical approach. The Results section presents the key findings across five analytical dimensions, including temporal trends, geographical distribution, assignee activity, technological focus, and legal status. The Discussion interprets these findings in the context of global innovation strategies, highlighting the dominance of adaptation technologies, China's patenting dynamics, and commercialization challenges. Managerial implications are also outlined, emphasizing the strategic considerations for policymakers, firms, and research institutions. Finally, the Conclusion summarizes the key insights, acknowledges study limitations, and suggests directions for future research

3.2. Theoretical Framework

Green innovation plays a critical role in the transformation of agricultural systems toward sustainability. With agriculture being both a contributor to climate change and a sector highly vulnerable to its effects, the integration of green technologies has become essential in ensuring long-term resilience (Khanh Chi, 2022; Sun et al., 2023). Sustainable agricultural practices have evolved to include resource-efficient production systems, circular economy principles, and digital solutions designed to optimize inputs and reduce environmental footprints (Abbasi & Zhang, 2024; Sarfraz et al., 2023). The adoption of green innovations is largely influenced by policy incentives, technological advancements, and the economic viability of sustainability-driven practices (Puertas et al., 2023). Emerging economies, in particular, face challenges in balancing agricultural productivity with environmental stewardship, requiring robust frameworks that promote green innovation without jeopardizing food security (Smolenaar et al., 2024; Kumar & Sindhu, 2023). However, recent studies increasingly question whether traditional innovation metrics, like patent counts, accurately reflect on-the-ground sustainable progress, especially when comparing the policy-driven patent surges in emerging economies with the market-oriented innovation in developed nations (Spreafico et al., 2025; Mubeen et al., 2024; Rainville et al., 2024).

A key metric for evaluating technological progress in sustainable agriculture is the analysis of green patents, which serve as indicators of research intensity, commercialization potential, and policy-driven technological shifts (Li et al., 2024; Barragán-Ocaña et al., 2023). Patents provide insight into the pace of green innovation, the geographical distribution of technological leadership, and the role of intellectual property in the diffusion of sustainable practices (Kang et al., 2022; Liao et al., 2024). Patent analysis has revealed substantial disparities in innovation dynamics, with some countries leading in patent filings but demonstrating limited retention, while others maintain a long-term strategic approach to intellectual property protection (Zhang & Fujii, 2024; Jiang et al., 2022, Baglieri et al., 2014). This disparity has become a central theme in recent comparative innovation literature. For instance, while new research on Western firms links patent retention directly to commercialization strategies and market value (Broekel & Klarl, 2025; Blind et al., 2022), analyses of the Chinese system suggest that high patent abandonment rates are a structural outcome of subsidy-driven R&D policies that prioritize quantity over quality (Li & Branstetter, 2024; Li et al., 2023; Wu et al., 2022). This dichotomy between market-driven retention and policy-driven filings (Wang et al., 2024) is a central theme of our investigation. The global diffusion of green technologies remains uneven, often constrained by regulatory frameworks, market structures, and institutional capacities (Losacker, 2022). Despite the widespread recognition of the importance of green innovation, commercialization remains a challenge, with many patented technologies failing to transition from research to large-scale application (Ferrari et al., 2019; Perot, 2023).

Agricultural strategies for climate adaptation have increasingly relied on precision agriculture, water conservation measures, and soil management techniques aimed at enhancing resilience to extreme weather conditions (Mumtaz & Puppim de Oliveira, 2023; Casagrande et al., 2024). The development of climate-resilient crop varieties, advanced irrigation systems, and agroforestry techniques has contributed to sustaining agricultural productivity in the face of rising temperatures and shifting precipitation patterns (Xing & Wang, 2023; Van Tilburg & Hudson, 2022). However, adaptation measures often require substantial investment, limiting their accessibility to smallholder farmers in vulnerable regions (Skevas et al., 2022; Savari et al., 2021). The role of policy frameworks in incentivizing adaptation technologies remains a critical factor, as state interventions in the form of subsidies, grants, and research funding can significantly influence technology adoption rates (Quandt et al., 2023). Knowledge transfer and farmer education are also essential in ensuring that adaptive practices are effectively integrated into diverse agricultural landscapes (Pandey et al., 2022). While adaptation strategies seek to protect agricultural systems from the impacts of climate change, mitigation efforts focus on reducing greenhouse gas emissions associated with farming activities (Fuglie et al., 2024; Waheed et al., 2025). Carbon sequestration techniques, including biochar application, conservation tillage, and reforestation, have gained traction as viable mitigation strategies (Pavesi et al., 2024b; Abdalqadir et al., 2024; Liu et al., 2023). The reduction of methane emissions in livestock production has also become a central area of research, with dietary interventions and manure management practices demonstrating potential in curbing emissions (Black et al., 2021; Zhao et al., 2025). Technological advancements in fertilizer production, particularly through the development of low-emission alternatives, highlight the role of innovation in mitigating agriculture's environmental impact (Pan et al., 2022; Basnet et al., 2023). Despite these efforts, the implementation of mitigation strategies faces economic and structural barriers, with cost-effectiveness and scalability being key considerations in their widespread adoption (Laborde et al., 2021).

Alongside these established sustainable practices, digital agriculture technologies are rapidly emerging as powerful enablers of climate action in the sector. Innovations centered on the Internet of Things (IoT) (Salam, 2024; Farooq et al., 2019; Muangprathub et al., 2018), Artificial Intelligence (AI) (Usigbe et al, 2024; Leal Filho et al, 2022; Cheong et al., 2022), and blockchain (Sajja et al. 2022; Hou et al. 2021; Niknejad et al., 2021) are particularly noteworthy for their potential to enhance both climate adaptation and mitigation. For instance, IoT sensor networks combined with AI analytics facilitate precision agriculture, leading to optimized input use (e.g., water, fertilizers, pesticides), which helps conserve resources and reduce greenhouse gas emissions (Mansoor et al., 2025; Sharma & Shivandu, 2024). Such systems also bolster adaptive capacity by enabling farmers better to manage climate-related risks like droughts or pest outbreaks (Parra-López et al 2024). Blockchain technology, in turn, can improve the traceability of sustainably produced goods (Mukherjee et al., 2022; Saberi et al. 2018) and support frameworks for carbon accounting or climate finance in agriculture (Camel et al., 2024). These digital tools are increasingly recognized not merely as efficiency enhancers, but as foundational infrastructure for implementing modern climate policy frameworks. In the context of mitigation, for example, they are essential for the viability of carbon farming schemes under policies like the EU's Carbon Removal Certification Framework. AI, combined with IoT sensors and satellite imagery, provides the robust Measurement, Reporting, and Verification (MRV) required to certify soil carbon sequestration (Körner et al., 2025; Brummitt et al., 2024), while blockchain can ensure the transparent and immutable tracking of carbon credits (Ahmed & Shakoor, 2025; Swinkels, 2024). On the adaptation front, these technologies are crucial for enacting national climate resilience strategies. AI-driven predictive analytics can power early warning systems for droughts and pest outbreaks, often a cornerstone of national adaptation plans, enabling proactive resource management and supporting data-driven parametric insurance schemes that protect rural livelihoods (Reichstein et al., 2025; Masupha et al., 2025). The innovative potential of these digital tools in fostering climate-smart agriculture is increasingly reflected in patent filings. A growing body of "digital green patents" covers smart farming systems, data-driven decision support tools, and transparent supply chain solutions geared towards sustainability. These patents inherently support climate adaptation and mitigation objectives, though their primary technological focus on software, data analytics, and system integration means they may sometimes be found across a diverse range of patent classifications, distinct from or complementary to those traditionally associated with agricultural machinery or inputs (Li et al., 2025; Fang & Li, 2024; Li & Zhu, 2024). Yet, while the volume of these "digital green patents" grows, recent field studies are tempering early enthusiasm by revealing significant real-world adoption barriers, including high upfront costs, data interoperability issues, and a persistent digital skills gap among farmers (Saha et al., 2025; Wang et al., 2024; Dibbern et al., 2024). This emerging evidence highlights a critical disconnect between the patented potential of digital agriculture and its current practical impact, reinforcing this paper's core thesis. While the present study focuses on a defined set of established climate and agricultural patent codes to analyze core trends in adaptation and mitigation technologies, the rise of these digital green patents signifies a crucial and expanding frontier in the broader landscape of innovation for sustainable, climate-resilient agriculture.

The patent lifecycle, commercialization trends, and global diffusion of green technologies further shape the agricultural innovation landscape (Dong et al., 2022; Nelson et al., 2022). Patent abandonment rates indicate that many innovations remain within the research domain, failing to transition into commercial products or services (Van Holm et al., 2021; Hsu et al., 2020). In some cases, green patents are used as strategic assets by firms to secure competitive advantages rather than to facilitate technology diffusion (Wang & Zheng, 2022). Regional variations in patent enforcement and commercialization policies impact the effectiveness of intellectual property systems in promoting sustainability-driven innovation (Losacker, 2022). The role of international collaboration in technology transfer is critical in bridging gaps between research institutions, industry players, and policymakers, ensuring that green technologies are effectively disseminated across borders (Amentae et al., 2024; Coupet & Ba, 2022).

Green patents are a useful lens for understanding how agricultural climate innovation is evolving, but their real impact depends on more than just the number of filings. What matters is whether these technologies make it past the research stage, get adopted by the industry, and actually contribute to sustainability goals. The balance between climate adaptation and mitigation strategies presents both opportunities and roadblocks, with innovation often concentrated in certain regions while struggling to scale globally. To move beyond just counting patents, we take a closer look at their lifecycle—where they originate, who's filing them, how they spread, and whether they're being retained or abandoned. The next section breaks down our approach, covering data collection, classification methods, and the key factors we analyze to get a clearer picture of how green patents are shaping the future of agricultural climate technologies.

3.3. Methodology

3.3.1. Data Collection & Scope

This study is based on patent families, which group together multiple patents protecting the same invention across jurisdictions. While patents and patent families differ in legal terms, they are treated interchangeably throughout this study to align with Orbit Intelligence's methodology. The dataset includes all patent families filed up until December 31, 2024, providing a comprehensive snapshot of technological developments in agricultural climate innovation. While Orbit Intelligence provides historical patent data dating as far back as records exist, our analysis focuses on the last 30 years, starting from the 1990s. This decision is grounded in prior research, which identifies the 1990s as the turning point for structured green innovation, marking the emergence of sustainability-driven technological advancements and their integration into business strategies (Pavesi et al., 2024a). By aligning with this timeframe, we ensure that our analysis captures the period in which green patents began to play a significant role in innovation ecosystems, policy frameworks, and market dynamics. Patent data and analytics for this study were retrieved from Orbit Intelligence, a widely recognized patent analysis platform that provides structured metadata, legal status tracking, and visualization tools for patent-based research. Orbit has been extensively used across multiple disciplines to examine innovation trends, assess technological diffusion, and evaluate the commercialization potential of emerging patents. For example, Da Silveira et al. (2021) employed Orbit to analyze agricultural machinery patents in Brazil, focusing on technological advancements in emission reduction. Similarly, Frisio & Ventura (2021) used Orbit to track global innovation trends in plant-based vaccine production, highlighting how patent data can provide insight into the trajectory of technological development. Orbit's strength lies in its ability to integrate various analytical dimensions, including priority and application year trends, assignee activity, geographical distribution, and patent classification mapping. This functionality has proven valuable in diverse sectors, from healthcare business methods (Da Veiga et al., 2024) to sustainability trends in aquaculture (Leal et al., 2025). Its capacity for legal status tracking, distinguishing between active and expired patents, is particularly crucial for evaluating which technologies are merely speculative filings and which have a real chance of market impact. This feature allows researchers to assess whether innovations are retained, commercialized, or abandoned, an essential aspect when analyzing green patents and their contribution to agricultural climate adaptation and mitigation. Moreover, Orbit facilitates patent landscape visualization, enabling a structured approach to identifying key players, regional innovation hubs, and technological clusters. This study leverages these capabilities to build a comprehensive picture of green patent activity in agriculture, distinguishing between adaptation and mitigation-focused innovations while assessing their global diffusion. By integrating multiple dimensions of patent analysis, Orbit ensures that our findings are not limited to raw filing counts but instead provide a nuanced view of how green technologies are emerging, evolving, and scaling within the agricultural sector. This study's analysis is based on patent data sourced from the Orbit Intelligence platform. Orbit aggregates data from the European Patent Office's comprehensive PATSTAT database with direct information feeds from other major patent offices, establishing it as a standard tool for large-scale innovation research (Priore, 2024; Kadlec et al., 2023). However, like all patent databases, it is subject to certain methodological caveats. Data coverage and update timeliness are not uniform across all countries, which may lead to underrepresentation or reporting lags for some jurisdictions. Moreover, inherent differences in national legal frameworks and classification practices can affect the direct comparability of patenting activity across borders.

The data also reflects only patented inventions and can be influenced by corporate strategies that may favor trade secrets over patents. While this dataset provides a robust foundation for our analysis, these potential biases are acknowledged in the interpretation of our findings (Karataş et al., 2024).

3.3.2. Patent Search Strategy & Classification Codes

To systematically identify agricultural climate adaptation and mitigation technologies, we constructed an advanced search query using International Patent Classification (IPC) and Cooperative Patent Classification (CPC) codes, which categorize patents based on technological focus. The query used was:

(((Y02P OR Y02A)/IPC/CPC AND (A01G-025/00 OR A01G-023/00 OR A01N-025/00 OR C09K-017/00 OR A01N-065/00 OR E02D-003/00)/IPC/CPC) AND (EPD < 2024-12-31))

This query integrates two core components (Tab. 1): Climate-Specific Technologies (Y-Class in CPC) – these codes capture patents related to climate change adaptation and mitigation, including water conservation, soil stabilization, and environmentally friendly agricultural practices – and Targeted Agricultural & Environmental Technologies (IPC & CPC) – these codes refine the search by focusing on specific agricultural inputs and practices, such as greenhouse technologies, irrigation, biopesticides, fertilizers, and soil stabilization techniques.

Category	**Code**	**Description**
Climate-Specific Technologies	Y02A	Climate adaptation technologies, such as water conservation, soil stabilization, and resilient crop production techniques
	Y02P	Climate change mitigation technologies, including environmentally friendly fertilizers, sustainable agricultural methods, and pollution reduction processes
Targeted Agricultural & Environmental Technologies	A01G-023/00	Greenhouses and climate-controlled farming systems
	A01G-025/00	Water-saving irrigation techniques
	A01N-025/00	Biopesticides and natural plant protection agents
	A01N-065/00	Climate-resilient herbicides and plant-growth regulators
	C09K-017/00	Soil-conditioning compositions (e.g., fertilizers, biostimulants)
	E02D-003/00	Soil stabilization and erosion control solutions

Table 3.1 – CPC and IPC codes used in the Orbit search query. Source: Author's elaboration.

Table 3.1 outlines the specific patent classification codes used to construct the search query for this study. The combination of broad climate-focused codes (Y02A, Y02P) with targeted agricultural application codes ensures a comprehensive yet relevant dataset for answering the study's research questions.

To guarantee a focused yet comprehensive dataset, we combined climate-focused Y02 classifications with A01, C09K, and E02D codes, each targeting a critical aspect of agricultural climate adaptation. Y02 categories capture mitigation and adaptation technologies broadly, while A01 and C09K focus on direct applications in soil treatment, irrigation, and plant protection. E02D-003/00 was included to account for climate-resilient soil stabilization and erosion control, crucial for mitigating the effects of extreme weather, improving land-use sustainability, and ensuring long-term agricultural viability. These classifications collectively align with major agricultural adaptation strategies, emphasizing resilient input management, mechanization, and environmental sustainability.

To ensure the accuracy and relevance of the dataset, a series of data-cleaning procedures were applied. Duplicate removal was conducted to eliminate redundant patent family records and prevent overcounting. Assignee name standardization was implemented to consolidate different naming variations, ensuring consistency across the dataset. Patent status validation categorized patents as either "alive" (granted or pending) or "dead" (lapsed, revoked, or expired), allowing for a clear distinction between active and inactive innovation trends. The initial dataset, retrieved from Orbit Intelligence, contained 13,743 patent families related to agricultural climate adaptation and mitigation technologies, covering all filings up to December 31, 2024. Following the data-cleaning process, which included duplicate removal, name standardization, and legal status validation. The final dataset comprised 13,727 patent families. To further ensure reliability, a subset of patent families was manually inspected to verify classification accuracy and minimize false positives. Additionally, assignee names were cross-referenced with global company registries to consolidate variations and ensure uniformity.

This methodological approach, summarizing both the search query strategy and data-cleaning process, is visually represented in Figure 3.1, which provides a comprehensive overview of the dataset construction and refinement.

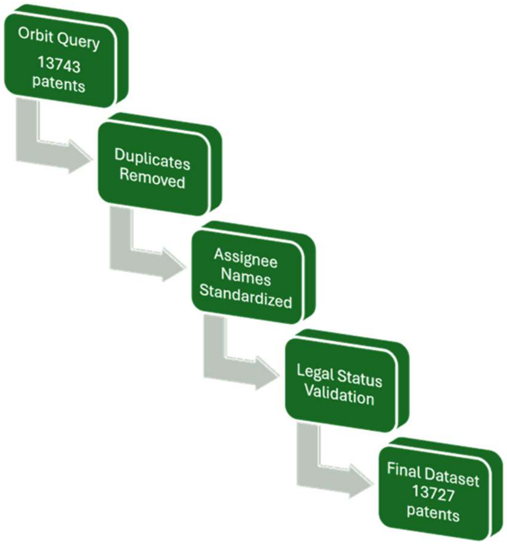

Figure 3.1 Methodological Flowchart. Source: Author's elaboration.

3.3.3. Patent Analysis Dimensions

The analysis follows Orbit Intelligence's structured methodology from the "Analysis Module", covering five key analytical dimensions:

1) Temporal Trends: tracking priority, application, and publication years to identify innovation waves;
2) Geographical Distribution: identifying where patents are filed, published, and protected;
3) Assignees & Inventors: analyzing which institutions and individuals lead innovation;
4) Technological Landscape: categorizing patents by broad and specialized technical domains;
5) Patent Lifecycle & Legal Status: assessing the enforcement status of patents, distinguishing between active and inactive innovations.

This structured approach ensures a comprehensive and systematic assessment of global patenting activity in agricultural climate adaptation and mitigation technologies.

Insight Box: A Comparative Case Study Methodology

To enrich the findings of this broad-scale analysis, this chapter employs a comparative case study methodology. While the primary dataset provides a comprehensive overview of green agricultural innovation, it is complemented by targeted insights from a separate, focused analysis of a cutting-edge technological sub-domain: green and digital "twin patents". This second dataset, comprising 12,162 active patent families, isolates high-tech inventions that are at the nexus of the green and digital transitions. This focus is achieved through two key methodological distinctions from the main analysis. First, the patent search strategy differs fundamentally in scope and logic. The main analysis uses a broad query that combines general climate change classifications (e.g., Y02A for adaptation, Y02P for mitigation) with codes for established agricultural applications like irrigation (A01G) and soil conditioning (C09K). In contrast, the case study employs a highly specific search using a strict 'AND' operator to isolate patents that are simultaneously classified as green (under the Y02 scheme) and foundational digital technologies, such as Artificial Intelligence (G06N), data processing (G06F), and IoT (H04L). Second, the scope of legal status is deliberately different. To analyze the full innovation lifecycle and crucial abandonment trends, the main study includes both active ("alive") and inactive ("dead") patents. The case study, however, is limited to active ("alive") patents to exclusively map the contested, state-of-the-art technological frontier, filtering out obsolete or discontinued R&D paths. By strategically incorporating key findings from this case study into the main analysis through "Insight Boxes", we can contrast broad trends with those at the technological frontier, deepen our understanding of specific phenomena (e.g., assignee strategies), and provide concrete evidence for emerging paradigm shifts. This approach allows the chapter to maintain its broad scope while leveraging a deep-dive analysis to reveal more nuanced and forward-looking dynamics.

3.4. Results

3.4.1. Temporal Trends: How Has Green Innovation Evolved?

The evolution of patent filings over time is a crucial indicator of innovation trends in agricultural technologies aimed at climate adaptation and mitigation. Analyzing priority years, application years, and publication years from 1994 to 2024 provides a comprehensive yet focused view of how technological advancements, policy interventions, and market dynamics have shaped patenting activity. This timeframe captures the most relevant developments in agricultural climate innovation, as earlier records are often incomplete or less reflective of contemporary research and policy-driven innovation. Additionally, the 1990s marked the emergence of international climate agreements and sustainability-driven research initiatives, making this 30-year span particularly significant for tracking long-term trends. The dataset reveals a significant rise in patent filings over the past three decades, with a notable acceleration after 2010. In the early years of the dataset, from 1994 to 1998, patent filings were relatively low, averaging 50–60 patents per year. By contrast, from 2015 onwards, the number of patents surged, reaching peak activity in 2017, with 1,555 applications, 1,544 priority filings, and 1,475 publications. This increase in patenting activity indicates a period of heightened innovation and investment in agricultural climate adaptation technologies. The steady rise throughout the 2000s suggests a growing focus on climate-related challenges and technological advancements, potentially driven by international climate agreements, government funding programs, and increased awareness of sustainable agricultural practices.

Priority Year

The priority year represents the moment an inventor first claims a novel idea, marking the initial step in the patenting process. Analyzing priority years provides insight into when technological advancements in agricultural climate adaptation and mitigation first emerged. Figure 3.2 shows the annual count of patent families by priority year from 1994 to 2024, along with a polynomial trend line that highlights the trajectory of innovation over time. The trend emphasizes the steady growth in filings until 2015, followed by a sharp surge in 2016–2017 and a subsequent stabilization, possibly indicating a structural shift in patenting behavior. During the 1990s and early 2000s, priority filings remained relatively low, with fewer than 100 patents per year. However, starting in 2005, a steady increase became evident, with filings surpassing 200 per year by 2010. This upward trajectory reflects a growing emphasis on climate-focused agricultural innovation, likely spurred by increasing global awareness of environmental challenges and advancements in green technology. A particularly sharp acceleration occurred between 2015 and 2017, culminating in 2017 with 1,544 priority filings, the highest in the dataset. Figure 2 illustrates a clear three-phase evolution in innovation: a long period of low activity, a sharp acceleration peaking in 2017, and a subsequent decline in recent years. This peak suggests that a surge of innovation occurred in response to evolving regulatory frameworks and market demand for sustainable solutions. Since priority filings precede application years, this period marks the conceptualization and early-stage development of many of today's key agricultural climate technologies. Following the peak in 2017, priority filings remained high but began to decline after 2022, with a notable drop in 2023 and 2024. This decline may indicate a shift in research priorities, evolving market conditions, or changes in patenting strategies by major players. The priority year trends provide a historical foundation for understanding the timing and drivers of innovation in agricultural climate technologies, setting the stage for the subsequent analysis of patent applications and publications.

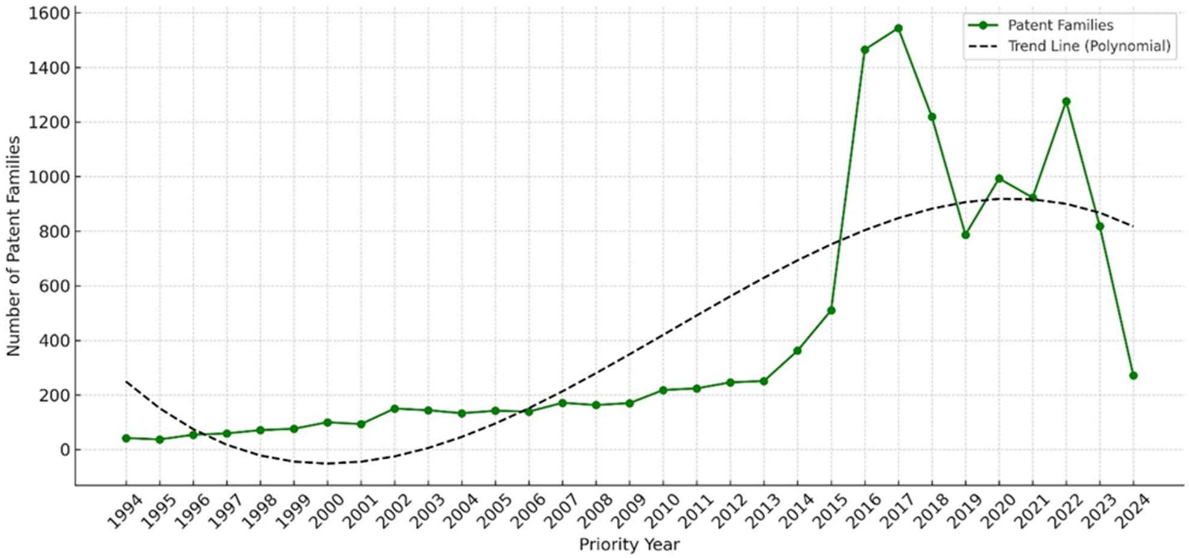

Figure 3.2 First Priority Year. Source: Author's elaboration on Orbit data.

Application and Publication Year

Patent applications and publications generally follow the trends observed in priority filings, reflecting the progression of innovations from conceptualization to formal legal protection and eventual public disclosure. However, a short but noticeable lag exists between these stages, as patents move through the review and examination process.

Following the surge in priority filings from 2015 to 2017, applications peaked in 2017 at 1,555, just ahead of the 1,544 priority filings recorded that year. This tight alignment suggests that a significant share of patented innovations moved swiftly through the system, likely fueled by favorable policy incentives and increased investment in green technologies. Publications, which typically follow 18–24 months after applications, also reached their peak in 2017 at 1,475, confirming that the mid-2010s represented the height of innovation activity in agricultural climate technologies.

Even as priority filings declined post-2017, applications and publications remained high through 2020–2022, consistently exceeding 900 per year, reinforcing the idea that many of the technologies initiated during the peak years were still entering the system with a built-in delay. However, by 2023, applications dropped to 825, and publications fell to 734, with further declines seen in 2024 (272 applications, 215 publications so far). This downturn, closely tracking the earlier decline in priority filings, suggests that the agricultural climate innovation wave of the mid-to-late 2010s is now tapering off, likely due to shifting research priorities, evolving regulatory landscapes, or changing commercialization dynamics.

3.4.2. Geographical Distribution of Green Innovation in Agriculture

The geographical distribution of patents provides critical insights into where innovation in agricultural technologies for climate adaptation and mitigation is being driven and protected. By analyzing priority, protection, and publication countries, we can assess which regions are leading in green innovation, where patents are actively protected, and where technological knowledge is being disseminated. Given the temporal trends outlined in Section 3.3.1, which highlighted a rapid increase in patent filings post-2010 and a peak in 2017, the geographical dimension helps contextualize these trends by identifying the dominant players in global agricultural climate innovation. This analysis is based on all available patent data until the end of 2024.

Priority Country

The priority country represents the jurisdiction where a patent application was initially filed before seeking protection in other regions. It reflects the origins of innovation and the countries where research and development in agricultural climate adaptation is most concentrated. Figure 3.3a shows the distribution of patent families by priority country, revealing which nations have been most active in initiating protection for agricultural climate technologies. Figure 3.3b visualizes the same data as a world heatmap, highlighting the spatial intensity of early-stage innovation. Unsurprisingly, China dominates the dataset, accounting for 10,088 patent families, which is nearly ten times higher than the second-ranking country, the United States (1,185 families). This overwhelming lead underscores China's aggressive innovation strategy in green agricultural technologies, supported by strong state policies, domestic research institutions, and corporate R&D investments. Other significant contributors include:

- The United States (1,185 patent families), maintaining a strong but distant second position, likely reflecting the role of large agribusiness corporations, universities, and federal R&D funding in climate-resilient agriculture;
- The World Intellectual Property Organization (WO) with 1,148 families suggests substantial patent filings through the Patent Cooperation Treaty (PCT), which facilitates multi-country patent applications;
- Japan (1,113 families) and South Korea (286 families), both known for advanced agricultural engineering and biotechnology applications, also show strong contributions;
- The European Patent Office (EP, 266 families), Russia (162 families), and Germany (123 families) indicate a diverse but relatively lower level of priority filings in Europe compared to Asia and North America;
- Emerging contributors include Australia (162), the Philippines (63), and India (47), which are increasingly prioritizing innovation in climate-resilient agriculture.

Taken together, the chart and map clearly establish China as the primary engine of patent filings in this domain, outpacing all other nations combined and setting the stage for a deeper analysis of its innovation strategy. China's overwhelming lead aligns with broader global trends in green innovation, where the country has become the dominant force in patent filings across multiple sustainability domains. The extent to which this dominance translates into commercialized technologies and market leadership will be further explored in the protection and publication country analyses.

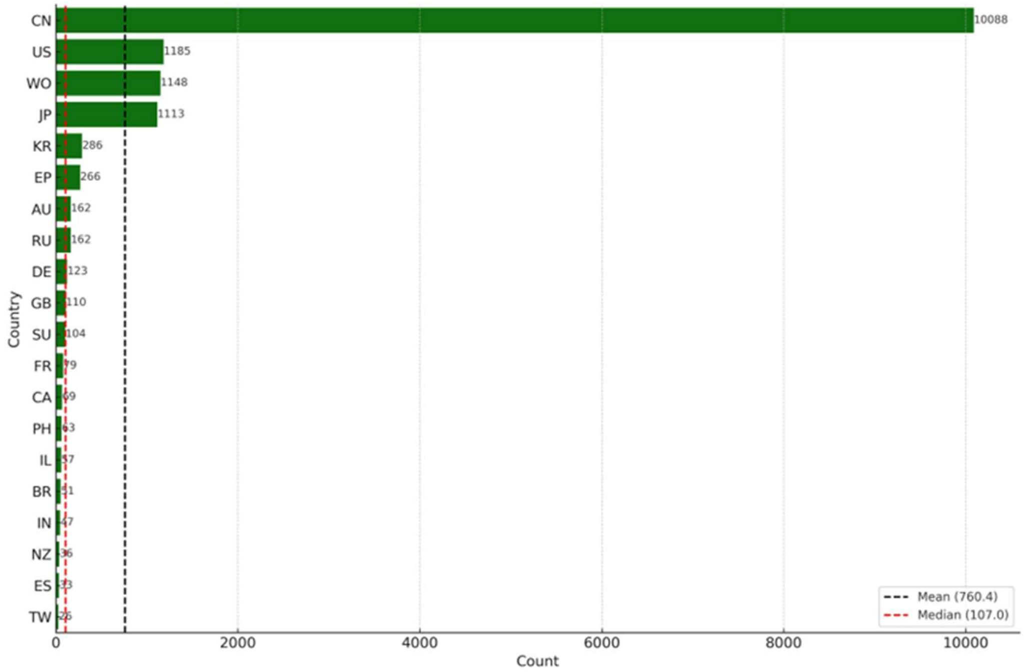

Figure 3.3a Top 20 Priority Countries. Source: Author's elaboration on Orbit data.

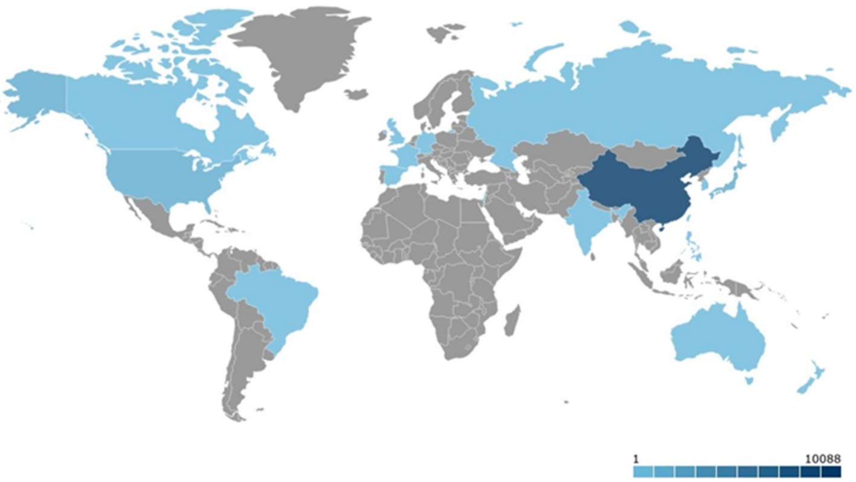
Priority country (without EP and WO)

Figure 3.3b Heat Map of the Top 20 Priority Countries. Source: Orbit.

Where Are Agricultural Climate Patents Protected and Published?

Patent publication and protection trends closely follow priority filings, reinforcing China's position as the dominant player in agricultural climate innovation. However, some deviations emerge, highlighting differences between where patents originate, where they are publicly disclosed, and where firms seek legal enforcement.

As expected, China leads in both publication (10,615 families) and protection (3,962 families), confirming its role as the primary generator, disseminator, and protector of agricultural green technology patents. However, protection filings are notably lower than priority and publication counts, suggesting that a significant share of patents filed and published in China are not actively maintained—a trend explored further in the legal status section. The United States, Japan, and Korea maintain strong positions across all three categories, though with significantly lower volumes than China. The European Patent Office (EP) and the World Intellectual Property Organization also play major roles in patent dissemination, reflecting their function in facilitating multi-jurisdictional patent applications. Emerging markets like Brazil, India, Mexico, and South Africa show higher publication than priority counts, indicating that patents from external markets—likely originating from China, the U.S., and Europe—are being published there. Meanwhile, protection filings in these regions remain relatively high, suggesting that firms see commercial potential in securing legal rights within these growing agricultural markets.

Overall, the alignment between priority, publication, and protection data confirms China's dominance but also underscores differences in patenting strategies across regions. While some countries, particularly the U.S., Japan, and Germany, prioritize long-term IP protection, China's high-volume approach results in many patents being published but not actively maintained—raising questions about their commercialization trajectory.

3.4.3. Top Assignees: Who Leads in Agricultural Climate Innovation?

In patent analysis, the assignee refers to the entity that owns the intellectual property rights to an invention. This can be a corporation, university, government institution, or individual, reflecting different innovation models. In the case of agricultural climate adaptation and mitigation technologies, patent ownership can indicate who is driving research and development (R&D), who is commercializing new solutions, and where global technological leadership lies. Figure 3.4 displays the top 20 assignees by patent family count, highlighting the leading organizations in agricultural climate innovation and their relative intensity of intellectual property ownership. A clear pattern emerges in this domain: China dominates the patent landscape, with 13 out of the top 20 assignees being Chinese institutions. This reflects a state-driven innovation model where universities and research institutes, rather than private corporations, are the primary forces behind technological advancements. This finding aligns with the geographical analysis (Section 3.3.2), where China was the undisputed leader in patenting activity.

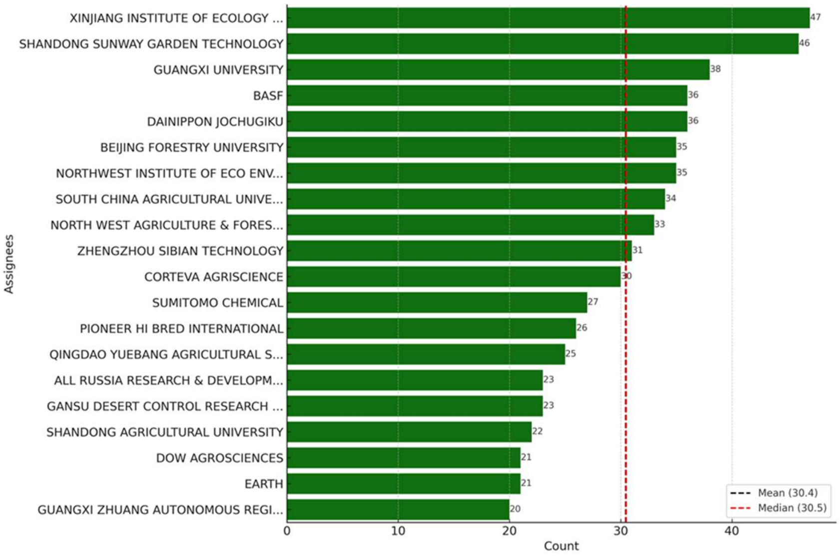

Figure 3.4 Top 20 Assignees. Source: Author’s elaboration on Orbit data.

The data in Figure 3.4 reinforces the finding of China’s dominance, revealing that its innovation system is overwhelmingly driven by public research institutions and universities rather than private corporations. The top three assignees are:

1) Xinjiang Institute of Ecology & Geography, Chinese Academy of Sciences (47 patents): a leading public research institute under the Chinese Academy of Sciences (CAS), focused on ecological research, desertification control, and sustainable land use, all crucial in climate adaptation strategies;
2) Shandong Sunway Garden Technology (46 patents): a Chinese company specializing in green infrastructure, ecological restoration, and environmental technology. Its rapid patenting activity suggests a targeted innovation push rather than long-term sustained R&D;
3) Guangxi University (38 patents): a major Chinese research university, active in agricultural science, environmental engineering, and climate-adaptive farming techniques.

All three leading assignees are Chinese academic or research institutions, confirming that China’s state-backed research plays the most substantial role in agricultural climate technology development.

Only seven of the top 20 assignees are non-Chinese, reflecting the limited role of international players in this patent space. These include three Japanese firms, one German multinational, one Russian state institute, and three U.S.-origin companies (now consolidated under Corteva Agriscience):

1) BASF (Germany, 36 patents, ranked 4th): the world’s largest chemical company, heavily invested in agrochemicals, seed technology, and sustainable farming solutions. Unlike many Western corporations, BASF has maintained consistent patenting activity over decades;
2) Dainippon Jochugiku (Japan, 36 patents, ranked 5th): a Japanese firm specializing in pest control technologies, including insecticides and repellents for agricultural use—a crucial component in climate-adaptive farming;

3) Sumitomo Chemical (Japan, 27 patents, ranked 12th): a diversified chemical company with a strong agrochemical division, focusing on precision agriculture and biotechnology;
4) All-Russia Research & Development Institute of Canning & Vegetable Drying Industry (Russia, 23 patents, ranked 15th): a state-run Russian research institute, dedicated to food preservation and post-harvest processing—a critical technology in reducing food waste and ensuring climate resilience in supply chains;
5) Corteva Agriscience (30 patents, ranked 11th): formed in 2019 as the agricultural division of DowDuPont, incorporating Dow AgroSciences, Pioneer Hi-Bred International, and DuPont's seed and crop protection businesses;
6) Pioneer Hi-Bred International (26 patents, ranked 13th): a former seed genetics leader, now integrated into Corteva;
7) Dow AgroSciences (21 patents, ranked 18th): once a standalone agribusiness, now fully merged into Corteva.

If these three U.S. entities were consolidated under Corteva's umbrella, they would hold a combined 77 patents, making them the largest single non-Chinese assignee and placing them above the current Chinese leader. However, their dispersed presence in the dataset contrasts sharply with China's centralized, state-backed approach, where institutions operate under coordinated national research strategies.

When Did These Assignees Emerge?

Analyzing assignee activity from 1994 to 2024 reveals distinct emergence patterns, largely aligning with major global and national policy shifts. Figure 3.5 visualizes the annual patenting activity of the top 20 assignees from 1994 to 2024. Each bubble represents the number of patent families filed by a given assignee in a specific year, with larger bubbles indicating higher filing volumes. This allows for an immediate visual comparison of both the timing and intensity of innovation efforts across institutions.

Figure 3.5 Top 20 Assignees 1994-2024. Source: Author's elaboration on Orbit data.

a) China’s Late-Stage Surge (2015–2020)

Many of the leading Chinese institutions entered the patent landscape only in the past decade, reflecting the country’s aggressive push in agricultural climate innovation. Shandong Sunway Garden Technology (ranked 2nd) had an explosive entry in 2016, filing nearly all its patents in that year (46 patents). This suggests a focused burst of innovation rather than sustained long-term activity. Guangxi University (ranked 3rd) started patenting significantly post-2016, with its peak in 2017. Zhengzhou Sibian Technology (ranked 10th) filed almost all of its 31 patents in 2016, another example of a targeted intellectual property protection strategy. Northwest Institute of Eco-Environment & Resources (ranked 7th) was largely inactive until 2021, reflecting a continuing late-stage expansion of Chinese institutional involvement in green tech.

b) Western Corporations: Slow and Steady Engagement

In contrast to China’s state-led bursts of patent activity, Western firms demonstrate long-term, incremental innovation. BASF (ranked 4th) has shown steady engagement in patenting since the early 2000s, suggesting consistent R&D investment rather than policy-driven surges. Sumitomo Chemical (ranked 12th) and Dainippon Jochugiku (ranked 5th) exhibit a low but steady patenting rate over time, reflecting specialization in niche agrochemical and pest control technologies. Corteva (ranked 11th) and Pioneer Hi-Bred International (ranked 13th) follow a gradual trajectory, with noticeable post-2010 engagement, particularly in seed genetics and crop protection technologies. Overall, China’s late-emerging but dominant presence contrasts with long-standing but less concentrated corporate engagement in the West.

Insight Box 3: The “De-Sectorization” of R&D – How “Twin Patents” are Reshaping the Competitive Landscape

While the broader green patent landscape shows a mix of academic institutions and traditional agribusiness incumbents, a focused analysis of the “twin patent” category reveals a more radical shift: the “de-sectorization” of innovation. In the specific domain of high-tech “twin patents”, the leading non-Chinese assignees are not the familiar names from the agrochemical or seed sectors. Instead, they are global giants from entirely different industries, e.g. Deere & Co. (Agricultural Machinery), LG Electronics (Consumer Electronics & IoT), and GM Global Technology Operations (Automotive). The entry of these players confirms that the core challenges of modern agriculture are being reframed as problems of data, systems integration, and autonomous control. This trend, where deep expertise in software and cyber-physical systems becomes more critical than traditional domain knowledge, signals that the boundaries of the agricultural industry are blurring.

Co-Assignment Trends: Localized Collaboration vs. Corporate Consolidation

Patent co-assignment, the practice of multiple entities sharing ownership of a patent, provides insights into collaboration dynamics within agricultural climate innovation. Unlike industries such as pharmaceuticals, where corporate-academic partnerships are common, co-assignment in this sector is surprisingly limited. To analyze co-assignment, we used Orbit Intelligence’s network visualization tool, which allows adjustments of two key parameters:

1) Minimum node size (the number of patents an assignee must have to appear in the visualization);
2) Minimum link size (the number of shared patents required to establish a visible connection).

Setting both parameters at the default maximum of 20 yielded no visible co-assignment links, meaning no assignees shared at least 20 patents. So, we progressively lowered the threshold to 10 and below, until 6 revealed only one connection—between Corteva Agriscience and Pioneer Hi-Bred International. However, since this link stems from corporate restructuring rather than meaningful research collaboration, it was not considered informative for broader co-assignment trends. Therefore, the threshold was further reduced to 5, at which point six co-assigned relationships emerged, forming the basis for this analysis. Figure 3.6 visualizes co-assignment relationships among assignees based on shared ownership of patent families. Each node represents an institution or company, and links between nodes indicate co-owned patents. The size of each node reflects the number of patents held, while the thickness of the connecting lines corresponds to the volume of co-assigned patents between entities. This network layout highlights the rarity and localized nature of collaborative patenting in the dataset. Among the few co-assignment cases, a clear geographical pattern emerges. Chinese co-assignees are overwhelmingly institutional and regionally clustered, with collaborations taking place between universities and research institutes located within the same province or city. Notably:

- Xinjiang Agricultural University and Xinjiang Institute of Ecology & Geography (Chinese Academy of Sciences) share patents and are located just 8.7 km apart, reinforcing localized cooperation;
- South China Agricultural University and Zhongkai University of Agriculture & Engineering, both based in Guangdong province, are separated by 15.7 km, suggesting province-level partnerships rather than broader national collaboration.

Figure 3.6 Assignee Collaborations. Source: Orbit.

This localized institutional clustering contrasts sharply with Western corporate-driven co-assignment, where the only notable connection in the dataset is between Corteva Agriscience and Pioneer Hi-Bred International (6 shared patents). However, this is not a true research collaboration but rather a result of corporate restructuring, as Pioneer Hi-Bred is now a subsidiary of Corteva. The absence of cross-region or industry-academia collaborations within China suggests a more fragmented knowledge transfer system, where research institutions operate in isolated ecosystems rather than engaging in wide-scale, interdisciplinary patenting efforts. Unlike in the U.S. or Europe, where patents are frequently co-owned by corporations and universities, China's innovation strategy appears to prioritize independent institutional research rather than direct industry-academia partnerships. The findings indicate that while China dominates patenting activity (Section 3.3.1), its innovation model remains highly localized and institution-centric, with limited interregional cooperation and industry-academic integration. This fragmentation is further reflected in patent retention trends: as seen in Fig. 13, a significant 63.2% of all patents in the dataset are no longer active, with a particularly high share of lapsed patents (5,335 families, 38.9%), suggesting frequent abandonment due to non-payment of maintenance fees. In contrast, U.S., Japanese, and German firms exhibit stronger long-term patent retention, emphasizing strategic intellectual property protection over short-term filing activity. This contrast raises important questions about the commercialization and scalability of agricultural climate technologies developed under different innovation models, with Western firms prioritizing enforceable patents while Chinese institutions focus on broad but transient patenting efforts.

Inventor Trends: Who Is Driving Agricultural Climate Innovation?

From 1994 to 2024, China overwhelmingly dominates agricultural climate innovation, with 29 of the top 30 inventors based in the country. This strong concentration aligns with the findings on assignees (Section 3.3.1) and geographical distribution (Section 3.3.2), reinforcing the state-driven, institution-centered model that characterizes China's approach to green technology development. The only non-Chinese inventor in the top 30, based in Russia, holds a modest number of patents, emphasizing the near-total dominance of Chinese researchers in this field. Many of the most prolific patent filers appear to be associated with institutional or collective research efforts, where patents are assigned to universities and research institutes rather than credited to individuals. This suggests a model in which innovation is largely driven by state-backed research programs rather than market-driven corporate R&D. Among the top contributors, several researchers have individually filed dozens of patents, particularly in areas related to climate-smart agriculture, soil management, and biopesticides, with significant peaks in patenting activity during key policy periods. Despite this high volume of patent filings, nearly all leading inventors operate exclusively within China, with minimal international presence. Only a handful have filed patents in WO (World Intellectual Property Organization) applications, the U.S., or Europe, indicating that China's agricultural green innovation remains largely domestic and is not widely extended to global markets. This contrasts with Western firms, where patenting strategies often prioritize international protection for commercial competitiveness. The absence of major European, American, or Japanese inventors among the top contributors further highlights the localized nature of China's research ecosystem, where innovation is closely tied to national policy incentives rather than global intellectual property expansion.

3.4.4. Technological Trends: What Types of Innovations Are Being Patented?

Figure 3.7 illustrates the technological domains of the patents in the dataset, using a hexagonal map where each cell represents a technology category. The color intensity indicates the number of patent families, with darker red hues reflecting higher activity. The technological landscape of agricultural climate innovation is primarily dominated by chemistry, engineering, and specialized machinery, reflecting a strong focus on crop protection, soil treatment, and climate-resilient agricultural infrastructure. Two standout categories dominate the dataset:

1) Basic Materials Chemistry – Preservation, Pesticides, Biocides, Disinfectants (7,236 patents)
2) Other Special Machines – Agricultural Machinery, Animal Husbandry (7,207 patents)

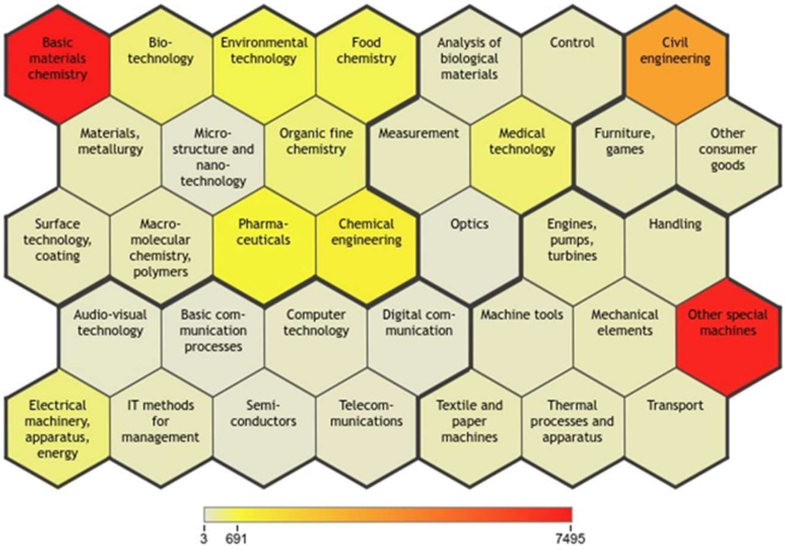

Figure 3.7 – Technology Domains. Source: Orbit

These fields account for the vast majority of patents, underscoring that pest control, chemical treatments, and mechanization are central to innovation in climate-adaptive agriculture. This aligns with previous findings on assignee trends (Section 3.3.1), where China's research institutions are leading in areas linked to state-supported food security strategies. Beyond these dominant domains, several specialized sub-fields highlight key research directions. Figure 3.8 displays the sub-technical domains within agricultural climate patents, ranking them by the number of patent families. The chart highlights which areas are most targeted for technological innovation, offering a more granular view of R&D priorities.

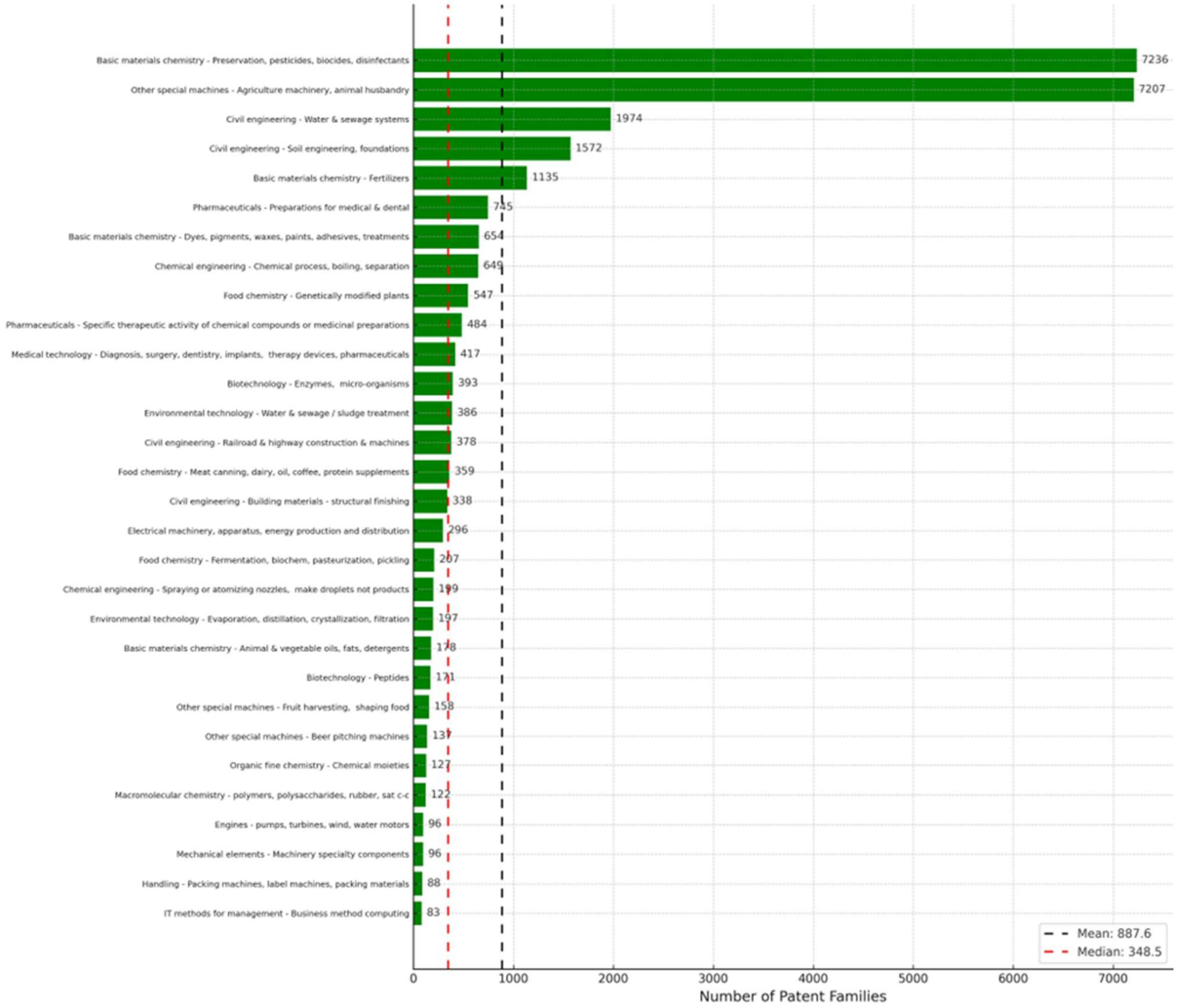

Figure 3.8 Sub-technical Domains. Source: Author's elaboration on Orbit data.

The detailed breakdown in Figure 8 shows that innovation is concentrated in foundational areas for climate resilience, particularly water and soil management, fertilizers, and biostimulants, with food processing and mechanization as other key fields. In water management, research focuses on irrigation, land stabilization, and flood-resistant infrastructure, particularly in regions prone to climate variability, as seen in "Civil Engineering – Water & Sewage Systems" (1,974 patents) and "Soil Engineering" (1,572 patents), while "Environmental Technology – Water & Sewage / Sludge Treatment" (386 patents) reinforces the importance of water security and waste reuse in sustainable farming. In fertilizers and biostimulants, major R&D efforts in soil nutrition, biofertilizers, and synthetic amendments are represented by "Basic Materials Chemistry – Fertilizers" (1,135 patents), while "Biotechnology – Enzymes & Microorganisms" (393 patents) suggests innovation in biological soil treatments as an alternative to chemical inputs. Food security and processing patents show continued investment in genetic resilience to climate stress, with "Food Chemistry – Genetically Modified Plants" (547 patents) leading the category, alongside research in preservation technologies aimed at reducing post-harvest losses, including "Food Chemistry – Fermentation, Pasteurization, Pickling" (207 patents) and "Meat Canning, Dairy, Oil, Coffee, and Protein Supplements" (359 patents). In mechanization and smart agriculture, advancements in precision harvesting and automation are reflected in "Other

Special Machines – Fruit Harvesting, Shaping Food” (158 patents), while “Chemical Engineering – Spraying or Atomizing Nozzles” (199 patents) suggests the growing use of precision application technologies for fertilizers, pesticides, and water-saving irrigation. Additionally, “IT Methods for Management – Business Method Computing” (83 patents), though a smaller category, hints at the emerging role of digital tools, AI-driven farm management, and blockchain-based agricultural supply chains. Overall, the dominance of agrochemical, engineering, and mechanization patents aligns with broader trends observed in assignee and inventor activity (Sections 3.3.1 and 3.3.2). While China’s patenting focus remains largely domestic, the key innovation themes—pest control, soil improvement, mechanization, and food security—are globally relevant.

Insight Box 4: A Paradigm Shift from Chemistry to Code

While the broader landscape of agricultural climate innovation remains dominated by traditional R&D fields, such as chemistry and machinery, the analysis of high-tech “twin patents” reveals a radical and comprehensive paradigm shift in technological focus. The technological core of this emerging wave is not physical or chemical, but informational. The top three technology domains for “twin patents” are:

1. Computer Technology (5,074 families)
2. IT Methods for Management (3,053 families)
3. Control (3,039 families)

This finding provides clear, quantitative evidence that the innovation frontier has moved from optimizing physical inputs (e.g., fertilizers, pesticides) to creating integrated, intelligent, cyber-physical systems. The central challenge is no longer soil chemistry, but software architecture, data analytics, and AI-driven automation. This confirms that the next agricultural revolution is fundamentally an information technology revolution.

3.4.5. Legal Status: Are Agricultural Climate Patents Being Maintained?

Patent legal status provides critical insights into how actively agricultural climate innovations are protected, commercialized, or abandoned. While China dominates in patent filings (Section 3.3.3), a key question is: how many of these patents are actually maintained? The data reveal a stark contrast between China’s high patent abandonment rate and the stronger long-term protection strategies of U.S., German, and Japanese firms.

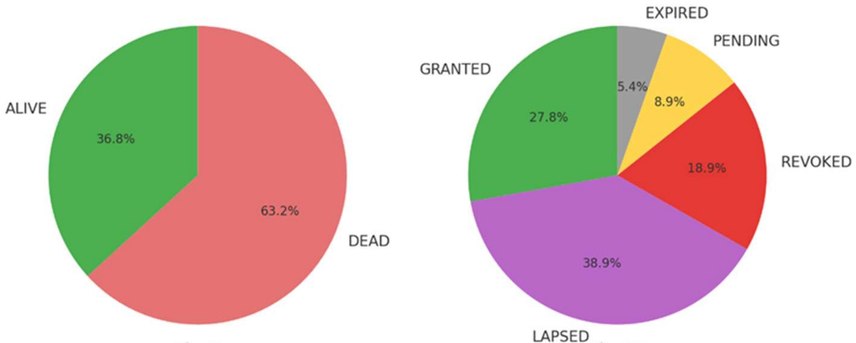

Fig. 9 **Fig. 10**

Figure 3.9 – Legal State | Figure 3.10 – Legal Status. Source: Author’s elaboration on Orbit data.

Figures 3.9 and 3.10 provide a snapshot of the legal situation of the 13,727 patent families in the dataset. Figure 3.9 illustrates the overall legal state, distinguishing between Alive (36.8%, 5,045 families) and Dead (63.2%, 8,682 families) patents. This high share of inactive patents raises questions about the long-term commitment to innovation, especially in countries like China that dominate initial filings (see Section 3.3.3). Figure 3.10, on the other hand, offers a more granular view of the legal status categories. A breakdown of this figure is presented in Table 3.2, which details each category's meaning and size

Category	Subcategory	Patent Families	% of Total	Description
Alive Patents	Granted	3,820	27.8%	Actively maintained and legally enforceable, indicating commercial viability or strategic protection.
	Pending	1,225	8.9%	Still under examination, representing the next wave of potential agricultural climate innovations.
Dead Patents	Lapsed	5,335	38.9%	Abandoned due to non-payment of maintenance fees, suggesting either a lack of commercial viability or strategic withdrawal by the assignees.
	Revoked	2,601	19.0%	Challenged and invalidated, typically due to prior art conflicts, lack of novelty, or opposition proceedings.
	Expired	746	5.4%	Reached the end of the 20-year protection term, meaning their technologies are now in the public domain and freely available for use.

Table 3.2 Legal Status breakdown. Source: Authors' elaboration.

As shown in Table 3.2, a significant majority (63.2%) of the patents analyzed are no longer active, with patents "lapsed" due to non-payment of fees constituting the single largest category (38.9%). This key finding highlights a systemic challenge in the long-term maintenance of agricultural climate innovations and forms the basis for analyzing the different retention strategies of key countries and assignees.

The Strategy in Patent Retention

This distribution suggests that while China dominates in filing patents, a large share is not retained. In contrast, firms from the U.S., Germany, and Japan strategically maintain and protect their patents, emphasizing long-term commercial and legal value. This divergence in retention strategies may stem from different national innovation models. In China, on one side, state-led research incentives encourage patent filings, but long-term enforcement is often deprioritized, leading to higher abandonment rates. On the other side, in the U.S. and Germany, patenting follows a market-driven approach, where patents are selectively maintained to ensure commercial exploitation. Finally, Japanese firms strike a middle ground, demonstrating a commitment to long-term patent retention while balancing selective abandonment. Figure 3.11 shows the distribution of granted, pending, and dead patents among the top 20 assignees, with color-coded bars that highlight stark differences in patent retention strategies. A clear divide emerges while Chinese institutions largely abandon their patents, reflecting short-term or volume-driven approaches, U.S., German, and Japanese firms demonstrate a stronger commitment to long-term protection, actively retaining and maintaining their intellectual property over time.

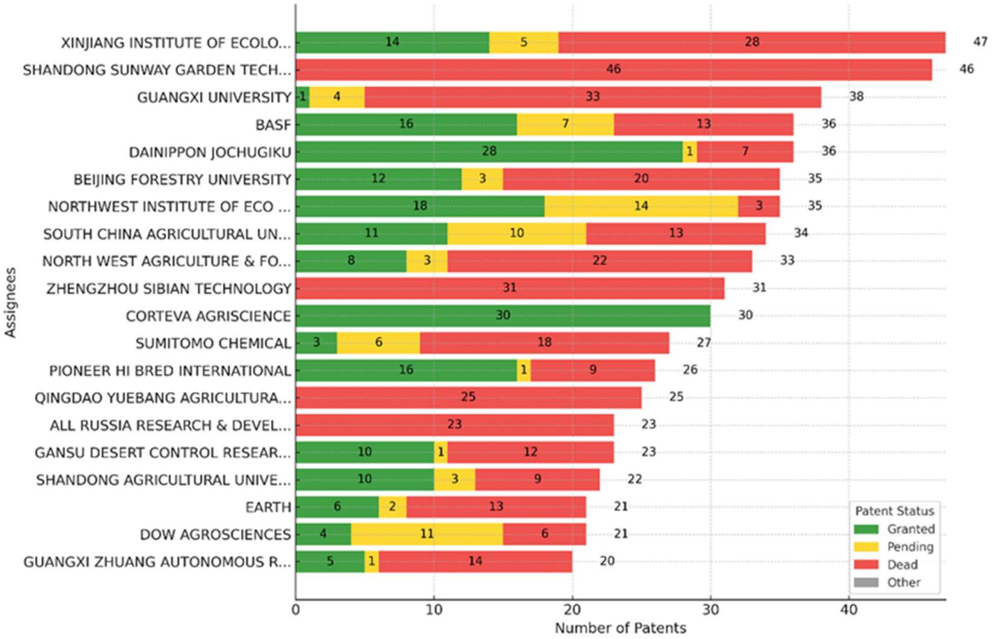

Figure 3.11 Top 20 Assignees by Legal Status. Source: Author's elaboration on Orbit data.

China's High Patent Abandonment Rate

Several major Chinese research institutions have very low patent retention rates. Shandong Sunway Garden Technology (46 dead, 0 granted, 0 pending) has abandoned every single patent, suggesting short-term patenting bursts with little follow-through on commercialization or enforcement.

Zhengzhou Sibian Technology (31 dead, 0 granted, 0 pending) follows the same trend, reinforcing the pattern of high-volume, low-retention patenting. Guangxi University (1 granted, 4 pending, 33 dead) and Northwest Agriculture & Forestry University (8 granted, 3 pending, 22 dead) also fail to retain a significant portion of their patents. Even leading Chinese research institutes struggle to maintain patents. Xinjiang Institute of Ecology & Geography (14 granted, 5 pending, 28 dead) retains only about 30% of its patents, while Beijing Forestry University (12 granted, 3 pending, 20 dead) exhibits a similar pattern of high abandonment rates.

U.S. and German Firms: Long-Term IP Protection

U.S. and German multinational corporations demonstrate significantly stronger patent retention rates. BASF (Germany, 16 granted, 7 pending, 13 dead) maintains a high proportion of its patents, reflecting a deliberate strategy of long-term IP protection. Corteva Agriscience (U.S., 30 granted, 0 pending, 0 dead) stands out as the only assignee with zero abandoned patents, suggesting a highly strategic, commercial approach to patent protection. Pioneer Hi-Bred International (U.S., 16 granted, 1 pending, 9 dead) and Dow AgroSciences (U.S., 4 granted, 11 pending, 6 dead) reinforce the trend of sustained IP enforcement in U.S. agribusiness.

Japan: A Strong Patent Retention Culture

Japanese firms also show a commitment to long-term IP protection, though their strategies differ slightly from their U.S. and European counterparts. Dainippon Jochugiku (Japan, 28 granted, 1 pending, 7 dead) exhibits a remarkably strong retention rate, keeping nearly 80% of its patents alive. Sumitomo Chemical (Japan, 3 granted, 6 pending, 18 dead) maintains a notable portion of its patents, though with a higher abandonment rate than Dainippon

Russia: Total Patent Abandonment

The All-Russia Research & Development Institute of Canning & Vegetable Drying Industry (23 dead, 0 granted, 0 pending) has abandoned 100% of its patents, indicating either a shift in research focus or lack of financial and strategic commitment to maintaining IP.

Ultimately, these contrasting strategies raise questions about long-term innovation impact: Does China’s high-volume patenting model accelerate technological diffusion, or does it hinder commercialization? Conversely, do Western firms’ selective strategies prioritize exclusivity over widespread technology adoption? The answer may depend on whether patents are viewed primarily as a means of innovation diffusion or as tools for competitive advantage.

3.5. Discussion

The previous section outlined the key trends in agricultural climate innovation, from the temporal distribution of patents to geographical patterns, assignee behavior, and legal status dynamics. While these findings provide a comprehensive snapshot of patenting activity, a deeper examination is needed to understand the broader forces shaping these trends. This discussion highlights three interrelated aspects: (i) the dominance of adaptation over mitigation technologies, (ii) the nature of China’s patenting strategy and its implications, and (iii) the fragmented nature of institutional collaboration. These insights help contextualize the results within global innovation dynamics and provide a basis for policy and market considerations.

3.5.1. Adaptation vs. Mitigation: Understanding the Patent Landscape

This study aimed to capture both adaptation and mitigation technologies in agricultural innovation, using a query that integrated climate-focused CPC/IPC codes with classifications related to soil management, irrigation, plant protection, and agricultural infrastructure. However, the dataset overwhelmingly reflects adaptation-oriented innovations. Most patents focus on water management, soil stabilization, biopesticides, and climate-resilient agricultural practices, while explicit mitigation technologies, such as carbon sequestration, low-emission fertilizers, and biochar for carbon storage, are far less prevalent. This emphasis on adaptation reflects structural and economic realities. Unlike energy or transportation, where mitigation efforts dominate through carbon capture and renewable energy, agriculture is biologically dependent on environmental conditions. Farmers must respond to shifting precipitation patterns, soil degradation, and pest dynamics, making adaptation an immediate necessity. Policy incentives reinforce this trend, with programs such as China’s Five-Year Plans, the EU’s Common Agricultural Policy (CAP), and U.S. farm subsidies prioritizing resilience and sustainable land use over direct emissions reductions. The lack of stringent carbon pricing in agriculture further weakens incentives for mitigation-oriented innovations.

Commercial feasibility also plays a role. Adaptation technologies, such as drought-resistant crops and precision irrigation, offer clear economic benefits and are quickly adopted by farmers. By contrast, large-scale mitigation solutions often require systemic changes and long-term investment, which may lack immediate financial incentives. Nonetheless, some adaptation technologies in the dataset indirectly contribute to mitigation. Soil management practices like biochar application enhance carbon storage, and precision agriculture helps reduce excess fertilizer use, cutting nitrous oxide emissions. Future agricultural innovation must ensure that adaptation strategies align with broader decarbonization goals rather than merely addressing short-term climate pressures.

This general trend is clearly reflected in our technological patent analysis. The landscape in Figure 7 offers a stark policy lesson: the overwhelming dominance of patents in “Basic Materials Chemistry” and “Agricultural Machinery” suggests that the current innovation ecosystem remains locked in a path dependency favoring traditional, input-intensive agricultural models. For policymakers, this indicates that existing R&D incentives may be inadvertently reinforcing an outdated paradigm rather than fostering a transition towards agroecological or circular economy approaches. This highlights a critical need for more targeted industrial and innovation policies to stimulate disruptive innovation in underrepresented yet vital areas. Furthermore, the sub-domain analysis in Figure 8 reinforces this point, showing a largely reactive innovation posture. The strong focus on water management and soil engineering demonstrates that R&D is primarily responding to immediate climate adaptation pressures. While essential, this reactive stance risks neglecting proactive climate mitigation. A key policy implication is the need to rebalance innovation portfolios to incentivize dual-benefit technologies. For instance, policies could explicitly reward innovations, such as biochar or nitrogen-fixing microbes, that simultaneously enhance soil resilience (adaptation) and reduce greenhouse gas emissions (mitigation). Without such a systemic policy view, agricultural innovation may solve short-term adaptation problems while failing to contribute effectively to long-term decarbonization goals.

3.5.2. China’s Dominance and the Nature of Its Patenting Strategy

The dataset confirms China’s overwhelming dominance in agricultural climate innovation, accounting for over ten times the patent families of the second-ranking country. However, China’s patenting strategy differs significantly from that of Western nations, not only in the scale of filings but also in its short-term retention patterns, institutional emphasis, and limited collaboration.

The 2016–2017 Patent Boom: Policy and Incentives

China’s surge in patent filings peaked in 2016–2017, closely aligning with a series of government policies aimed at technological self-sufficiency and green innovation. Figure 3.12 overlays China’s major climate and industrial policy milestones with the annual count of agricultural climate-related patent families (by priority year). The figure highlights a strong temporal correlation between key policy announcements and patenting activity The 12th Five-Year Plan (2011–2015) laid the foundation for green development by introducing explicit climate targets, followed by the National Plan for Tackling Climate Change (2014–2020), which reinforced emission reduction goals and expanded forest coverage. The 13th Five-Year Plan (2016–2020) emphasized sustainable development, setting peak carbon emissions and renewable energy targets, while Made in China 2025 (2015–2025) further reinforced investment in energy-efficient and clean technology industries, including climate-resilient agricultural practices. The National Strategy for Climate Change Adaptation (2013) and the Carbon Neutrality Commitment (2020) also played critical roles in shaping the innovation landscape by driving advancements in adaptation and mitigation technologies. Domestic pressures, including worsening desertification and concerns over national food security, further accelerated research investment, contributing to the patenting boom observed during this period. However, the decline in patent activity after 2020 suggests a structural shift in innovation priorities. While earlier policies predominantly focused on adaptation technologies—such as irrigation, soil stabilization, and biological pest control—recent policy frameworks, particularly the 2024–2028 Agricultural Biotechnology Development Plan, signal a growing emphasis on mitigation-oriented technologies. This shift aligns with China’s broader carbon neutrality commitment to peak emissions before 2030 and achieves neutrality by 2060, likely redirecting research incentives toward gene editing for carbon-efficient crops, soil-based carbon sequestration, and methane reduction strategies rather than the adaptation-heavy innovations that dominated earlier cycles. The observed slowdown in agricultural climate patenting may, therefore, reflect this transition, as China recalibrates its innovation ecosystem to align with long-term emission reduction goals rather than short-term resilience strategies.

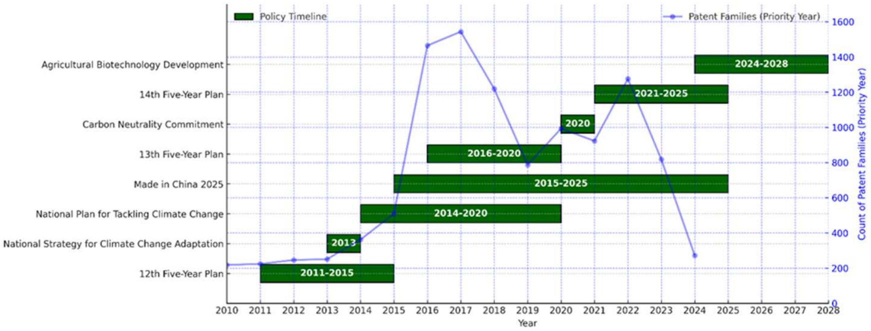

Figure 3.12 China’s climate and industrial policy timeline (2011-2028) with patent filing trends. Source: Author’s elaboration.

Short-Term Innovation? The High Abandonment Rate of Chinese Patents

Despite high patenting activity, China's retention rates are low. Most patents have lapsed due to non-payment of maintenance fees or have been abandoned outright, including those held by leading research institutions. This suggests a patenting strategy driven more by short-term incentives than by long-term technological development. One explanation is the research funding model in China, where patents serve as performance metrics for institutions rather than as assets for commercialization. As funding cycles shift, many patents are left unmaintained, leading to their high expiration rate. This pattern is not unique to agricultural innovation—China has seen similar trends in other high-tech sectors, such as solar panels and electric vehicles, where an initial boom in patent filings was followed by a wave of abandoned IP as government priorities evolved. Unlike in industries where domestic manufacturing ensured technology diffusion, the agricultural sector lacks a comparable industrial pipeline to sustain long-term retention. In contrast, U.S., German, and Japanese firms retain patents as long-term strategic assets, directly tied to business models and commercial interests. In these economies, firms often view patent portfolios as a means of securing competitive advantage, attracting investment, and sustaining R&D pipelines. The contrast suggests that while China's patenting system efficiently drives research output, it lacks the mechanisms to sustain intellectual property beyond state-driven funding cycles. Whether this model will evolve toward greater long-term retention remains an open question, especially as China seeks to transition from a quantity-based to a quality-based innovation strategy.

Institutional Dominance and the Fragmented Nature of Innovation

Unlike Western economies, where agricultural R&D is primarily driven by private firms, China's patent landscape is dominated by universities and public research institutes. This reflects a state-driven innovation model in which institutions drive climate-related technological advancements. While this approach has led to a high volume of research output, it also introduces structural inefficiencies, particularly in commercialization and long-term patent retention. A key consequence of this model is that many patents remain detached from market-driven innovation. Since universities and research centers often lack direct pathways to commercialization, patents are frequently filed to meet institutional performance metrics rather than to serve as long-term business assets. This helps explain the high abandonment rates observed among Chinese assignees, as maintaining patents beyond their initial filing holds little strategic value in the absence of strong industry buy-in. Without private-sector involvement to push innovations beyond the research stage, many of these technologies may never transition from academic output to scalable agricultural solutions.

Compounding this challenge is the absence of significant collaboration between patent assignees. In contrast to the U.S. and Europe, where university-industry partnerships and multinational co-assignment structures are common, China's patenting landscape remains largely institution-centric and regionally fragmented. The few co-assignment cases observed in the dataset primarily involve local collaborations between universities and research centers within the same geographic area, rather than cross-regional or international networks. For example, Xinjiang Agricultural University and the Xinjiang Institute of Ecology & Geography (Chinese Academy of Sciences) share patents, but these institutions are located just 8.7 km apart, reinforcing the notion that collaboration remains spatially constrained rather than extending through national or international networks. This highly localized structure further limits the scalability and diffusion of innovations. In Western economies, co-assigned patents are often linked to joint R&D programs, industry partnerships, or multinational innovation consortia, which facilitate knowledge transfer and market adoption. Indeed, literature suggests that collaborating with external stakeholders is a key ingredient for effective green innovation, even more so than for traditional innovation (De Marchi et al., 2022). The lack of such mechanisms in China suggests that many patents remain confined within institutional silos, reducing their impact on broader technological development.

While China has proven highly effective at mobilizing state-backed research to accelerate patenting activity, its weak integration between research institutions and private firms, coupled with limited interregional cooperation, raises questions about the long-term impact of its agricultural climate innovations. Unless commercialization pathways strengthen, many of these patents risk remaining isolated research outputs rather than transformative technologies with real-world applications.

Insight Box 5: Beyond Volume – Strategic Intent in China's "Twin Patent" Push

The analysis of "twin patents" provides a deeper explanation for the strategic divergence between China's state-led model and the West's corporate-led approach, revealing a potential global "division of innovative labor". This becomes evident through two key lenses. First, an analysis of technological specialization shows that the core Artificial Intelligence (AI) patent landscape is exclusively dominated by Chinese universities, which account for all top 20 assignees. Global corporations like Deere and LG are entirely absent, suggesting that China is concentrating on creating foundational AI models—the "brains"—while Western firms focus on integrating such intelligence into complex, marketable systems, or the "body". Second, this strategic difference is quantified by commercial intent, as measured by patent family size. Western corporations exhibit large, international families (Deere: 7.8; GM: 8.1), signaling a clear strategy of global commercial protection. In stark contrast, top Chinese universities have minimal family sizes (South China Agricultural University: 1.3), confirming a focus on domestic technological sovereignty rather than global market deployment. This evidence suggests China's high-volume, low-retention strategy in the "twin patent" space is not a flaw, but a deliberate policy to build a foundational, domestic knowledge base in critical technologies, while Western firms pursue a more focused strategy of creating globally defensible commercial assets.

3.5.3. Africa's Role in Agricultural Climate Innovation

African nations are increasingly prioritizing climate adaptation and mitigation in agricultural innovation, demonstrating a clear focus on sustainable solutions. To assess this effort, we calculated the share of climate adaptation and mitigation patents as a proportion of total agricultural patents for each country. This metric provides a more meaningful comparison by highlighting not just absolute patent numbers but the extent to which agricultural innovation is directed toward climate solutions. While many countries file large numbers of agricultural patents, only a fraction focus specifically on sustainability. By considering this ratio, we identify which regions are embedding climate resilience into their agricultural R&D strategies. Figure 3.13 illustrates these findings by displaying the top 20 countries ranked by the share of agricultural patents related to climate adaptation and mitigation. Unlike raw patent counts, the figure reveals which countries are strategically prioritizing sustainability within their innovation ecosystems.

The results show that while China (25%) leads globally in this area, the African Regional Industrial Property Organization (AP) (22%) ranks second, followed closely by South Africa (15%) and Algeria (16%). These figures, all above the global average of 13%, highlight the continent's strong commitment to tackling climate challenges through technology. The AP is a regional patent office that facilitates intellectual property cooperation among 19 African nations, providing a shared legal framework for innovation. The fact that 22% of agricultural patents within AP are climate-focused reflects an intentional effort by its members to address environmental vulnerabilities such as drought, soil degradation, and pest control. AP's framework allows emerging economies to protect and commercialize climate-resilient agricultural technologies, ensuring regional innovation benefits local farmers and industries. As Africa's most patent-intensive agricultural economy, South Africa (15%) plays a central role in climate adaptation innovation. With over 1,100 agricultural patents, the country leads in pest-resistant crops, biological pest control, and advanced irrigation methods. Companies such as Corteva Agriscience, BASF, and Pioneer Hi-Bred International have been actively patenting technologies in insecticidal proteins, fungicidal treatments, and microbial-based pest control, strengthening the country's position as a leader in sustainable agriculture. Beyond South Africa and AP, Algeria (16%), Morocco (13%), and Egypt (11%) are notable contributors to climate-smart agriculture. Their patents focus on water management, resilient crop breeding, and sustainable fertilizers, key solutions for ensuring food security in water-scarce regions.

While Africa's absolute patent numbers remain lower than major economies, its relative emphasis on climate resilience is striking. The continent's research and innovation efforts reflect a deliberate shift toward sustainable farming, positioning African nations as key players in the global transition to climate-adaptive agriculture.

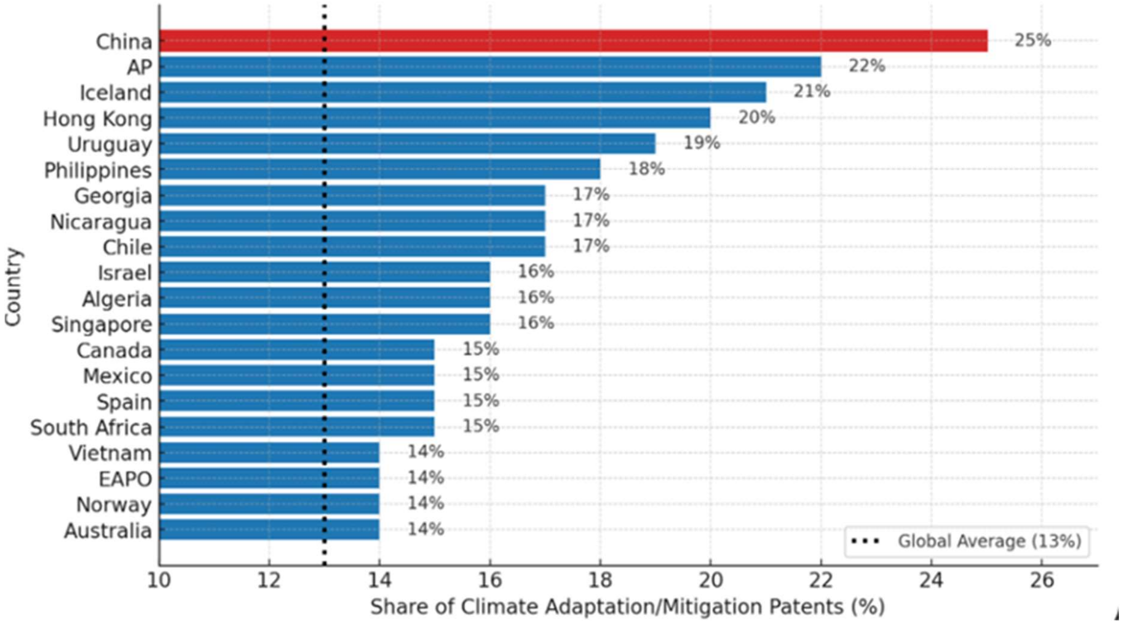

Figure 3.13 Top 20 Countries by Share of Climate Adaptation & Mitigation Patents in Agriculture. Source: Authors' elaboration from Orbit data.

3.5.4. Managerial Implications

The findings of this study offer several key takeaways for businesses, policymakers, and research institutions operating at the intersection of agriculture, climate adaptation, and technology development. Firstly, for firms involved in agricultural R&D, the overwhelming dominance of adaptation-focused patents signals a clear market trend: technologies that enhance resilience to climate change, e.g. water management solutions, soil improvement techniques, and biopesticide, are driving innovation. However, the relative scarcity of explicit mitigation patents suggests a gap in carbon-neutral agricultural solutions. Companies looking to differentiate themselves in the green technology market may benefit from investing in dual-purpose innovations, i.e. technologies that not only enhance adaptation but also contribute to emissions reductions. Examples include biochar applications that enhance soil fertility while sequestering carbon, nitrogen-efficient fertilizers that reduce N_2O emissions, or methane-reducing feed additives. These innovations could position firms ahead of future regulatory shifts, particularly as agricultural emissions become a stronger focus in carbon pricing mechanisms and sustainability reporting frameworks. Furthermore, China's high-volume, low-retention patenting model presents both opportunities and challenges for businesses and investors. On one hand, the vast number of patents filed by Chinese research institutions indicates a wealth of untapped innovation, particularly in climate-resilient agriculture. On the other hand, the rapid abandonment of patents raises concerns about the long-term viability and scalability of these technologies. For companies seeking partnerships or technology acquisitions, this suggests a potential opportunity to capitalize on underutilized IP from Chinese universities and research centers. Firms with strong commercialization capabilities may find value in licensing or acquiring abandoned patents and adapting them for market deployment, particularly in regions with similar climatic and agricultural challenges. However, navigating China's fragmented innovation ecosystem—where collaboration between institutions and firms remains limited—may require stronger government-industry partnerships to enhance technology transfer mechanisms. Equally significant is that China's state-driven R&D system demonstrates that public research institutions can play a central role in driving patent-intensive innovation. However, the lack of sustained industry engagement and commercialization pathways has led to high abandonment rates. This raises an important consideration for universities and public research bodies worldwide: how can they ensure that patent filings translate into real-world agricultural solutions rather than remaining academic outputs with no commercial impact?

For universities and policymakers, this highlights the need for stronger technology transfer offices, incubators, and university-industry collaboration mechanisms. Hybrid models, where universities work closely with agribusinesses from the early stages of R&D, may help create a pipeline for patent retention and commercial success. Additionally, patent funding structures could shift from incentivizing sheer patent volume toward prioritizing patent maintenance, licensing success, and commercialization metrics. Finally, it should also be emphasized that the lack of co-assignment in China's patent dataset stands in stark contrast to the more collaborative R&D approaches in Western economies. For multinational firms and research institutions, this suggests that China's agricultural climate innovations may not be fully integrated into global technology ecosystems. To accelerate agricultural innovation, cross-border partnerships between Chinese and non-Chinese institutions could be mutually beneficial. While China offers a high volume of innovation, international partners bring expertise in scalability, regulatory compliance, and global market deployment. Expanding co-assignment practices and joint R&D programs could help bridge gaps between localized research efforts and global market needs. For policymakers, fostering international patenting initiatives and knowledge-sharing agreements could enhance technology transfer efficiency while ensuring that climate innovations reach farmers worldwide. Similarly, Africa's approach to climate innovation, particularly through the African Regional Industrial Property Organization (AP), highlights the potential of regional patent cooperation. Unlike China's centralized state-driven model, African innovation efforts rely more on regional collaboration and international partnerships. AP facilitates patenting across 19 member states, demonstrating a strong commitment to climate adaptation and mitigation in agriculture. However, like China, the challenge lies in ensuring that patents translate into real-world applications rather than remaining isolated research outputs. Strengthening cross-border cooperation, fostering co-assignment practices, and expanding technology-sharing initiatives could help scale African agricultural innovations, particularly in critical areas such as water management, soil restoration, and pest control.

A broader framework for international cooperation—linking China's extensive research output with Africa's regionalized innovation systems—could further enhance global agricultural resilience. Joint R&D programs, facilitated licensing agreements, and shared technology hubs could help bridge the gap between innovation and large-scale implementation. For both China and Africa, aligning patenting strategies with commercialization pathways remains essential in ensuring that climate-smart agricultural technologies reach the farmers and industries that need them most.

3.5.5. Policy Lessons from China's Innovation Model for the Global South

The emergence of China as the world's dominant force in agricultural climate patenting offers a compelling case study for developing nations. However, as our findings reveal, China's unique model, characterized by massive, state-driven patent volume (Section 3.2.1), high rates of abandonment (Section 3.5), and a fragmented, institution-centric innovation system (Section 3.3.2), provides critical, and often cautionary, lessons for countries in the Global South. As these nations formulate their own intellectual property strategies to foster climate resilience, they can learn from China's experience to build more efficient, sustainable, and impactful innovation ecosystems. This subsection responds directly to growing concerns around how global patent trends can inform technology policy in climate-vulnerable regions outside China.

Lesson 1: The Pitfall of Prioritizing Patent Volume over Viability

A key finding of this study is the sheer scale of China's patenting activity, accounting for over 10,000 patent families, nearly ten times that of the United States. This surge, driven by state policies and incentives, initially suggests unparalleled innovative capacity. However, this narrative is complicated by the fact that 63.2% of all patents in the dataset are inactive, with the largest share (38.9% or 5,335 families) being "lapsed" due to non-payment of maintenance fees (Section 3.3.5). The case of leading assignees like Shandong Sunway Garden Technology, which has abandoned all 46 of its patents, exemplifies this trend of "quantity over retention". For nations in the Global South with limited R&D budgets, emulating a strategy that rewards sheer patent volume is likely wasteful, leading to a "patent bubble" where metrics look good on paper, but little real-world technological progress is made. The policy lesson is clear: incentives should shift away from merely subsidizing the act of filing and toward supporting the entire innovation lifecycle. A more effective model may be reflected in the strategy observed in several African nations, where a higher proportion of agricultural patents are climate-focused (Section 3.4.3), indicating a strategic prioritization of quality and local relevance over sheer volume.

Lesson 2: The Necessity of a Commercialization Bridge

Our analysis reveals that China's innovation landscape is dominated by universities and public research institutes, with 13 of the top 20 assignees belonging to this category (Section 3.3.3). Compounding this, collaborations are rare and, when they occur, tend to be hyper-localized between institutions in close proximity, with minimal industry involvement. This illustrates a significant disconnect between the creators of knowledge (academia) and the engines of commercialization (industry), as discussed in Section 3.4.2. For the Global South, this highlights a crucial point: funding academic research is not enough. Without a robust "bridge" to translate inventions into market-ready products, valuable inventions are likely to remain on paper rather than producing a tangible impact, leading to their eventual abandonment. Policymakers must therefore focus on building this bridge by investing in effective Technology Transfer Offices, creating frameworks that encourage public-private research consortia, and launching incubators and post-patent grants to help innovations survive the perilous journey from lab to market.

Lesson 3: The Strategic Opportunity in Abandoned Innovation

The high volume of lapsed and expired patents, particularly from China, should not be viewed solely as a sign of inefficiency. It also represents a massive and continuously refreshing global repository of technology entering the public domain. For nations in the Global South, this represents a significant strategic opportunity to become "smart adopters", leveraging what is known in strategic management as a "second-mover advantage". Rather than needing to invent from scratch, they can legally adapt, improve, and deploy these publicly available technologies for regional contexts without incurring licensing costs. The policy implication is the need to establish national or regional "patent intelligence" programs to systematically monitor global patent databases and identify high-potential technologies that are no longer protected, creating a powerful and cost-effective pathway for technological advancement and climate adaptation.

Therefore, the findings of this study suggest that a "one-size-fits-all" approach to innovation policy is ill-advised. Rather than simply replicating China's high-volume model or the corporate-driven Western approach, nations in the Global South can forge a more effective, tailored hybrid strategy. Such a strategy would learn from China's cautionary tale about the "quantity trap", adopt the commercial focus seen in the West, and embrace the spirit of strategic prioritization and regional cooperation exemplified by frameworks like the African Regional Industrial Property Organization. By focusing on local needs, building commercialization pathways, and strategically leveraging global knowledge, these nations can ensure their innovation policies lead to tangible and sustainable climate solutions on the ground.

3.6. Conclusions

This study highlights the strong dominance of adaptation technologies over mitigation-focused ones in agricultural climate patenting. While our search covered both categories, the data indicate that most innovations address resilience to environmental stressors rather than emissions reduction. This reflects the sector's immediate need to manage climate risks rather than shift toward low-carbon practices. However, given agriculture's role in global emissions, stronger incentives may be needed to accelerate innovation in mitigation strategies such as low-emission fertilizers, soil carbon sequestration, and methane reduction. China's overwhelming presence in agricultural climate patents, particularly following the 2016–2017 boom, underscores the impact of government-led innovation policies.

However, the short-lived nature of many Chinese patents—often abandoned or lapsed—suggests that patenting was largely driven by research incentives rather than long-term commercial strategies. Unlike Western firms, which maintain patents as strategic assets, China's innovation landscape is dominated by universities and research institutes, with limited industry involvement. The lack of co-assignment further reinforces a fragmented innovation system that may hinder large-scale commercialization. These findings suggest that a stronger link between research and industry is needed to ensure long-term impact. China's patenting surge highlights its research capacity but also raises concerns about whether these innovations translate into real-world applications. Meanwhile, the heavy focus on adaptation technologies suggests that climate policy should better integrate emissions reduction incentives into agricultural innovation.

3.6.1. Limitations & Future Research

The findings of this study should be interpreted in light of several limitations. First, patents protect formalized inventions but do not guarantee successful market innovations, a point powerfully illustrated by our own findings on high patent abandonment rates. It is crucial to acknowledge that, especially in the Circular Economy, many process innovations rely on non-patentable know-how, operational adjustments, and trade secrets rather than formal intellectual property. Therefore, this analysis maps the codified technological potential rather than the full spectrum of market-implemented solutions. Second, our analysis does not capture non-patented innovation, a critical aspect in agriculture, including trade secrets and open-source ag-tech, suggesting that innovation in regions like the Global South may be underestimated. Third, the results are specific to the Orbit Intelligence database. While Orbit is a comprehensive data aggregator, alternative providers (e.g., Derwent, Lens.org) employ different algorithms for data cleaning, assignee standardization, and patent family consolidation. Consequently, quantitative results could differ slightly if based on another provider, although the broad technological and geographical trends are expected to be robust. Finally, this study treats each patent family as a single unit, without differentiating between high-value breakthrough inventions and minor, incremental improvements. Future research could provide a more holistic view by triangulating these findings with other data sources, such as commercialization metrics and firm-level surveys.

Despite these limitations, this study provides key insights into the evolving landscape of agricultural climate innovation. Ensuring that patents contribute not only to resilience but also to emissions reduction will be crucial for the sector's long-term sustainability.

CHAPTER IV – A NEW PARADIGM: THE “TWIN TRANSITION”

The preceding chapters have traced an analytical path across different scales. Chapter one mapped the broad theoretical framework of sustainable business models through a bibliometric analysis. The second investigated the practical design of a circular model via a specific case study on biochar, testing its potential viability. The third chapter then broadened the perspective again, using patent data to map the global landscape of green innovation in agriculture, revealing which technologies are being developed and by whom. However, mapping the “what” and the “who” of innovation does not yet answer a fundamental question for firms and policymakers: which innovation strategy creates durable economic value? After analyzing the architecture of business models and the geography of inventions, the investigation must now converge on the impact of these strategies on firm performance. This final chapter takes precisely this step, introducing a new strategic paradigm: the “Twin Transition”. The analysis shifts from observing green and digital innovations as parallel paths to evaluating their synergistic convergence. Consequently, the empirical approach evolves from a descriptive mapping of patents to an econometric analysis on a large panel of European agricultural firms. The goal is to rigorously test whether the integration of green and digital technologies is not just a policy vision, but a concrete and superior source of competitive advantage.

Abstract

This final empirical chapter evaluates the economic returns of different innovation strategies within the European Union's “Twin Transition” framework. It investigates whether the synergistic integration of green and digital technologies creates a superior competitive advantage for agricultural firms. The central hypothesis is that an integrated “Twin Innovation” strategy yields more durable productivity gains than pursuing either green or digital innovation alone. To test this, the study employs a Two-Way Fixed-Effects model on a longitudinal panel of 1,284 innovative European firms over 25 years, analyzing the dynamic impact of different patent stocks on labor productivity. The results are clear: while standalone green innovation offers only a fleeting productivity advantage and standalone digital innovation shows no significant effect, the integrated “Twin” strategy is the only one that generates a positive, highly significant, and durable increase in performance, with effects lasting at least five years. This chapter delivers a data-driven verdict that validates the Twin Transition not just as a policy vision, but as a superior strategic paradigm for creating lasting value in the modern agri-food sector.

4.1. Introduction

The global agricultural sector stands at a critical juncture, confronted by the dual imperatives of ensuring food security for a growing population while simultaneously mitigating its significant environmental impact. This sector embodies a profound paradox: it is both a primary driver of environmental degradation, accounting for 10-12% of global CO_2 emissions through activities like livestock production, fertilizer use, and land-use changes, and a direct victim of its consequences. The agricultural system is increasingly exposed to climate-related shocks, including temperature variability, altered precipitation patterns, and the rising frequency of extreme weather events. This precarious position necessitates a radical transformation, moving beyond traditional paradigms toward a model that is both resilient and sustainable. In response to these global challenges, the European Union has championed the “Twin Transition” as a cornerstone of its innovation and industrial policy. This framework represents a paradigmatic shift, positing that environmental sustainability and digital transformation are not separate objectives but convergent, synergistic forces. The core idea is to leverage the advancements of Industry 4.0, such as Artificial Intelligence, IoT, and predictive analytics, to accelerate the green transition towards goals like carbon footprint reduction and sustainable resource utilization. This synergistic approach aligns with the emerging paradigm of Industry 5.0, which moves beyond the efficiency-centric focus of Industry 4.0 to emphasize resilience, human-centricity, and sustainability. By integrating digital tools not merely for productivity but for environmental stewardship, the Twin Innovation model represents a concrete step towards this regenerative industrial framework. Despite the urgency, the agricultural sector has historically been characterized by a persistent “innovation deficit”. When compared to other industries, its investment in research and development is markedly lower (0.5% vs. 3.2% in manufacturing), and its share of patents is minimal (2% vs. 25% in the ICT sector). This results in an approach that is often reactive and dependent on external technologies rather than proactive and driven by endogenous innovation. This gap highlights a critical question: How can agricultural firms bridge this deficit and effectively harness innovation to enhance competitiveness while aligning with the ambitious sustainability goals set by policies like the European Green Deal and the Farm to Fork Strategy?

This paper addresses this question by providing empirical evidence on the economic returns of different innovation strategies within the Twin Transition framework. We move beyond treating green and digital innovations as separate phenomena and instead investigate their convergence. Our central hypothesis is that a “Twin Transition” strategy, where digital and green innovations are pursued concurrently to create integrated solutions, positively and durably contributes to increasing the productivity of agricultural enterprises. We argue that the synergistic effects of these “twin innovations” unlock a superior and more lasting competitive advantage than can be achieved by pursuing either technological path in isolation. To test this hypothesis, we analyze a panel dataset of 1,284 innovative European agricultural firms over a 25-year period. By employing a Two-Way Fixed-Effects model, we assess the impact of green, digital, and integrated “twin” patent stocks on firm-level labor productivity.

This paper is structured as follows: Section 2 reviews the policy context and the theoretical framework. Section 3 describes our data and methodology. Section 4 presents the empirical results. Section 5 discusses the findings, their strategic implications, and the study’s limitations. Finally, Section 6 concludes with directions for future research.

4.2. Theoretical Framework

4.2.1. The EU Policy Architecture for the Twin Transition

The European Union has strategically positioned itself as a global leader in sustainable development by architecting an integrated policy framework that addresses digital opportunities and environmental challenges in parallel. This deliberate convergence of policy streams, known as the “Twin Transition”, is not merely an aggregation of separate initiatives but a coherent strategy designed to foster a mutually reinforcing relationship between digital and green transformations (Tabares et al., 2025). The underlying premise is that digitalization can act as a powerful enabler for sustainability, while the green transition can, in turn, drive innovation in the digital sector. This architecture creates a clear institutional context that shapes the competitive landscape for all industries, with particularly profound implications for the agricultural sector.

At the heart of the green agenda is the European Green Deal, a comprehensive roadmap to make the EU's economy sustainable and achieve climate neutrality by 2050 (Vela Almeida et al. 2023). This overarching strategy sets ambitious targets for emissions reduction, resource efficiency, and ecosystem restoration, cascading down into more specific legislative packages like the "Fit for 55" plan. For agriculture, the Green Deal translates into direct pressure to adopt more sustainable practices and reduce its environmental footprint. Running parallel to this is the Digital Transformation Agenda, exemplified by initiatives such as the Digital Decade Strategy. This strategy aims to empower businesses and citizens for a human-centric, sustainable, and prosperous digital future, with concrete targets for 2030 in areas like digital skills, secure digital infrastructures, and the digitalization of public services and businesses. While not exclusively focused on agriculture, this agenda provides the foundational tools and infrastructure necessary for the sector to innovate (Giannone & Santaniello, 2018).

These two macro-trends are explicitly linked and applied to the agri-food system through targeted policies. The Farm to Fork Strategy is a central component of the Green Deal, aiming to make food systems fair, healthy, and environmentally friendly. It sets specific targets, such as reducing the use of pesticides and fertilizers and increasing organic farming, which are difficult to achieve without leveraging advanced digital tools. Supporting this transformation is the Common Agricultural Policy (CAP), one of the EU's most significant financial instruments (Mezzacapo, 2024). With a budget of €387 billion for the 2021-2027 period, the CAP is increasingly designed to reward farmers who adopt sustainable and digital practices, acting as a powerful financial lever for modernization. As argued by Myshko et al. (2024), this multi-layered policy architecture creates a powerful institutional environment of both "push" and "pull" factors. The regulatory requirements of the Green Deal and Farm to Fork strategy push firms to change their practices, while the financial incentives of the CAP and the opportunities offered by the Digital Decade pull them toward innovative, technology-driven solutions. It is within this complex interplay of regulation, investment, and technological opportunity that the imperative for "twin" innovation emerges as a key strategic response for agricultural firms seeking to thrive.

4.2.2. Digital Technologies as Solutions for Agriculture

The digital transformation is fundamentally reshaping the agricultural sector, steering it away from traditional, experience-based practices towards a paradigm of data-driven precision management. Digital technologies are not merely incremental improvements; they represent a suite of tools that can enhance efficiency, optimize resource use, and unlock new sources of competitive advantage (Ye, 2025). These innovations operate on two interconnected levels: the first involves precision technologies that gather data and act at the field level, while the second encompasses data-centric technologies that create value through advanced information processing. At the field level, precision technologies provide the essential infrastructure for granular farm management. A vast network of connected devices, often referred to as the Internet of Things (IoT), includes soil sensors, weather stations, and drones that enable the real-time collection of crucial parameters like moisture levels, nutrient content, and crop health. This constant flow of information allows farmers to move from scheduled interventions to needs-based decisions. This capability is further enhanced by Global Positioning Systems (GPS) combined with Variable Rate Application (VRA) equipment, which permit the precise application of inputs such as water and fertilizers only where and when they are needed. This targeted approach significantly reduces waste, cost, and environmental impact. Complementing these are advances in robotics and automation. The deployment of autonomous machinery, from tractors to specialized weeding robots, addresses challenges like labor shortages while dramatically increasing operational precision, often with a level of accuracy unattainable through manual labor. The true strategic value of this hardware, however, is unlocked by digital and data technologies that transform raw data into operational intelligence. Artificial Intelligence (AI) and Machine Learning algorithms are essential for processing the massive datasets generated on modern farms. They can identify complex patterns to predict yields, forecast disease outbreaks, and recommend optimal management strategies, often forming the core of sophisticated Decision Support Systems (DSS), an area where patented innovation is rapidly growing (Avola et al., 2024). Furthermore, technologies like Digital Twins allow for the creation of virtual replicas of fields or entire farms, enabling the simulation of different management scenarios without real-world risk. In parallel, in an era of heightened consumer demand for transparency, Blockchain offers a secure and immutable ledger for tracking products from farm to fork, enhancing supply chain traceability and verifying sustainability claims.

Collectively, these integrated technologies enable a fundamental shift from a reactive to a proactive and predictive management approach. By turning raw data into a competitive asset, digitalization provides the agricultural sector with the tools necessary to tackle its long-standing challenges of productivity and sustainability.

4.2.3. Green Technologies for Climate Mitigation and Adaptation

In parallel with the digital transformation, green innovation is fundamental to addressing the agricultural sector's twofold challenge: reducing its own environmental impact while simultaneously adapting to a changing climate. Green technologies do not constitute a homogeneous body of work but rather a strategic portfolio of solutions operating on two complementary fronts: climate change mitigation and adaptation (Pavesi et al., 2024). On the mitigation front, the primary goal is to reduce direct greenhouse gas emissions. Technologies such as precision fertilization, enabled by the digital tools previously discussed, allow for an optimized use of nutrients, thereby curbing nitrous oxide (N_2O) emissions—a gas with a far greater global warming potential than CO_2. Other innovations focus on the valorization of agricultural by-products within a circular economy framework. Anaerobic digestion, for example, converts livestock manure and crop residues into biogas, a renewable energy source, while also reducing methane (CH_4) emissions. Another promising technology in this domain is biochar, a carbon-rich soil amendment produced through the pyrolysis of waste biomass. Its application to soil not only improves fertility and water retention but also represents a stable and durable form of carbon sequestration, actively removing CO_2 from the atmosphere. On the adaptation front, technologies aim to strengthen the resilience of agricultural systems to environmental stressors. The development of resilient crop varieties through genetic improvement and modern biotechnologies is crucial for ensuring yield stability under conditions of drought, extreme temperatures, or new biotic pressures. Alongside genetic solutions, systemic approaches like agroforestry—which integrates trees and crops on the same plot of land—are emerging. This practice improves local microclimate regulation, protects the soil from erosion, and enhances biodiversity, creating a more stable and productive system. Finally, resource management strategies such as rainwater harvesting represent a direct and pragmatic response to growing water scarcity in many European regions (Abbass et al., 2022).

These technologies, encompassing both mitigation and adaptation, form the “green” pillar of the transition. They provide the substantive solutions to make agriculture sustainable, while digital technologies often act as the catalysts for their effective and large-scale implementation.

4.2.4. The Convergence Hypothesis: Synergies in Twin Innovation

While the preceding sections have outlined the distinct contributions of digital and green technologies, treating them as separate pillars fails to capture the full scope of the Twin Transition. The most profound innovations emerge not from pursuing these paths in parallel, but from their strategic integration. We define “twin innovations” as solutions that are fundamentally both green and digital in their design, leveraging digital capabilities to achieve superior environmental outcomes, and vice versa. These integrated technologies, such as AI-powered precision irrigation, IoT-enabled soil health monitoring, and blockchain-verified sustainable supply chains, represent the pinnacle of agricultural innovation within the current policy and market landscape.

The core of our argument rests on the concept of synergy. The value created by combining green and digital technologies is greater than the sum of their individual effects. Digital tools act as powerful enablers for green solutions; for instance, AI can optimize the performance of a drought-resistant crop variety by prescribing hyper-specific watering schedules, achieving a level of resource efficiency that neither the technology nor the crop could attain alone. Conversely, sustainability objectives provide a clear strategic direction for digital investments, preventing them from becoming technologically sophisticated yet unproductive endeavors. This synergy creates complex, deeply embedded, and difficult-to-imitate firm capabilities that can serve as a source of durable competitive advantage (Bianchini et al., 2023).

Innovation Creation versus Technology Adoption: A Strategic Choice

Before proceeding to our central hypothesis, it is essential to justify our analytical focus on firms that create innovations, specifically those that patent their own twin transition technologies, rather than firms that merely adopt existing technologies developed externally. While the innovation literature has traditionally emphasized technology adoption as a key driver of firm performance, there are compelling theoretical and empirical reasons to prioritize the study of innovation creators in the context of twin innovation strategies.

Innovation creators develop fundamentally different and more durable competitive advantages compared to technology adopters. Recent research demonstrates that firms engaging in patent creation develop unique appropriability strategies that provide “inimitable strategic positions based on the exclusivity value patented innovation creates” (Zhao et al., 2023). This exclusivity enables patent creators to sustain competitive advantages through aggressive knowledge isolation, emphasizing differentiated abilities to lower costs or provide superior value that adopters cannot replicate (ibid.). In the twin transition context, this exclusivity is particularly valuable as it allows firms to control the integration mechanisms between digital and green technologies, maximizing synergistic effects. Patent creators also develop superior dynamic capabilities compared to adopters. Research shows that innovation capability, defined as a firm’s ability to transform knowledge into products, processes, and systems, is positively associated with firm performance (Wang et al., 2024). However, the interactive effects of innovation capability with other organizational capabilities are particularly pronounced for innovation creators. Specifically, firms that create innovations demonstrate enhanced “sensing, seizing, and transforming capabilities” that allow them to strategically manage both internal and external knowledge as a source of competitive advantage (de Aro & Perez, 2021). This strategic management capability represents a meta-capability that is essential for successfully orchestrating twin innovation synergies. Furthermore, innovation creators possess unique mechanisms for both value creation and value appropriation that adopters lack.

Recent empirical evidence indicates that “innovation resources advantage positively influences firm performance”, with innovation creators showing significantly higher resource utilization efficiency compared to adopters (Wang & Zhong, 2024). Patent creators can choose between appropriating their patented technology to gain a competitive advantage or licensing it strategically, providing them with multiple value capture mechanisms (Zhao et al., 2023). This flexibility in value appropriation strategies is particularly crucial for twin innovations, where the optimal commercialization strategy may involve complex licensing arrangements across both digital and green technology domains.

This leads us to the central hypothesis of our research, which directly reflects the framework outlined in the initial presentation. We propose that the simultaneous pursuit of both innovation streams within a unified strategy yields positive performance outcomes. Therefore, we formally state our hypothesis as follows:

Hypothesis 1 (H1): *A “Twin Transition” framework, where digital innovation and green innovation are pursued simultaneously, positively contributes to increasing the productivity of agricultural enterprises.*

This hypothesis will be empirically tested by examining the relationship between the accumulation of “twin” patents and firm-level labour productivity. Our analysis will then further explore the nature of this contribution, specifically its magnitude and persistence over time, compared to other innovation strategies.

4.3. Methodology

To empirically test our hypothesis, we employ a quantitative research design based on a longitudinal analysis of firm-level data. This section provides a detailed and justified account of the data sources, the systematic sample construction process, the operationalization of our variables, and the econometric strategy.

4.3.1. Data Source and Sample Construction

The empirical foundation of this study is a unique firm-level panel dataset constructed by merging two distinct databases from Moody’s: Orbis Financial and Orbis Intellectual Property (IP). This infrastructure was deliberately chosen for three critical reasons. First, Orbis offers unparalleled pan-European coverage, essential for a study focused on the EU27 policy context. Second, its integration of standardized financial data with a dedicated intellectual property module allows for the direct and reliable linking of a firm’s economic performance to its specific innovation activities. Third, the data undergoes extensive quality control, ensuring a high degree of reliability and comparability across countries (Liu et al., 2024).

The construction of our final analytical sample followed a rigorous, multi-step filtering process designed for transparency and replicability, as visually summarized in the accompanying Figure 4.1.

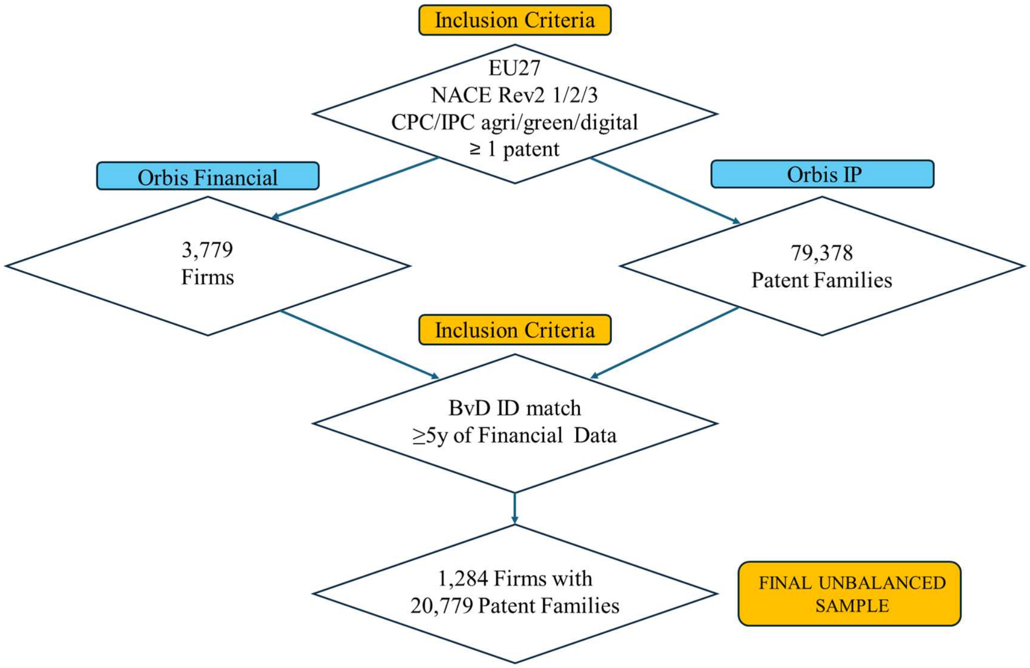

Figure 4.1 Methodological Flowchart. Source: Author's elaboration.

Step 1: Defining the Sectoral Universe

The process began by defining the relevant population. We included all active firms located within the 27 European Union member states. The sectoral boundary was defined using the NACE Rev. 2 statistical classification of economic activities, which is the official EU standard, ensuring objectivity and comparability. We included firms with a primary activity in Division 01 (Crop and animal production, hunting and related service activities), Division 02 (Forestry and logging), and Division 03 (Fishing and aquaculture). This choice was made to capture the "primary sector" in its broader sense, acknowledging that innovation relevant to the Twin Transition occurs across all of these interconnected domains, not just in traditional farming.

Step 2: Identifying the Innovative Population and Defining the Unit of Analysis

We then restricted our sample to firms demonstrating formal innovative activity by identifying those with at least one patent. This step is crucial as it defines the unit of analysis for this study. It is important to clarify that by selecting patenting firms within these NACE codes, our sample does not primarily consist of traditional farms or farming enterprises. Instead, it captures the key technology developers and innovators for the agricultural system. These are often upstream firms (e.g., manufacturers of agricultural machinery, seed and fertilizer producers, biotech companies) or downstream actors (e.g., food processing companies innovating in supply chain traceability) whose primary business is the creation and sale of technology and innovative products used in agriculture. Our study, therefore, analyzes the performance of the innovation-producing firms that constitute the technological backbone of the modern agri-food sector.

Step 3: Matching and Final Filtering

The criteria were applied to the Orbis Financial and IP databases, yielding initial pools of firms and patents. These were matched using the unique Bureau van Dijk ID (BvD ID). A final temporal filter was applied, retaining only firms with at least five years of consistent financial data. This threshold was strategically selected to allow for a robust longitudinal analysis of productivity trends using the fixed-effects estimator, ensuring that the observed effects are persistent rather than artifacts of transient market entries or short-term volatility. This systematic process yielded our final unbalanced panel dataset of 1,284 firms and their 20,779 patent families over the period from 1996 to 2024.

4.3.2. Variables and Measures

Our measure of firm performance is Labour Productivity, defined as the ratio of a firm's Value Added to its total number of employees in a given year. This choice is deliberate and justified on several grounds. First, Value Added is theoretically superior to revenue as an output measure because it nets out the cost of intermediate goods and services, thus isolating the economic value created directly by a firm's own factors of production (labour and capital). Second, labour productivity is a standard and widely used metric in economic studies of firm performance, ensuring comparability with the broader literature (Yousaf, 2022). While Total Factor Productivity (TFP) is an alternative, its calculation requires strong assumptions and reliable data on the capital stock, which is notoriously difficult to measure accurately, making labour productivity a more robust and transparent choice. For our regression analysis, we use the natural logarithm of this variable, a standard procedure to reduce the influence of outliers, mitigate skewness, and allow for the interpretation of coefficients as semi-elasticities.

We measure a firm's innovation capabilities using its patent portfolio (Hegde et al., 2023). We operationalize this as the cumulative stock of patents, which is methodologically superior to using an annual flow (i.e., patents filed in a single year). The stock formulation is justified by the theory that innovation is a cumulative process, where a firm's current innovative potential is a function of its entire history of R&D efforts (Corrocher et al., 2021). A stock variable better represents this accumulated knowledge base and technological capability. The classification of these stocks is based on the Cooperative Patent Classification (CPC) system, chosen for its high granularity, international standardization, and objective, rule-based structure:

- Green Patents: The classification of green patents relies on the CPC code Y02. This is not an arbitrary choice; the Y02 scheme was specifically created by the world's leading patent offices to tag technologies related to climate change mitigation or adaptation. It is therefore the most authoritative and objective standard available for identifying green innovation (Hindle 2024);
- Digital Patents: The list of CPC codes defining digital patents was compiled based on established taxonomies in prior academic literature on Industry 4.0 (Bianchini et al., 2023). This ensures that our definition is grounded in existing research and accurately captures key digital domains like AI and robotics;
- Twin Patents: Our central concept of "twin" innovation is operationalized via a strict Boolean "AND" logic: a patent is classified as "Twin" if and only if its record contains both a Y02 (Green) tag and at least one of the designated Digital tags. This precise, non-ambiguous operationalization is the most direct and objective test of our synergy hypothesis, identifying inventions that verifiably exist at the intersection of the two technological domains.

Category	IPC/CPC Codes	Description
Agri-Food	A01	Agriculture, Forestry & Animal Husbandry
	A21	Baking & Dough
	A22	Butchering & Meat Processing
	A23	Foods & Food Stuff
“Green”	Y02	Technologies or applications for mitigation or adaptation against climate change
“Digital”	G06N, G06F	Artificial Intelligence & Digital Data Processing
	H04L, G08C	IoT & Communications
	B25J, G05B, G05D, B60W	Robotics & Advanced Control Systems
	B33Y	Additive Manufacturing

Table 4.1 Patent Codes

4.3.3. Econometric Strategy

The primary econometric challenge in estimating the returns to innovation is potential endogeneity arising from unobserved firm heterogeneity. For instance, firms with better management (an unobserved characteristic) might be both more innovative and more productive, leading to a spurious correlation. To address this, a panel data approach is essential, and we select a Two-Way Fixed-Effects (TWFE) model as the most robust estimation strategy. This choice is explicitly justified over common alternatives. A Pooled OLS model would ignore the panel structure of the data and would almost certainly yield biased results due to omitted variables (i.e., the unobserved firm-specific characteristics). A Random Effects (RE) model, while accounting for firm-specific effects, rests on the strong and often untenable assumption that these unobserved effects are uncorrelated with the explanatory variables. This assumption is likely violated in our case, as factors like management quality are almost certainly correlated with a firm’s innovation strategy. The Fixed-Effects (FE) estimator, by contrast, makes no such assumption. It controls for all time-invariant heterogeneity, observed or unobserved, by analyzing the within-firm variation over time. It is therefore the more consistent and appropriate choice for our research question (Yang et al., 2024; Ai et al., 2024). The model is specified as:

$$\log\left(Labour\_Productivity_{it}\right) = \beta_1 Tech\_Comp_{i,t-k} + \alpha_i + \theta_t + \epsilon_{it}$$

The two-way nature of the model is also a critical feature. The firm fixed effects (αi) accomplish the control for firm-specific heterogeneity described above. The year fixed effects (θt) control for any time-specific shocks common to all firms, such as macroeconomic cycles, major policy reforms (e.g., CAP), or energy price shocks. Including both is necessary to isolate the effect of firm-specific innovation from these confounding factors. A lag structure (k) for the innovation variables, ranging from one to five years, is included because the economic returns on R&D are rarely instantaneous. This dynamic specification is essential to capture the potentially delayed impact of innovation and to test for its persistence over time, a core element of our analysis. Finally, we cluster our standard errors at the firm level. This is the standard best practice in panel data analysis to correct for potential serial correlation within a firm's observations over time, ensuring that our statistical inference is valid and reliable.

4.4. Preliminary Results

This section presents the empirical findings of our study. We begin by providing a descriptive overview of the innovation landscape within our sample of European agricultural firms, detailing both the prevalence and the geographical distribution of different technological strategies. We then present the core econometric results from our main model, which examines the dynamic impact of these strategies on labour productivity. Finally, we confirm the robustness of our main findings through a series of alternative model specifications and dependent variables.

4.4.1. The Landscape of Innovation in European Agriculture: A Descriptive Analysis

Before proceeding to the econometric analysis, it is essential to understand the characteristics of innovation within our sample of 1,284 firms. Table 4.2 provides a quantitative breakdown of the different technological categories under investigation, while Figure 4.2 illustrates their geographical distribution across the EU27.

Innovation Category	Number of Firms	% of Total Firms	Number of Patents	% of Total Patents
Agri-Food	556	38.0%	10,465	50.4%
Digital	127	8.7%	623	3.0%
Green	173	11.8%	1,409	6.6%
Twin	**15**	**1.0%**	**54**	**0.3%**

Table 4.2 Descriptive Statistics of Patent Categories (1996-2024) Note: The total number of firms is 1,284. Firms may belong to multiple categories if they hold patents in different domains.

A detailed examination of Table 4.2 reveals a clear hierarchy in the innovation strategies pursued by European agricultural firms. The data shows that the sector's inventive activity remains predominantly anchored in the Agri-Food domain, which accounts for over half (50.4%) of all patents in our sample and is pursued by a significant portion (38.0%) of the innovative firms. This suggests that the core R&D focus is still largely directed towards traditional agricultural challenges and solutions. In line with the policy push of the Twin Transition, both Green and Digital innovation are established phenomena. However, they represent a considerably smaller fraction of the total inventive output. Green patents constitute 6.6% of the total, developed by 11.8% of the firms, while Digital patents are even less frequent, at 3.0% of the total, produced by 8.7% of the firms. This indicates that while these strategic avenues are being explored, they are far from mainstream within the sector's innovation landscape. The most striking insight from this descriptive analysis, however, is the profound rarity of Twin innovation. Only 15 firms in our entire sample of innovators (a mere 1.0%) have developed patents that are simultaneously green and digital. These "twin" patents, which represent the tangible output of an integrated innovation strategy, constitute a negligible 0.3% of the total patent portfolio. This finding is critical: it highlights that while the concept of the Twin Transition is a central pillar of EU policy, its practical implementation at the firm level, through the creation of truly integrated technologies, is at a frontier strategy pursued by a very small and select group of pioneers, as of the time of writing.

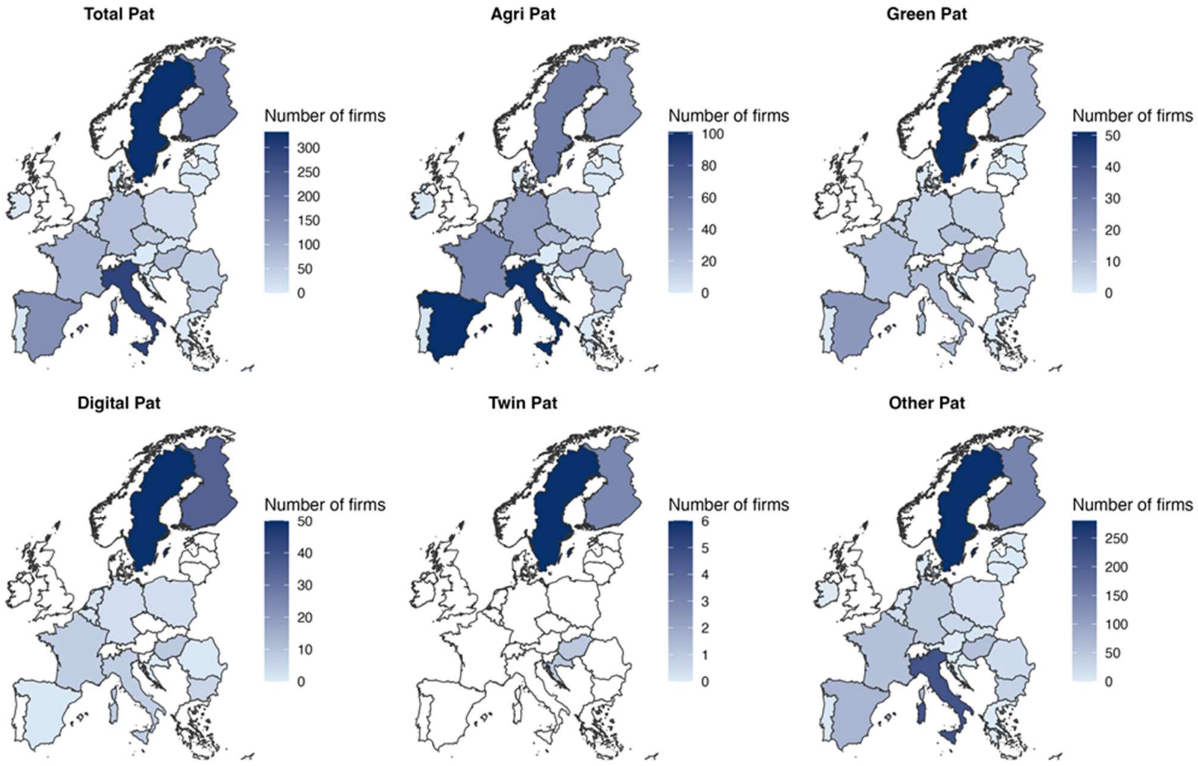

Figure 4.2 Geographical Distribution of Innovative Firms by Patent Category (1996–2024). Source: Author's elaboration.

This quantitative picture is further illuminated by the geographical analysis presented in Figure 4.2. The choropleth maps reveal distinct spatial patterns in innovation. The top-left map, showing the distribution of Total Patents, confirms that innovative activity in the agricultural sector is highly concentrated in a few key countries, with Germany, France, and Italy emerging as the dominant innovation hubs. This pattern is largely mirrored in the distribution of Agri-Pat and Other Pat, indicating that these traditional innovation powerhouses drive the bulk of the sector's inventive output. The distribution of specialized innovation, however, tells a different story. The map for Green Patents shows that while the traditional leaders are still significant, there is a notable concentration of green innovators in the Nordic countries, suggesting a regional specialization in sustainable technologies. An even stronger geographical clustering is evident for Digital Patents, which are overwhelmingly concentrated in Germany and Scandinavia, a pattern consistent with the broader distribution of Europe's digital economy. Finally, the map for Twin Patents, despite being based on a very small number of firms, reinforces this narrative of specialization and rarity. The few "twin" innovators appear as isolated hotspots, primarily located within the established hubs of green and digital expertise. Geographically, while absolute patent volumes are driven by major economies like Germany and Italy, Figure 4.2 reveals a significant intensity of 'Twin' and 'Digital' patenting in the Nordic countries, particularly Sweden. Despite a smaller absolute number of firms compared to Continental Europe, Sweden's high density of digital-green innovation aligns with its leadership in the Digital Economy and Society Index (DESI), suggesting a qualitative advantage in high-tech agricultural solutions. This geographical evidence suggests that the capacity to develop such integrated technologies is not widespread but is instead emerging at the intersection of pre-existing, specialized knowledge bases. This descriptive evidence sets the stage for our central research question: does this rare, geographically concentrated, and theoretically powerful strategy yield superior economic returns? We will turn to the econometric results to answer this question in Section 4.4.2. and following.

4.4.2. The Nature of Twin Innovators and Innovations: A Qualitative Look

Our descriptive statistics show that "twin" innovators are exceptionally rare. Before assessing their economic performance, it is crucial to understand who these pioneering firms are and what their synergistic technologies look like in practice. A qualitative review of the 15 "twin" firms and their 54 patents reveals distinct archetypes that give a tangible face to our statistical categories. This analysis transforms "twin innovation" from an abstract concept into a concrete business phenomenon. We can identify three main profiles of "twin innovators":

- The Global Ag-Tech Leaders: This group includes large, multinational corporations, often in sectors like agricultural chemicals, seed production, or heavy machinery. For these firms, twin innovation is a strategic tool to defend and expand their market leadership. They leverage vast R&D budgets to develop integrated, proprietary platforms that lock in customers. An example is a global agriscience company that develops a patented system combining genetically resilient seeds (a green innovation) with a proprietary digital platform that uses satellite imagery and AI to provide tailored planting and treatment advice for those specific seeds (a digital innovation). Their competitive advantage comes from selling a closed, high-performance ecosystem;
- The Sustainable Process Innovators: This category is populated by agile Small and Medium-sized Enterprises (SMEs), often operating in traditional sectors like food processing or waste management. Their innovation is not about creating a blockbuster technology, but about radically re-engineering their production and supply chain processes. An example from our sample is a Central European company that patented a system for converting agricultural waste into high-grade organic fertilizer. Their

innovation is “twin” because it combines a green process (waste valorization, circular economy) with a digital layer of sensors and software that monitors the chemical composition and quality of the process in real-time to guarantee a standardized, high-quality final product. Their advantage lies in operational efficiency and the creation of premium, certified sustainable products;

- The Frontier-Tech Startups: The third group consists of small, highly specialized, research-intensive startups, often spin-offs from universities. These firms focus on a single, cutting-edge technology. For instance, a Nordic startup in our sample holds patents for autonomous, solar-powered robotic systems for micro-weeding. This innovation is intrinsically “twin”: it is green because it enables a massive reduction in herbicide use, and it is digital because it relies on advanced robotics, machine vision, and AI to distinguish weeds from crops. Their business model is often based on licensing their technology or being acquired by a larger player.

These innovators are developing three primary archetypes of “twin technologies”:

- Crop Efficiency & Resilience Platforms: This is the most prevalent category. These are integrated systems, not single products. They combine hardware (like IoT soil sensors, drones) and software (AI-powered analytics) to provide farmers with real-time, actionable advice. A patent in this space might cover a method for using drone-based hyperspectral imagery (digital) to detect early-stage plant stress and automatically trigger a precision irrigation system (green, water-saving). The goal is to optimize input use (water, fertilizer, energy) while maximizing yield and resilience;
- Transparent & Circular Supply Chains: These innovations use digital tools to verify and monetize sustainable practices. Patents here often describe systems using Blockchain or QR codes to create an immutable “digital passport” for a food product. This allows a consumer to scan a product and see its entire journey, verifying claims about its low carbon footprint or organic status (green). The technology enables new business models based on certified sustainability, turning a “green” attribute into a verifiable, premium asset;
- Field Automation & Robotics for Sustainability: This category includes autonomous machines designed to perform agricultural tasks in an environmentally friendly way. Beyond the weeding robots mentioned earlier, this includes autonomous electric tractors that reduce on-farm fossil fuel consumption (green) while using GPS and LiDAR for navigation and operational optimization (digital). The innovation lies in creating machines that are not just automated but are designed from the ground up to be sustainable.

This qualitative analysis is crucial. It demonstrates that the 15 firms in our “twin” category are not a random sample; they are strategic actors developing complex, systemic solutions. Perhaps the most important insight from this review is that the “twin” innovation strategy is not confined to a single type of firm or a narrow technological domain. It is a transversal logic that can be applied across the entire agri-food value chain. It is being successfully deployed by actors of vastly different scales (from multinational leaders to agile SMEs and frontier-tech startups) and with diverse business models (from selling integrated platforms to creating certified sustainable products and licensing cutting-edge robotics). This heterogeneity is a powerful indicator that “twin innovation” is not a niche technological fad, but a fundamental and broadly applicable strategic paradigm for creating value in the modern agricultural economy. Having established what we are measuring and its diverse nature, we now proceed to quantify its economic impact.

4.4.3. The Dynamic Impact of Innovation on Labour Productivity

The core empirical findings of our study are presented in a series of tables, each detailing the results of our Two-Way Fixed-Effects model at a different time lag, from one to five years. By analyzing the evolution of the coefficients across these tables, we can construct a detailed narrative of the dynamic relationship between different innovation strategies and firm-level labour productivity, ultimately providing a robust test of our central hypothesis (H1).

The analysis begins with the immediate short-term effects, as detailed in Table 4.3, which presents the regression outputs for a one-year lag (t-1). Here, we observe that both traditional and single-domain green innovations are associated with positive productivity gains. Specifically, the stock of Agri Patents shows a positive and marginally significant relationship ($\beta = 0.016$, $p < 0.1$), as does the stock of Green Patents ($\beta = 0.009$, $p < 0.1$). This suggests that these innovations do provide an initial, albeit modest, competitive boost. However, even at this early stage, a critical distinction emerges. The stock of Digital Patents, when analyzed in isolation, yields a coefficient that is small and statistically indistinguishable from zero, offering no evidence of a productivity return. In stark contrast, the stock of Twin Patents is associated with a positive, economically meaningful, and highly statistically significant coefficient ($\beta = 0.014$, $p < 0.001$). This initial result already hints at the superior performance of an integrated innovation strategy.

D.V. – Lab. Prod. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-1)	0.01356* (0.00629)					
Agri Pat (t-1)		0.01575† (0.00838)				
Green Pat (t-1)			0.00938† (0.00478)		0.00665 (0.00619)	
Digital Pat (t-1)				0.00167 (0.01003)	-0.01177 (0.01219)	
Green× Dig (t-1)					0.00154 (0.00114)	
Twin Pat (t-1)						0.01371*** (0.00063)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	7698	7698	7698	7698	7698	7698
#Firms	1,284	1,284	1,284	1,284	1,284	1,284
#Years	28	28	28	28	28	28
R2	0.888	0.877	0.876	0.867	0.884	0.892
R2 Adj.	0.867	0.851	0.850	0.843	0.862	0.870

Table 4.3 OLS Model: Impact of Technological Competences on Labour Productivity (Lag t-1)

This narrative becomes progressively clearer and more compelling as we extend the time horizon. At a two-year lag (Tab. 4.4), the patterns begin to diverge sharply. The positive effects of Agri and Green patent stocks persist but their statistical significance remains weak (with Green patents at $p < 0.1$ and Agri patents losing significance). The coefficient for Digital patents remains statistically insignificant. The effect of Twin innovation, however, not only persists but more than doubles in magnitude to become the strongest performance driver in the entire analysis ($\beta = 0.028$, $p < 0.001$). This suggests that the productivity gains from synergistic innovations require some time to fully materialize but are substantially larger than those from any other strategy.

D.V. – Lab. Prod. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-2)	0.01204†					
	(0.00686)					
Agri Pat (t-2)		0.01351				
		(0.00901)				
Green Pat (t-2)			0.00872†		0.00768	
			(0.00484)		(0.00568)	
Digital Pat (t-2)				0.00558	-0.00021	
				(0.00944)	(0.01213)	
Green×Dig (t-2)					0.00053	
					(0.00136)	
Twin Pat (t-2)						0.02812***
						(6.0105e-04)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	6428	6428	6428	6428	6428	6428
#Firms	1,177	1,177	1,177	1,177	1,177	1,177
#Years	27	27	27	27	27	27
R2	0.881	0.866	0.879	0.868	0.872	0.903
R2 Adj.	0.870	0.843	0.855	0.847	0.851	0.881

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Tab 4.4 OLS Model: Impact of Technological Competences on Labour Productivity (Lag t-2)

By the third year (Tab 4.5), the short-term advantages of single-domain innovation have largely evaporated. The coefficients for both Agri and Green patent stocks are no longer statistically significant, indicating that their competitive benefits have fully eroded. The Digital patent stock continues to show no effect. The Twin Patent stock, however, maintains its strong, positive, and highly significant relationship with labour productivity ($\beta = 0.013$, $p < 0.001$). This marks a critical juncture: three years after the innovation event, only the integrated, synergistic strategy is still yielding measurable economic returns.

D.V. – Lab. Prod. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-3)	0.01062					
	(0.00833)					
Agri Pat (t-3)		0.01256				
		(0.00981)				
Green Pat (t-3)			0.00617		0.00785	
			(0.00637)		(0.00729)	
Digital Pat (t-3)				0.01291	0.03027	
				(0.01480)	(0.02998)	
Green×Dig (t-3)					-0.00452	
					(0.00567)	
Twin Pat (t-3)						0.01260***
						(0.00057)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	5258	5258	5258	5258	5258	5258
#Firms	1,071	1,071	1,071	1,071	1,071	1,071
#Years	26	26	26	26	26	26
R2	0.869	0.876	0.875	0.868	0.864	0.915
R2 Adj.	0.850	0.852	0.853	0.851	0.853	0.892

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table 4.5 OLS Model: Impact of Technological Competences on Labour Productivity (Lag t-3)

This finding is powerfully reinforced at the four and five-year lags. At t-4 (Tab. 4.6), all single-domain innovation variables (Agri, Green, and Digital) have coefficients that are statistically zero. Yet, the Twin Patent stock is once again associated with a large, positive, and highly significant productivity premium ($\beta = 0.020$, $p < 0.001$). This pattern culminates at the five-year lag (Tab. 4.7), where, despite the smaller sample size and the extended time horizon, the Twin Patent stock is the only innovation variable that retains a positive and highly statistically significant coefficient ($\beta = 0.013$, $p < 0.001$).

D.V. – Lab. Prod. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-4)	0.00374					
	(0.01151)					
Agri Pat (t-4)		0.00250				
		(0.01377)				
Green Pat (t-4)			0.00349		0.00183	
			(0.00850)		(0.00858)	
Digital Pat (t-4)				0.00425	0.05275	
				(0.00650)	(0.03780)	
Green×Dig (t-4)					-0.01187	
					(0.00823)	
Twin Pat (t-4)						0.01969***
						(0.00062)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	4190	4190	4190	4190	4190	4190
#Firms	895	895	895	895	895	895
#Years	25	25	25	25	25	25
R2	0.886	0.877	0.876	0.888	0.895	0.922
R2 Adj.	0.857	0.850	0.851	0.869	0.873	0.899

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table 4.6 OLS Model: Impact of Technological Competences on Labour Productivity (Lag t-4)

D.V. – Lab. Prod. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-5)	-0.00017					
	(0.01222)					
Agri Pat (t-5)		0.00045				
		(0.01293)				
Green Pat (t-5)			-0.00143		-0.00283	
			(0.01003)		(0.01020)	
Digital Pat (t-5)				0.00228	0.04221	
				(0.00452)	(0.03672)	
Green×Dig (t-5)					-0.00980	
					(0.00837)	
Twin Pat (t-5)						0.01340***
						(0.00074)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	3297	3297	3297	3297	3297	3297
#Firms	811	811	811	811	811	811
#Years	24	24	24	24	24	24
R2	0.891	0.897	0.911	0.899	0.905	0.934
R2 Adj.	0.882	0.874	0.890	0.875	0.881	0.912

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table 4.7 OLS Model: Impact of Technological Competences on Labour Productivity (Lag t-5)

In summary, the dynamic analysis provides an unequivocal story. The productivity gains associated with traditional and single-domain green innovation are transitory, disappearing within three years. Standalone digital innovation appears to have no discernible impact on productivity in this sector. It is only the Twin innovation strategy—the one that synergistically combines green and digital elements into a unified whole—that generates a durable and sustained increase in firm productivity, with positive and significant effects lasting at least five years after the initial innovation. This provides powerful empirical support for our hypothesis H1, demonstrating that it is the convergence of technologies, rather than their siloed application, that drives long-term competitive advantage.

4.4.4. Additive Effects vs. True Synergy: An Important Distinction

Before concluding our main analysis, we address a crucial alternative explanation: is the superior performance associated with “twin” innovation simply the additive result of a firm holding both green and digital capabilities, or does it stem from truly integrated, synergistic inventions? A firm could, for instance, develop separate green technologies and digital tools, and the observed effect might be the sum of these two independent streams. To test this, we estimate a model (Model 5 in our tables) that includes the separate stocks of Green Patents and Digital Patents alongside their multiplicative interaction term (Green × Digital). The results from this specification are consistently revealing across all time lags. The interaction term is small in magnitude and never approaches statistical significance. This is a critical finding. It strongly suggests that simply possessing a portfolio containing separate green and digital innovations is not sufficient to generate the durable productivity premium we observe. The effect is not driven by firms that are good at green innovation and also happen to be good at digital innovation. Instead, the evidence points squarely to the conclusion that the performance gains are uniquely attributable to the development of integrated innovations—single patents that are intrinsically both green and digital. This provides powerful evidence that the “twin” effect is a result of true technological synergy, captured by our more precise Twin Patent variable, rather than a mere aggregation of separate knowledge bases.

4.4.5. Robustness Checks

To ensure that our central findings are robust and not an artifact of our specific methodological choices, we conduct two rigorous sets of sensitivity analyses. These tests subject our main conclusion, the superior and durable impact of twin innovation, to alternative econometric specifications and a different measure of firm performance. The full results of these tests are presented for the reader’s consideration, respectively in Appendix A and Appendix B.

Alternative Econometric Model: Robustness to the PPML Estimator

Our main specification employs an OLS estimator on a logarithmized dependent variable. While this is a standard and well-accepted practice in the literature, it carries two potential econometric limitations. First, the logarithmic transformation cannot handle observations with zero or negative values for the dependent variable, which are consequently dropped from the sample, potentially introducing selection bias. Second, OLS can be sensitive to heteroskedasticity, where the variance of the error term is not constant across observations. Although we mitigate this by using cluster-robust standard errors, a more inherently robust estimator can provide stronger validation. We therefore re-estimate our models using the Poisson Pseudo-Maximum Likelihood (PPML) estimator. The PPML estimator is particularly well-suited for models with log-dependent variables because it is consistent even in the presence of heteroskedasticity and naturally accommodates zero values in the dependent variable, using the level of productivity rather than its log.

$$Labour\_Productivity_{it} = exp\ (\beta 1 Tech\_Comp_{i,t-k} + \alpha_i + \theta_t) + \epsilon_{it}$$

The results of this alternative specification, detailed in Tables A1 through A5 in the appendix, fully corroborate our main findings. The estimated coefficients are not directly comparable in magnitude to the OLS results, but their sign, significance, and relative importance are entirely consistent. Across all five time lags, the coefficient for the Twin Patent stock remains positive, economically large, and highly statistically significant ($p < 0.001$). The coefficients for the single-domain innovations, meanwhile, remain either weakly significant in the short term or statistically insignificant in the long term. The consistency of our core result across both OLS and PPML estimators provides strong evidence that our findings are not driven by a specific econometric technique or by the treatment of zero-value observations.

Alternative Dependent Variable: Robustness to the Performance Metric

A second potential concern is that our results might be specific to our chosen performance metric, labour productivity based on Value Added. To ensure our findings reflect a broader phenomenon of firm performance and are not simply an artifact of a single metric, we conduct a second robustness check using an alternative dependent variable: Operating Revenue. We re-estimate our main Two-Way Fixed-Effects model using the logarithm of operating revenue as the outcome. Since revenue is a function of a firm's scale, we now explicitly include the logarithm of the number of employees as a key control variable on the right-hand side of the equation, effectively estimating a technology-augmented production function. This allows us to test whether innovation contributes to top-line growth, holding firm scale constant.

$$log\ (OpRev_{it}) = \beta_1 Tech\_Comp_{i,t-k} + \beta_2 log\ (Employees_{i,t-k}) + \alpha_i + \theta_t + \epsilon_{it}$$

The results of this analysis, presented in Tables B1 through B5 in the appendix, are qualitatively identical to our main findings. The Twin Patent stock is once again associated with a positive and highly statistically significant premium on operating revenue across all five-time lags. Conversely, the single-domain innovation strategies show the same pattern of transitory or insignificant effects observed in our main models. This test is crucial as it demonstrates that the benefits of twin innovation are not confined to improving internal efficiency (as measured by productivity) but also translate into enhanced market performance (as measured by revenue). This confirms that our central result, the superior and durable economic return of synergistic twin innovation, is not sensitive to a specific choice of performance metric but reflects a more fundamental driver of firm growth and competitive advantage.

4.5. Discussion

Our empirical analysis has told a clear and unequivocal story: in the complex arena of European agriculture, the path to a durable competitive advantage is narrow and specific. It is not paved with just any innovation. It is paved with an integrated, synergistic form of innovation that merges the green and digital worlds. The purpose of this section is to move beyond the statistical coefficients and discuss what this finding truly means—for the managers making investment decisions in the field and for the policymakers shaping the competitive landscape from Brussels.

4.5.1. The Durable Advantage of Synergistic Innovation

The central message of our results is not just that "twin" innovation is better, but why it is fundamentally different. The fleeting advantages offered by standalone green or agricultural patents are predictable in a competitive market; they represent incremental improvements that are relatively easy for competitors to understand and replicate. The absolute failure of standalone digital patents to move the needle on productivity is the most cautionary tale in our data, revealing that technology without a clear mission fails to create value. This is where twin innovation changes the game. As we demonstrated in Section 4.4.2, a technology like a blockchain-based traceability system for "carbon farming" isn't just a new product; it is a new socio-technical system. It requires new skills, new processes, and fundamentally new sustainable business models. This systemic complexity is what creates a durable competitive advantage. It is difficult, slow, and expensive for competitors to copy an entire business model. The persistent, high returns to twin patents are the economic signature of a firm that has successfully built a complex, hard-to-imitate strategic capability. The fact that this logic is being successfully applied by actors as diverse as multinational leaders, agile SMEs, and frontier-tech startups proves its power. It is not a strategy confined to a specific business size or market position; it is a fundamental paradigm for value creation in the modern agricultural economy.

4.5.2. The Managerial Imperative: A Transversal Logic for a Diverse Sector

The implications of our findings for farm managers, agricultural entrepreneurs, and corporate strategists are profound, and the transversal nature of twin innovation makes them broadly applicable, though context-dependent. The first imperative, the demolition of internal silos, holds true for all. An R&D budget split between a “sustainability department” and an “IT department” is a recipe for failure. However, the expression of this integration will differ. For a Global Ag-Tech Leader, this means building large, cross-functional teams to develop proprietary platforms. For an SME, it means the owner or a small management team must personally embody this dual competence, thinking about process efficiency and sustainability as two sides of the same coin. For a Startup, the entire founding team is often the embodiment of this synergy from day one. Secondly, the call for organizational change is universal, but its implementation is not one-size-fits-all. While all firms must commit to building new capabilities, the key strategic decision is “make versus buy”. A large corporation might have the resources to “make” these capabilities in-house. For most SMEs and startups, this is impossible. Their strategic imperative is therefore not internal development, but ecosystem engagement. The fact that twin innovation is a transversal logic means that a firm of any size can adopt it, provided it can identify the right partners. An SME in the Po Valley, for instance, doesn’t need to build an AI team; it needs to partner with a local tech startup or a university spin-off. A startup with a brilliant robotic weeding technology needs to partner with a large machinery manufacturer to scale production and distribution. The key managerial capability is no longer just R&D management, but partnership and network management.

4.5.3. The Policy Challenge: From One-Size-Fits-All to a Portfolio Approach

The transversal nature of twin innovation has radical implications for policymakers. If the actors are diverse, then the policy support mechanisms must be equally diverse. A “one-size-fits-all” policy will inevitably fail to support the full spectrum of innovators. The evidence demands a shift from funding generic projects to cultivating a portfolio of tailored support instruments. For the Global Ag-Tech Leaders, this might mean supporting pre-competitive, large-scale R&D consortia under programs like Horizon Europe to tackle grand challenges. For the Sustainable Process Innovators—the SMEs that form the backbone of Europe’s rural economy—the need is for more accessible instruments: direct grants or tax incentives for adopting certified green-digital technologies, and support for regional “digital innovation hubs” that can provide technical expertise. For the Frontier-Tech Startups, the critical needs are different again: access to venture capital, regulatory sandboxes to test disruptive technologies (like autonomous drones or gene-edited crops) in a safe environment and streamlined patenting processes. In essence, policy should shift its focus from supporting a strategy to supporting an ecosystem. The goal is not to pick winners, but to ensure that firms of all sizes and types have the resources and the collaborative environment they need to engage with the twin innovation paradigm. Fostering these interconnected ecosystems, where a startup from here in Milano can collaborate with a German machinery giant and a Spanish food processor, is the most effective use of public funds to build a competitive, resilient, and sustainable European agricultural sector.

4.6. Conclusions

This paper set out to investigate the economic returns of the “Twin Transition” within the European agricultural sector. Motivated by a pervasive EU policy focus on the convergence of green and digital transformations, we hypothesized that an integrated innovation strategy would yield superior and more durable performance gains compared to pursuing either path in isolation. Through a large-scale, longitudinal analysis of 1,284 innovative firms over 25 years, we have found robust and compelling evidence to support this hypothesis. Our results demonstrate a clear hierarchy of innovation strategies: while traditional and standalone green innovations provide only transitory productivity boosts, and standalone digital innovation shows no discernible impact at all, it is the synergistic “twin” innovations that are the sole drivers of sustained, long-term competitive advantage. This conclusion carries significant weight for both managers and policymakers. It suggests that the greatest value creation in the modern agricultural economy lies at the intersection of sustainability and digitalization, demanding a strategic shift away from siloed innovation management and towards the cultivation of complex, integrated socio-technical systems. Our qualitative analysis further reveals that this is not a niche strategy confined to a single type of firm, but a transversal logic being successfully applied by a diverse set of actors, from multinational leaders to agile SMEs and frontier-tech startups. However, the strength of these conclusions must be considered in light of the study’s inherent limitations, which themselves illuminate a clear path for future research.

4.6.1. Limitations of the Study

A commitment to academic rigour requires a transparent and critical acknowledgment of the boundaries of our research design. While we have taken extensive steps to ensure the robustness of our findings, several limitations must be carefully considered when interpreting the results.

First, and perhaps most importantly, this study is bounded by its reliance on patents as the primary proxy for innovation. While patents are a standard and objective measure of codified technological invention, they are an imperfect measure of the broader concept of innovation. This choice has several profound implications. It systematically overlooks non-patentable forms of innovation that are critically important, especially in a sector like agriculture. This includes process innovations, the development of novel and sustainable business models, proprietary know-how, and service-based innovations. Consequently, our study may be underestimating the innovative activity of SMEs, which often compete through process efficiency and business model agility rather than formal R&D. Our results should therefore be interpreted not as a measure of the returns to all innovation, but as the returns to formal, codified technological invention.

Second, the construction of our sample, which is restricted to patenting firms, introduces a necessary but significant selection bias. Our findings are, by design, about the differential returns to various innovation strategies among the population of existing innovators. We cannot, from this analysis, make causal claims about whether a non-innovating farm should begin to innovate, nor can we generalize our findings to the entire population of agricultural enterprises, the vast majority of which do not patent. Our study is an analysis of the technological frontier of the sector, not the sector as a whole.

Third, our choice of performance metric, while standard, is necessarily narrow. We use labour productivity (based on Value Added) as our primary dependent variable, which is a robust measure of economic efficiency. However, it is not a direct measure of profitability, market share, or, most critically, environmental performance. This is a crucial limitation. We demonstrate that twin innovation leads to a productivity premium, but we cannot claim from our data that these firms are necessarily more profitable or that they have a lower environmental footprint. It is theoretically possible that a firm could increase its productivity through an innovation that also externalizes environmental costs. While the “green” tag on the patents suggests a positive environmental intention, our study does not provide evidence of the actual environmental impact. We measure the private economic returns to a “green” strategy, not the public environmental returns.

Finally, while our Two-Way Fixed-Effects model is a powerful tool for mitigating omitted variable bias, and our robustness checks confirm the stability of the results, we must be cautious in claiming definitive causality. Despite controlling for all time-invariant firm characteristics and common time shocks, we cannot completely rule out the possibility of endogeneity from unobserved, time-varying factors. For example, the appointment of a new, visionary CEO could lead to both the adoption of a twin innovation strategy and other unobserved managerial improvements that jointly drive productivity. While our use of a five-year lag structure provides strong evidence of precedence, the interpretation of our coefficients as purely causal effects should be made with this note of academic caution.

4.6.2. Future Research Directions

The limitations detailed above do not diminish the importance of our findings, but rather, they illuminate a fertile and exciting agenda for future research. This agenda can be structured along two main complementary pathways: quantitative and qualitative. On the quantitative front, several avenues emerge directly from our analysis. While our fixed-effects model establishes a robust and persistent correlation, future research should aim to further probe the issue of reverse causality. The application of more advanced econometric techniques, such as the use of instrumental variables or dynamic panel models like the Generalized Method of Moments (GMM), could help to better isolate the causal pathways that link a firm’s stock of twin patents to its subsequent performance. Furthermore, our analysis could be extended to investigate the heterogeneity of these effects. Future work could explore how the impact of twin innovation varies by firm size, specific agricultural sub-sector (e.g., crop production vs. livestock), or in response to different regional policy environments, providing a more granular understanding of the contexts in which this strategy is most effective. Finally, a crucial next step is to measure the broader impact of twin innovation. Future research should endeavor to link patent and economic data with a wider array of performance metrics, including firm profitability, market value, and, most importantly, key environmental performance indicators (e.g., CO_2 emissions per unit of output). This would allow for a direct test of the “double dividend” hypothesis: does the productivity premium from twin innovation also come with a tangible environmental premium? On the qualitative front, the research agenda is equally rich. The most immediate and promising avenue is to conduct in-depth case studies of the twin innovator profiles we identified. This would provide a rich, textured understanding of the specific business models, organizational capabilities, and strategic decision-making processes that allow these firms to succeed, exploring the non-patentable aspects of innovation that our study could not capture. Building on this, a broader ecosystem analysis is needed to map the firm-university-SME collaboration networks that appear to underpin the emergence of twin innovation. Understanding these network dynamics is crucial for grasping how the necessary interdisciplinary knowledge is created and shared. Lastly, future research should undertake a direct policy evaluation. While our study discusses policy implications, dedicated studies are needed to assess the real-world impact of specific policies, like the EU Green Deal’s funding mechanisms, on the behaviour and performance of these innovative firms, providing crucial feedback for the design of future innovation policy.

CONCLUSIONS

This dissertation embarked on an inquiry into one of the most critical challenges of our time: steering the green transition within the global agri-food sector. Framed by the ambitious policy landscape of the European Union's National Recovery and Resilience Plan and its embodiment in the AGRITECH National Research Center, this research sought to move beyond aspirational goals to dissect the two core engines of this transition: the business models that give it strategic form, and the innovation dynamics that provide its technological fuel. Through a multi-scalar and multi-methodological investigation, this thesis has constructed a coherent and cumulative argument, the key findings of which are synthesized here. Specifically, this work validates the central thesis posited at the outset: that the green transition is not merely a technological hurdle, but a structural challenge requiring a multi-level strategic reconfiguration. The research trajectory confirms this hypothesis through a cumulative evidence chain. Chapter 1 established the theoretical necessity for integrated business models; Chapter 2 demonstrated their design viability through the circular biochar framework; Chapter 3 mapped the global technological supply, revealing a critical gap between invention and adoption; and finally, Chapter 4 provided the empirical verdict, proving that only the synergistic "twin" strategy generates durable economic value. Collectively, these findings confirm that sustainability acts as a competitive driver only when embedded within a coherent, digitally-enabled strategic architecture. The investigation into business models began in the first chapter, where a bibliometric cartography revealed that concepts of sustainability and circularity are central pillars of the academic discourse. This established a clear theoretical imperative: the transition requires new strategic architectures. The second chapter then moved from theory to practice, providing a crucial proof-of-concept. The in-depth case study demonstrated that these abstract principles can indeed be forged into a viable, multidimensional, and strategically coherent business model for a real-world green technology, providing a tangible link between a firm's operational design and its sustainability goals. The second pillar of the inquiry, innovation dynamics, was first explored on a global scale. The panoramic survey of the patent landscape in the third chapter uncovered a complex and paradoxical reality. It revealed a massive volume of inventive activity, particularly driven by China, existing alongside low strategic retention and a profound disconnect between the act of invention and the creation of durable, market-ready innovation. This analysis highlighted a systemic inertia in the global innovation engine, which remains heavily skewed towards short-term adaptation technologies over long-term mitigation solutions. It is at the intersection of these two pillars, business models and innovation dynamics, that the fourth and final chapter delivered the conclusive, empirical verdict. The econometric analysis acted as the definitive test of value, revealing with unequivocal clarity that the path to sustained economic performance is narrow and specific. The evidence clearly indicates that sustainable economic performance is derived not from the simple adoption of green technologies, but from embedding a synergistic innovation strategy that fuses green and digital capabilities within the firm's core business model. Firms that operate merely as adopters risk falling behind in the green transition, whereas those that demonstrate proactive innovation offer integrated solutions with sustainable competitive advantage. The evidence demonstrated that only an integrated approach, one that fuses digital and green capabilities, is capable of generating a durable competitive advantage. Standalone innovation strategies were found to be economically unsustainable in the long run.

The primary contribution of this dissertation, therefore, is the provision of a holistic, evidence-based framework for understanding how to steer the green transition. It demonstrates that success is not a matter of technology alone, but of the strategic alignment between a firm's business model and its innovation strategy. It moves the conversation from "what to invent" to "how to build a sustainable enterprise". Methodologically, this work demonstrates the power of a multi-stage research design to dissect a complex, real-world phenomenon, integrating insights from four distinct analytical lenses to construct a robust and deeply contextualized conclusion. Ultimately, this thesis concludes that steering the green transition is not a technological problem, but a strategic one, where the future belongs to those who can master the intricate interplay between how they innovate and how they create value.

Managerial Implications: A Strategic Playbook

The findings of this dissertation, taken as a whole, converge on a single, unequivocal conclusion: the green transition demands a fundamental reinvention of how agricultural enterprises manage innovation, evaluate value, and engage with the world. The old paradigms of siloed R&D, narrow financial assessments, and self-contained innovation are no longer sufficient. This research offers a new strategic playbook for managers, entrepreneurs, and corporate strategists, built upon three core imperatives.

1. Embrace Systemic and Synergistic Innovation

The most critical directive emerging from this research is that durable competitive advantage is born from synergy, not from isolated actions. As the econometric analysis in Chapter 4 conclusively demonstrates, the demolition of internal silos between "sustainability" and "digital" departments is not just a recommendation but a prerequisite for success. An R&D budget split between these functions is a recipe for creating innovations with a fleeting impact at best. Lasting value is created by cross-functional teams that develop intrinsically integrated "Twin" solutions from day one. This principle of synergy extends to the nature of the technologies themselves. As highlighted in Chapter 3, while the current market is dominated by adaptation technologies, a significant strategic opportunity lies in developing dual-purpose innovations, such as the biochar applications explored in Chapter 2, that simultaneously enhance resilience and contribute to climate mitigation. This integrated approach is essential for positioning a firm ahead of future regulatory shifts and for transforming sustainability from a compliance requirement into a core strategic pillar, as advocated in Chapter 1.

2. Adopt a Holistic, Multi-Dimensional Framework for Value

The green transition requires a new understanding of "value. The case study in Chapter 2 provides a clear blueprint for this shift, demonstrating the power of tools like the Circular Triple-Layered Business Model Canvas (CTLBMC). Managers must move beyond traditional financial metrics and adopt a holistic assessment framework for new ventures and investments. This means actively evaluating the "cascading effects" of a business model across economic, environmental, and social dimensions. By understanding these interdependencies, managers can design more resilient strategies, build stronger public-private partnerships by clearly articulating shared value, and more effectively align their projects with policy priorities to secure funding and social license to operate. This approach institutionalizes a 360-degree view of performance, ensuring that strategic decisions are balanced, sustainable, and capable of capturing value that remains invisible to conventional financial analysis.

3. Master the Global Innovation Ecosystem

Finally, this thesis reveals that in the 21st century, innovation is no longer a purely internal pursuit. Competitive advantage is built through the ecosystem, not just inside the firm. As the patent analysis in Chapter 3 shows, the global inventive landscape is complex, dynamic, and geographically concentrated. Managers must develop the capability to engage with this global ecosystem, understanding the dynamics of innovation hubs like China, seeing both the opportunity in its vast and often untapped intellectual property and the challenge of navigating its fragmented institutional landscape. For most firms, particularly SMEs and startups, the key strategic decision is no longer “make versus buy”, but rather how to partner and co-create. The key managerial capability is shifting from R&D management to partnership and network management. This means forging alliances with local tech startups, university spin-offs (like those within the AGRITECH ecosystem), and international research bodies to access the interdisciplinary expertise required to build the synergistic, high-impact solutions that will define the future of agriculture.

Future Research and Research of a Future

The conclusions of this dissertation, while providing a robust framework for understanding the strategic dynamics of the green transition, also open up several avenues for future inquiry that can build directly upon these findings. The inquiry presented here has established the economic superiority of a synergistic innovation strategy; the next wave of research can now deepen and broaden this understanding.

An immediate and promising pathway lies in conducting qualitative deep-dives into the pioneering firms that successfully pursue synergistic innovation. While this thesis has mapped the codified, technological output of innovation, a rich and complementary field of inquiry lies in understanding the non-codified assets that enable success. Future case-based research can move beyond the “what” of invention to the “how” of implementation, seeking to uncover the tacit, non-replicable assets, the specific organizational capabilities, leadership styles, and collaborative routines, that allow these enterprises to successfully manage the complex process of synergistic innovation. Building on this dissertation’s central finding of an economic premium for certain strategies, the most critical quantitative step for the field is to test for the existence of a “double dividend”. This would require designing studies that rigorously link firm-level innovation and economic data with direct environmental performance indicators, such as greenhouse gas emissions per unit of output or resource use efficiency. Answering whether an integrated strategy is not only more profitable but also demonstrably “greener” is a vital question for both business strategy and public policy. Finally, to achieve a truly comprehensive understanding, future research can broaden the empirical aperture from the technological frontier, as studied in this thesis, to the entire agricultural landscape. Large-scale surveys and firm-level studies that include the vast population of non-patenting enterprises are needed to map the full spectrum of innovation dynamics, particularly among the SMEs and family farms that form the backbone of the sector. This would provide a complete picture of the barriers and drivers for technology adoption across the entire agri-food system.

Ultimately, this dissertation concludes that success in the green transition is not determined by technology alone, but by the strategy through which it is governed. The critical strategic question for an enterprise is not which green innovation to possess, but what business model to construct to create and capture value from it. Durable competitive advantage, as this research has shown, arises not from the act of invention itself, but from the mastery with which a firm aligns its innovation dynamics with its strategic architecture. Steering the green transition, therefore, is not a technological problem; it is, and always has been, a strategic one.

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APPENDIX A

D.V. – Lab. Prod.	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-1)	0.000†					
	(0.000)					
Agri Pat (t-1)		0.000				
		(0.000)				
Green Pat (t-1)			0.001		0.001	
			(0.001)		(0.001)	
Digital Pat (t-1)				0.020	-0.000	
				(0.022)	(0.016)	
Green×Dig (t-1)					0.000	
					(0.000)	
Twin Pat (t-1)						0.177***
						(0.024)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	7571	7571	7571	7571	7571	7571
#Firms	1,284	1,284	1,284	1,284	1,284	1,284
#Years	28	28	28	28	28	28
R2	0.910	0.906	0.912	0.908	0.910	0.907
R2 Adj.	0.906	0.906	0.906	0.906	0.906	0.906

Table A.1 Robustness Check using Poisson Pseudo-Maximum Likelihood (PPML) Estimator (Lag t-1)

D.V. – Lab. Prod.	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-2)	0.000*					
	(0.000)					
Agri Pat (t-2)		0.001†				
		(0.000)				
Green Pat (t-2)			0.002*		0.002†	
			(0.001)		(0.001)	
Digital Pat (t-2)				0.024	0.009	
				(0.030)	(0.030)	
Green×Dig (t-2)					0.000	
					(0.000)	
Twin Pat (t-2)						0.303***
						(0.021)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	6305	6305	6305	6305	6305	6305
#Firms	1,177	1,177	1,177	1,177	1,177	1,177
#Years	27	27	27	27	27	27
R2	0.916	0.919	0.915	0.919	0.918	0.919
R2 Adj.	0.917	0.917	0.917	0.917	0.917	0.917

Table A.2 – Robustness Check using Poisson Pseudo-Maximum Likelihood (PPML) Estimator (Lag t-2)

D.V. – Lab. Prod.	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-3)	0.000**					
	(0.000)					
Agri Pat (t-3)		0.001*				
		(0.000)				
Green Pat (t-3)			0.002*		0.002*	
			(0.001)		(0.001)	
Digital Pat (t-3)				0.013	0.005	
				(0.016)	(0.021)	
Green×Dig (t-3)					0.000	
					(0.000)	
Twin Pat (t-3)						0.137***
						(0.019)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	5066	5066	5066	5066	5066	5066
#Firms	1,071	1,071	1,071	1,071	1,071	1,071
#Years	26	26	26	26	26	26
R2	0.926	0.927	0.924	0.926	0.925	0.926
R2 Adj.	0.925	0.925	0.925	0.925	0.925	0.925

Table A.3 – Robustness Check using Poisson Pseudo-Maximum Likelihood (PPML) Estimator (Lag t-3).

D.V. – Lab. Prod.	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-4)	0.000					
	(0.000)					
Agri Pat (t-4)		-0.000				
		(0.001)				
Green Pat (t-4)			0.002*		0.002*	
			(0.001)		(0.001)	
Digital Pat (t-4)				0.011	0.080†	
				(0.017)	(0.042)	
Green×Dig (t-4)					-0.002*	
					(0.001)	
Twin Pat (t-4)						0.228***
						(0.016)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	4093	4093	4093	4093	4093	4093
#Firms	895	895	895	895	895	895
#Years	25	25	25	25	25	25
R2	0.932	0.930	0.931	0.932	0.934	0.933
R2 Adj.	0.932	0.932	0.932	0.932	0.932	0.932

Table A.4 – Robustness Check using Poisson Pseudo-Maximum Likelihood (PPML) Estimator (Lag t-4).

D.V. – Lab. Prod.	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-5)	0.000					
	(0.000)					
Agri Pat (t-5)		0.000				
		(0.000)				
Green Pat (t-5)			0.001		0.001	
			(0.001)		(0.001)	
Digital Pat (t-5)				0.010	0.055	
				(0.011)	(0.040)	
Green×Dig (t-5)					-0.001	
					(0.001)	
Twin Pat (t-5)						0.178***
						(0.020)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	3223	3223	3223	3223	3223	3223
#Firms	811	811	811	811	811	811
#Years	24	24	24	24	24	24
R2	0.952	0.951	0.954	0.953	0.952	0.950
R2 Adj.	0.951	0.951	0.951	0.951	0.951	0.951

Table A.5 – Robustness Check using Poisson Pseudo-Maximum Likelihood (PPML) Estimator (Lag t-5).

APPENDIX B

D.V. – Op. Rev. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-1)	0.01002***					
	(0.00276)					
Agri Pat (t-1)		0.01138**				
		(0.00355)				
Green Pat (t-1)			0.00676**		0.00619*	
			(0.00218)		(0.00270)	
Digital Pat (t-1)				0.00575	0.00142	
				(0.00457)	(0.00418)	
Green×Dig (t-1)					0.00014	
					(0.00037)	
Twin Pat (t-1)						0.00596***
						(0.00026)
Empl (t-1)	0.42725***	0.42731***	0.42736***	0.42781***	0.42732***	0.42806***
	(0.04678)	(0.04677)	(0.04679)	(0.04671)	(0.04681)	(0.04668)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	7708	7708	7708	7708	7708	7708
#Firms	1,191	1,191	1,191	1,191	1,191	1,191
#Years	28	28	28	28	28	28
R2	0.888	0.877	0.876	0.867	0.884	0.892
R2 Adj.	0.867	0.851	0.850	0.843	0.862	0.870

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table B.1 – Robustness Check using Operating Revenue as Dependent Variable (Lag t-1).

D.V. – Op. Rev. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-2)	0.00879**					
	(0.00332)					
Agri Pat (t-2)		0.00987*				
		(0.00414)				
Green Pat (t-2)			0.00599*		0.00584†	
			(0.00257)		(0.00303)	
Digital Pat (t-2)				0.00548	0.00390	
				(0.00460)	(0.00528)	
Green×Dig (t-2)					-0.00014	
					(0.00060)	
Twin Pat (t-2)					0.00584†	0.00977***
						(0.00054)
Empl (t-2)	0.44024***	0.44028***	0.44034***	0.44070***	0.44024***	0.44119***
	(0.05173)	(0.05172)	(0.05174)	(0.05164)	(0.05176)	(0.05160)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	6408	6408	6408	6408	6408	6408
#Firms	1,081	1,081	1,081	1,081	1,081	1,081
#Years	27	27	27	27	27	27
R2	0.881	0.866	0.879	0.868	0.872	0.903
R2 Adj.	0.870	0.843	0.855	0.847	0.851	0.881

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table B.2 – Robustness Check using Operating Revenue as Dependent Variable (Lag t-2).

D.V. – Op. Rev. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-3)	0.00802*					
	(0.00406)					
Agri Pat (t-3)		0.00904†				
		(0.00471)				
Green Pat (t-3)			0.00526		0.00624†	
			(0.00324)		(0.00375)	
Digital Pat (t-3)				0.00768	0.01721	
				(0.00711)	(0.01388)	
Green×Dig (t-3)					-0.00259	
					(0.00257)	
Twin Pat (t-3)						0.00587***
						(0.00026)
Empl (t-3)	0.47401***	0.47409***	0.47402***	0.47444***	0.47366***	0.47469***
	(0.05605)	(0.05602)	(0.05609)	(0.05593)	(0.05614)	(0.05591)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	5150	5150	5150	5150	5150	5150
#Firms	904	904	904	904	904	904
#Years	26	26	26	26	26	26
R2	0.869	0.876	0.875	0.868	0.864	0.915
R2 Adj.	0.850	0.852	0.853	0.851	0.853	0.892

Notes: † p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table B.3 – Robustness Check using Operating Revenue as Dependent Variable (Lag t-3).

D.V. – Op. Rev. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-4)	0.00536					
	(0.00505)					
Agri Pat (t-4)		0.00544				
		(0.00584)				
Green Pat (t-4)			0.00391		0.00324	
			(0.00397)		(0.00401)	
Digital Pat (t-4)				0.00272	0.02056	
				(0.00262)	(0.01517)	
Green×Dig (t-4)					-0.00446	
					(0.00329)	
Twin Pat (t-4)						0.00794***
						(0.00030)
Empl (t-4)	0.46357***	0.46362***	0.46361***	0.46402***	0.46380***	0.46415***
	(0.05970)	(0.05969)	(0.05971)	(0.05955)	(0.05971)	(0.05954)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	4,163	4,163	4,163	4,163	4,163	4,163
#Firms	821	821	821	821	821	821
#Years	25	25	25	25	25	25
R2	0.886	0.877	0.876	0.888	0.895	0.922
R2 Adj.	0.857	0.850	0.851	0.869	0.873	0.899

Notes: † p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table B.4 – Robustness Check using Operating Revenue as Dependent Variable (Lag t-4).

D.V. – Op. Rev. (log)	Mod.1 (Total)	Mod.2 (Agri)	Mod.3 (Green)	Mod.4 (Digital)	Mod.5 (G×D)	Mod.6 (Twin)
Total Pat (t-5)	0.00229					
	(0.00519)					
Agri Pat (t-5)		0.00261				
		(0.00550)				
Green Pat (t-5)			0.00116		0.00068	
			(0.00434)		(0.00444)	
Digital Pat (t-5)				0.00136	0.01413	
				(0.00164)	(0.01379)	
Green×Dig (t-5)					-0.00319	
					(0.00313)	
Twin Pat (t-5)						0.00499***
						(0.00037)
Empl (t-5)	0.50824***	0.50826***	0.50829***	0.50840***	0.50855***	0.50849***
	(0.05621)	(0.05618)	(0.05627)	(0.05608)	(0.05626)	(0.05607)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
#Obs.	3272	3272	3272	3272	3272	3272
#Firms	751	751	751	751	751	751
#Years	24	24	24	24	24	24
R2	0.891	0.897	0.911	0.899	0.905	0.934
R2 Adj.	0.882	0.874	0.890	0.875	0.881	0.912

Notes: † $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; Reported coefficients are standardized (z-scores); Cluster-robust standard errors at the firm level are reported in parentheses; Panel is unbalanced.

Table B.5 – Robustness Check using Operating Revenue as Dependent Variable (Lag t-5).

BIBLIOGRAPHY

Abbas, J., Sağsan, M., (2019). Impact of knowledge management practices on green innovation and corporate sustainable development: A structural analysis, Journal of Cleaner Production, Volume 229,

Abbasi, K. R., & Zhang, Q. (2024). Augmenting agricultural sustainability: Investigating the role of agricultural land, green innovation, and food production in reducing greenhouse gas emissions. Sustainable Development, 32(6), 6918-6933. https://doi.org/10.1002/sd.3060

Abbass, K., Qasim, M.Z., Song, H. (2022). A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ Sci Pollut Res 29, 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

Abdalqadir, M., Hughes, D., Rezaei Gomari, S. et al. (2024). A state-of-the-art review on factors affecting the enhanced weathering in agricultural soil: strategies for carbon sequestration and climate mitigation. Environmental Science and Pollution Research, 31, 19047–19070. https://doi.org/10.1007/s11356-024-32498-5

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. American Economic Review, 102(1), 131-166. https://doi.org/10.1257/aer.102.1.131

Adami, L., & Schiavon, M. (2021). From Circular Economy to Circular Ecology: A Review on the Solution of Environmental Problems through Circular Waste Management Approaches. Sustainability, 13(2), Article 2. https://doi.org/10.3390/su13020925

Adekoya, O. B., Ajayi, G. E., Suhrab, M., & Oliyide, J. A. (2022). How critical are resource rents, agriculture, growth, and renewable energy to environmental degradation in the resource-rich African countries? The role of institutional quality. Energy Policy, 164, 112888. https://doi.org/10.1016/j.enpol.2022.112888

Ahmed, N., & Shakoor, N. (2025). Advancing agriculture through IoT, Big Data, and AI: A review of smart technologies enabling sustainability. Smart Agricultural Technology, 10, 100848. https://doi.org/10.1016/j.atech.2025.100848

Ai, H., Islam, N., Mangla, S. K., Song, M., & Tan, X. (2024). Circular Economy, Open Innovation, and Green Innovation: Empirical Evidence from Prefecture-Level Cities in China. IEEE Transactions on Engineering Management, 71, 5706–5719. https://doi.org/10.1109/TEM.2024.3357350

Almeida, C., Agostinho, F., Giannetti, B., & Huisingh, D. (2015). Integrating cleaner production into sustainability strategies: An introduction to this special volume. Journal of Cleaner Production, 96, 1-9. https://doi.org/10.1016/j.jclepro.2014.11.083

Alvarado, R., Ortiz, C., Jiménez, N., Ochoa-Jiménez, D., & Tillaguango, B. (2021). Ecological footprint, air quality and research and development: The role of agriculture and international trade. Journal of Cleaner Production, 288, 125589. https://doi.org/10.1016/j.jclepro.2020.125589

Ambec, Stefan & Lanoie, Paul. (2008). Does It Pay to be Green? A Systematic Overview. Academy of Management Perspectives. 22. 45-62. https://doi.org/10.5465/AMP.2008.35590353

Amentae, T. K., Song, W., & Wang, J. (2024). Intellectual property rights in the agri-food chains: A systematic review and bibliometric analysis. World Patent Information, 77, 102279. https://doi.org/10.1016/j.wpi.2024.102279

An, D., Xi, B., Ren, J., Wang, Y., Jia, X., He, C., & Li, Z. (2017). Sustainability assessment of groundwater remediation technologies based on multi-criteria decision making method. Resources, Conservation and Recycling, 119, 36-46. https://doi.org/10.1016/j.resconrec.2016.08.002

Anwar, M., Clauss, T. & Meyer, N. Entrepreneurship in family firms: an updated bibliometric overview. Rev Manag Sci (2023). https://doi.org/10.1007/s11846-023-00650-z

Appio, F. P., Cesaroni, F., & Di Minin, A. (2014). Visualizing the structure and bridges of the intellectual property management and strategy literature: a document co-citation analysis. Scientometrics, 101(1), 623–661. https://doi.org/10.1007/s11192-014-1329-0

Aragon-Correa, J. A, Leyva-de la Hiz, D. I. (2016). The Influence of Technology Differences on Corporate Environmental Patents: A Resource-Based Versus an Institutional View of Green Innovations. Business Strategy and the Environment, 25(6), 421-434. https://doi.org/10.1002/bse.1885

Araújo, Y. R. V., de Góis, M. L., Junior, L. M. C., & Carvalho, M. (2018). Carbon footprint associated with four disposal scenarios for urban pruning waste. Environmental Science and Pollution Research, 25(2), 1863–1868. https://doi.org/10.1007/s11356-017-0613-y

Araujo, Y. R. V., Souza, B. I., & Carvalho, M. (2024). Greenhouse Gas Emissions Associated with Tree Pruning Residues of Urban Areas of Northeast Brazil. Resources, 13(9), Article 9. https://doi.org/10.3390/resources13090127

Aria, M., & Cuccurullo, C. (2017). bibliometrix: An R-tool for comprehensive science mapping analysis. Journal of Informetrics, 11(4), 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Ariluoma, M., Ottelin, J., Hautamäki, R., Tuhkanen, E.-M., & Mänttäri, M. (2021). Carbon sequestration and storage potential of urban green in residential yards: A case study from Helsinki. Urban Forestry & Urban Greening, 57, 126939. https://doi.org/10.1016/j.ufug.2020.126939

Avola, G., Distefano, M., Torrisi, A., & Riggi, E. (2024). Precision agriculture and patented innovation: State of the art and current trends. World Patent Information, 76, 102262. https://doi.org/10.1016/j.wpi.2024.102262

Ayaz, M., Feizienė, D., Tilvikienė, V., Akhtar, K., Stulpinaitė, U., & Iqbal, R. (2021). Biochar Role in the Sustainability of Agriculture and Environment. Sustainability, 13(3), Article 3. https://doi.org/10.3390/su13031330

Azzi, E. S., Karltun, E., & Sundberg, C. (2022). Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. Biochar, 4(1), 18. https://doi.org/10.1007/s42773-022-00144-3

Baglieri, D., Cesaroni, F., & Orsi, L. (2014). Does the nano-patent 'Gold rush' lead to entrepreneurial-driven growth? Some policy lessons from China and Japan. Technovation, 34(12), 746-761. https://doi.org/10.1016/j.technovation.2014.07.009

Bai, D., Ye, L., Yang, Z., & Wang, G. (2024). Impact of climate change on agricultural productivity: A combination of spatial Durbin model and entropy approaches. International Journal of Climate Change Strategies and Management, 16(4), 26-48.

Balasundram, S. K., Shamshiri, R. R., Sridhara, S., & Rizan, N. (2023). The role of digital agriculture in mitigating climate change and ensuring food security: An overview. Sustainability, 15(6), 5325. https://doi.org/10.3390/su15065325

Balogh, J. M. (2020). The role of agriculture in climate change: A global perspective. International Journal of Energy Economics and Policy, 10(2), 401-408.

Barkemeyer, R., Holt, D., Preuss, L., & Tsang, S. (2014). What Happened to the ‘Development’ in Sustainable Development? Business Guidelines Two Decades After Brundtland. Sustainable Development, 22(1), 15–32. https://doi.org/10.1002/sd.521

Barney, J. (1991). Firm Resources and Sustained Competitive Advantage. Journal of Management. https://doi.org/10.1177/014920639101700108

Barragán-Ocaña, A., Merritt, H., Sánchez-Estrada, O. E., Méndez-Becerril, J. L., & Longar-Blanco, P. (2023). Biorefinery and sustainability for the production of biofuels and value-added products: A trends analysis based on network and patent analysis. PLOS ONE, 18(1), e0279659. https://doi.org/10.1371/journal.pone.0279659

Basnet, S., Wood, A., Röös, E. et al. (2023). Organic agriculture in a low-emission world: Exploring combined measures to deliver a sustainable food system in Sweden. Sustainability Science, 18, 501–519. https://doi.org/10.1007/s11625-022-01279-9

Bekchanov, M., & Mirzabaev, A. (2018). Circular economy of composting in Sri Lanka: Opportunities and challenges for reducing waste related pollution and improving soil health. Journal of Cleaner Production, 202, 1107–1119. https://doi.org/10.1016/j.jclepro.2018.08.186

Bekchanova, M., Campion, L., Bruns, S., Kuppens, T., Jozefczak, M., Cuypers, A., & Malina, R. (2021). Biochar’s effect on the ecosystem services provided by sandy-textured and contaminated sandy soils: A systematic review protocol. Environmental Evidence, 10(1), 7. https://doi.org/10.1186/s13750-021-00223-1

Belhadi, A., Kamble, S.S., Khan, S.A.R. et al. Infectious Waste Management Strategy during COVID-19 Pandemic in Africa: an Integrated Decision-Making Framework for Selecting Sustainable Technologies. Environmental Management 66, 1085–1104 (2020). https://doi.org/10.1007/s00267-020-01375-5

Belussi, F., Orsi, L., & Savarese, M. (2019). Mapping Business Model Research: A Document Bibliometric Analysis. Scandinavian Journal of Management, 35(3), 101048. https://doi.org/10.1016/j.scaman.2019.101048

Benito, M., Masaguer, A., Moliner, A., & De Antonio, R. (2006). Chemical and physical properties of pruning waste compost and their seasonal variability. Bioresource Technology, 97(16), 2071–2076. https://doi.org/10.1016/j.biortech.2005.09.011

Berrone, P., Fosfuri, A., Gelabert, L., & Gomez-Mejia, L. R. (2013). Necessity as the mother of ‘green’ inventions: Institutional pressures and environmental innovations. Strategic Management Journal, 34(8), 891-909. https://doi.org/10.1002/smj.2041

Bhandari, D., Singh, R. K., & Garg, S. K. (2019). Prioritisation and evaluation of barriers intensity for implementation of cleaner technologies: Framework for sustainable production. Resources, Conservation and Recycling, 146, 156-167. https://doi.org/10.1016/j.resconrec.2019.02.038

Bhupendra, K. V., & Sangle, S. (2015). What drives successful implementation of pollution prevention and cleaner technology strategy? The role of innovative capability. Journal of Environmental Management, 155, 184-192. https://doi.org/10.1016/j.jenvman.2015.03.032

Bhupendra, K. V., & Sangle, S. (2016). Strategy to derive benefits of radical cleaner production, products and technologies: A study of Indian firms. Journal of Cleaner Production, 126, 236-247. https://doi.org/10.1016/j.jclepro.2016.03.115

Bi, G., Jin, M., Ling, L. et al. (2017). Environmental subsidy and the choice of green technology in the presence of green consumers. Annals of Operationss Research 255, 547–568. https://doi.org/10.1007/s10479-016-2106-7

Bianchini, S., Damioli, G. & Ghisetti, C. The environmental effects of the “twin” green and digital transition in European regions. Environ Resource Econ 84, 877–918 (2023). https://doi.org/10.1007/s10640-022-00741-7

Birkle, C., Pendlebury, D. A., Schnell, J., & Adams, J. (2020). Web of Science as a data source for research on scientific and scholarly activity. Quantitative Science Studies, 1(1), 363–376. https://doi.org/10.1162/qss_a_00018

Black, J. L., Davison, T. M., & Box, I. (2021). Methane emissions from ruminants in Australia: Mitigation potential and applicability of mitigation strategies. Animals, 11(4), 951. https://doi.org/10.3390/ani11040951

Blakeney, M. (2022). Agricultural innovation and sustainable development. Sustainability, 14(5), 2698. https://doi.org/10.3390/su14052698

Blind, K., Ramel, F. & Rochell, C. The influence of standards and patents on long-term economic growth. J Technol Transf 47, 979–999 (2022). https://doi.org/10.1007/s10961-021-09864-3

Bocken, N., Schuit, C., & Kraaijenhagen, C. (2018). Experimenting with a circular business model: lessons from eight cases. Environmental Innovation and Societal Transitions, 28, 79-95. https://doi.org/10.1016/j.eist.2018.02.001

Bocken, N., Short, S., Rana, P., & Evans, S. (2014). A literature and practice review to develop sustainable business model archetypes. Journal of Cleaner Production, 65, 42-56. https://doi.org/10.1016/j.jclepro.2013.11.039

Bohnsack, R., Pinkse, J., & Kolk, A. (2014). Business models for sustainable technologies: Exploring business model evolution in the case of electric vehicles. Research Policy, 43(2), 284-300. https://doi.org/10.1016/j.respol.2013.10.014

Boons, F., & Lüdeke-Freund, F. (2013). Business models for sustainable innovation: State-of-the-art and steps towards a research agenda. Journal of Cleaner Production, 45, 9-19. https://doi.org/10.1016/j.jclepro.2012.07.007

Boons, F., Montalvo, C., Quist, J., & Wagner, M. (2013). Sustainable innovation, business models and economic performance: An overview. Journal of Cleaner Production, 45, 1–8. https://doi.org/10.1016/j.jclepro.2012.08.013

Bottausci, S., Midence, R., Serrano-Bernardo, F., & Bonoli, A. (2022). Organic Waste Management and Circular Bioeconomy: A Literature Review Comparison between Latin America and the European Union. Sustainability, 14(3), Article 3. https://doi.org/10.3390/su14031661

Boyack, K. W., & Klavans, R. (2010). Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? Journal of the Association for Information Science and Technology, 61(12), 2389–2404. https://doi.org/10.1002/asi.21419

Broekel, T., & Klarl, T. (2025). The long-term evolution of technological complexity and its relationship with economic growth. Technovation, 144, 103233. https://doi.org/10.1016/j.technovation.2025.103233

Browne, D., O’Mahony, M., & Caulfield, B. (2012). How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated? Journal of Cleaner Production, 35, 140-151. https://doi.org/10.1016/j.jclepro.2012.05.019

Brummitt, C. D., Mathers, C. A., Keating, R. A., O’Leary, K., Easter, M., Friedl, M. A., DuBuisson, M., Campbell, E. E., Pape, R., Peters, S. J., & Kumar, A. A. (2024). Solutions and insights for agricultural monitoring, reporting, and verification (MRV) from three consecutive issuances of soil carbon credits. Journal of Environmental Management, 369, 122284. https://doi.org/10.1016/j.jenvman.2024.122284

Camel, A., Belhadi, A., Kamble, S., Tiwari, S., & Touriki, F. E. (2024). Integrating smart Green Product Platforming for carbon footprint reduction: The role of blockchain technology and stakeholders influence within the agri-food supply chain. International Journal of Production Economics, 272, 109251. https://doi.org/10.1016/j.ijpe.2024.109251

Cao, L., Jiang, H., Li, G., & Zhu, L. (2024). Haste makes waste? Quantity-based subsidies under heterogeneous innovations. Journal of Monetary Economics, 142, 103517. https://doi.org/10.1016/j.jmoneco.2023.09.004

Carley, Sanya & Konisky, David. (2020). The justice and equity implications of the clean energy transition. Nature Energy. 5. https://doi.org/10.1038/s41560-020-0641-6

Carvalho, J., Nascimento, L., Soares, M., Valério, N., Ribeiro, A., Faria, L., Silva, A., Pacheco, N., Araújo, J., & Vilarinho, C. (2022). Life Cycle Assessment (LCA) of Biochar Production from a Circular Economy Perspective. Processes, 10(12), Article 12. https://doi.org/10.3390/pr10122684

Casagrande, D., Emanuel, L., Freitas, C., & Oliveira, F. (2024). Climate adaptation policies and rural income: Evidence from social technologies in Brazil. World Development, 181, 106683. https://doi.org/10.1016/j.worlddev.2024.106683

Cefis, E., Grassano, N., & Tubiana, M. (2024). Firms' patenting and collective cumulative knowledge: evidence from the largest R&D investors in the world. Industry and Innovation, 32(4), 413–448. https://doi.org/10.1080/13662716.2024.2377700

CEWEP. (2021). Landfill taxes and restrictions. https://www.cewep.eu/wp-content/uploads/2021/10/Landfill-taxes-and-restrictions-overview.pdf

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient

Chen, X., Luo, Z., & Wang, X. (2017). Impact of efficiency, investment, and competition on low carbon manufacturing. Journal of Cleaner Production, 143, 388-400. https://doi.org/10.1016/j.jclepro.2016.12.095

Chen, Y., & Jin, S. (2023). Corporate Social Responsibility and Green Technology Innovation: The Moderating Role of Stakeholders. Sustainability, 15(10), 8164. https://doi.org/10.3390/su15108164

Chen, Y., Lai, SB. & Wen, CT. (2006). The Influence of Green Innovation Performance on Corporate Advantage in Taiwan. J Bus Ethics 67, 331–339. https://doi.org/10.1007/s10551-006-9025-5

Chen, YS. The Positive Effect of Green Intellectual Capital on Competitive Advantages of Firms. J Bus Ethics 77, 271–286 (2008). https://doi.org/10.1007/s10551-006-9349-1

Cheng, H., Fan, H., Hoshi, T., & Hu, D. (2024). State ownership, political connection, and innovation subsidies in China. Journal of the Japanese and International Economies, 71, 101287. https://doi.org/10.1016/j.jjie.2023.101287

Cheong, M., Sankaran, K., & Bastani, H. (2022). Artificial intelligence for climate change adaptation. Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 12(5), e1459. https://doi.org/10.1002/widm.1459

Chesbrough, H., & Rosenbloom, R. S. (2002). The role of the business model in capturing value from innovation: Evidence from Xerox Corporation's technology spin-off companies. Industrial and Corporate Change, 11(3), 529–555. https://doi.org/10.1093/icc/11.3.529

Coenen, L., & Díaz López, F. J. (2010). Comparing systems approaches to innovation and technological change for sustainable and competitive economies: An explorative study into conceptual commonalities, differences and complementarities. Journal of Cleaner Production, 18(12), 1149-1160. https://doi.org/10.1016/j.jclepro.2010.04.003

Cohen, M. C., Lobel, R., & Perakis, G. (2016). The Impact of Demand Uncertainty on Consumer Subsidies for Green Technology Adoption. Management Science, 62(5), 1225-1531. https://doi.org/10.1287/mnsc.2015.2173

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. Administrative Science Quarterly, 35(1), 128–152. https://doi.org/10.2307/2393553

Corrocher, N., Malerba, F., & Morrison, A. (2021). Technological regimes, patent growth, and catching-up in green technologies. Industrial and Corporate Change, 30(4), 1084-1107. https://doi.org/10.1093/icc/dtab025

Costantini, V., Crespi, F., Marin, G., & Paglialunga, E. (2017). Eco-innovation, sustainable supply chains and environmental performance in European industries. Journal of Cleaner Production, 155, 141-154. https://doi.org/10.1016/j.jclepro.2016.09.038

Coupet, J., & Ba, Y. (2022). Benchmarking university technology transfer performance with external research funding: A stochastic frontier analysis. The Journal of Technology Transfer, 47, 605–620. https://doi.org/10.1007/s10961-021-09856-3

Cruz, I. S., & Katz-Gerro, T. (2016). Urban public transport companies and strategies to promote sustainable consumption practices. Journal of Cleaner Production, 123, 28-33. https://doi.org/10.1016/j.jclepro.2015.12.007

Da Silveira, F., Ruppenthal, J. E., Lermen, F. H., Machado, F. M., & Amaral, F. G. (2021). Technologies used in agricultural machinery engines that contribute to the reduction of atmospheric emissions: A patent analysis in Brazil. World Patent Information, 64, 102023. https://doi.org/10.1016/j.wpi.2021.102023

Da Veiga, C. R. P., Da Veiga, C. P., Machado, M. S., Blanco, H. V., & Su, Z. (2024). Innovation in healthcare business methods: A comparative patent analysis. Journal of Open Innovation: Technology, Market, and Complexity, 10(4), 100428. https://doi.org/10.1016/j.joitmc.2024.100428

Dangelico, R. M., Pontrandolfo, P., & Pujari, D. (2013). Developing Sustainable New Products in the Textile and Upholstered Furniture Industries: Role of External Integrative Capabilities. Journal of Product Innovation Management, 30(4), 642-658. https://doi.org/10.1111/jpim.12013

Daou, A., Mallat, C., Chammas, G., Cerantola, N., Kayed, S., & Saliba, N. A. (2020). The Ecocanvas as a business model canvas for a circular economy. Journal of Cleaner Production, 258, 120938. https://doi.org/10.1016/j.jclepro.2020.120938

Ddiba, D., Andersson, K., Rosemarin, A., Schulte-Herbrüggen, H., & Dickin, S. (2022). The circular economy potential of urban organic waste streams in low- and middle-income countries. Environment, Development and Sustainability, 24(1), 1116–1144. https://doi.org/10.1007/s10668-021-01487-w

De Marchi, V., Molina-Morales, F. X., & Martínez-Cháfer, L. (2022). Environmental innovation and cooperation: A configurational approach. Technological Forecasting and Social Change, 182, 121835. https://doi.org/10.1016/j.techfore.2022.121835

De Stefano, C. M., Montes-Sancho, M. J., & Busch, T. (2016). A natural resource-based view of climate change: Innovation challenges in the automobile industry. Journal of Cleaner Production, 139, 1436-1448. https://doi.org/10.1016/j.jclepro.2016.08.023

Del Río González, P. (2009). The empirical analysis of the determinants for environmental technological change: A research agenda. Ecological Economics, 68(3), 861-878. https://doi.org/10.1016/j.ecolecon.2008.07.004

Delgado-López-Cózar, E., Robinson-García, N., & Torres-Salinas, D. (2014). The Google scholar experiment: How to index false papers and manipulate bibliometric indicators. Journal of the

Association for Information Science and Technology, 65(3), 446-454. https://doi.org/10.1002/asi.23056

Deng, Y., Cui, Y., Khan, S.U. et al. The spatiotemporal dynamic and spatial spillover effect of agricultural green technological progress in China. Environ Sci Pollut Res 29, 27909–27923 (2022). https://doi.org/10.1007/s11356-021-18424-z

Deng, Y., You, D., & Wang, J. (2019). Optimal strategy for enterprises' green technology innovation from the perspective of political competition. Journal of Cleaner Production, 235, 930-942. https://doi.org/10.1016/j.jclepro.2019.06.248

Desing, H., Brunner, D., Takacs, F., Nahrath, S., Frankenberger, K., & Hischier, R. (2020). A circular economy within the planetary boundaries: Towards a resource-based, systemic approach. Resources, Conservation and Recycling, 155, 104673. https://doi.org/10.1016/j.resconrec.2019.104673

Dewi, I. G. A. A. P., Krisnawijaya, N. N. K., Yunita, P. I., & Korry, P. D. P. (2022). Green technology for business: A bibliometric analysis. Binus Business Review, 13(2), 133-145. https://doi.org/10.21512/bbr.v13i2.7950

Dibbern, T., Romani, L. A. S., & Massruhá, S. M. F. S. (2024). Main drivers and barriers to the adoption of Digital Agriculture technologies. Smart Agricultural Technology, 8, 100459. https://doi.org/10.1016/j.atech.2024.100459

Dong, S., Gong, H., & Liu, T. (2022). Environmental technology spillovers and green start-up emergence: The moderating role of patent commercialization policy and patent enforcement. Environmental Science & Pollution Research, 29, 70070–70083. https://doi.org/10.1007/s11356-022-20791-0

Dou, G., & Choi, T. (2021). Does implementing trade-in and green technology together benefit the environment? European Journal of Operational Research, 295(2), 517-533. https://doi.org/10.1016/j.ejor.2021.03.017

Du, K., Cheng, Y., & Yao, X. (2021). Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities. Energy Economics, 98, 105247. https://doi.org/10.1016/j.eneco.2021.105247

Du, K., Li, P., & Yan, Z. (2019). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. Technological Forecasting and Social Change, 146, 297-303. https://doi.org/10.1016/j.techfore.2019.06.010

Duque-Acevedo, M., Belmonte-Ureña, L. J., Plaza-Úbeda, J. A., & Camacho-Ferre, F. (2020). The Management of Agricultural Waste Biomass in the Framework of Circular Economy and Bioeconomy: An Opportunity for Greenhouse Agriculture in Southeast Spain. Agronomy, 10(4), Article 4. https://doi.org/10.3390/agronomy10040489

Ebrahim, T. Y. (2020). Clean and sustainable technology innovation. Current Opinion in Environmental Sustainability, 45, 113-117. https://doi.org/10.1016/j.cosust.2020.11.004

Egerer, S., Cotera, R. V., Celliers, L., & Costa, M. M. (2021). A leverage points analysis of a qualitative system dynamics model for climate change adaptation in agriculture. Agricultural Systems, 189, 103052. https://doi.org/10.1016/j.agsy.2020.103052

Emission Factor Database. (2019). [Page]. European Environment Agency. https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/emission-factors-database

Fabrizi, A., Fiorelli, C. & Meliciani, V. The role of green networks for environmental innovation in European regions. J. Ind. Bus. Econ. (2025). https://doi.org/10.1007/s40812-024-00339-8

Falagas, M. E., Pitsouni, E. I., Malietzis, G. A., & Pappas, G. (2008). Comparison of PubMed, Scopus, Web of Science, and Google Scholar: strengths and weaknesses. FASEB journal: official publication of the Federation of American Societies for Experimental Biology, 22(2), 338–342. https://doi.org/10.1096/fj.07-9492LSF

FALKNER, R. (2016). The Paris Agreement and the new logic of international climate politics. International Affairs, 92(5), 1107–1125. https://doi.org/10.1111/1468-2346.12708

Fang, L., & Li, Z. (2024). Corporate digitalization and green innovation: Evidence from textual analysis of firm annual reports and corporate green patent data in China. Business Strategy and the Environment, 33(5), 3936-3964. https://doi.org/10.1002/bse.3677

Farooq, M. S., Riaz, S., Abid, A., Abid, K., & Naeem, M. A. (2019). A survey on the role of IoT in agriculture for the implementation of smart farming. IEEE Access, 7, 156237–156271. https://doi.org/10.1109/ACCESS.2019.2949703

Favot, M., Vesnic, L., Priore, R., Bincoletto, A., & Morea, F. (2023). Green patents and green codes: How different methodologies lead to different results. Resources, Conservation & Recycling Advances, 18, 200132. https://doi.org/10.1016/j.rcradv.2023.200132

Ferla, G., Caputo, P., Colaninno, N., & Morello, E. (2020). Urban greenery management and energy planning: A GIS-based potential evaluation of pruning by-products for energy application for the city of Milan. Renewable Energy, 160, 185–195. https://doi.org/10.1016/j.renene.2020.06.105

Fernandes, C. I., Veiga, P. M., Ferreira, J. M., & Hughes, M. (2021). Green growth versus economic growth: Do sustainable technology transfer and innovations lead to an imperfect choice? Business Strategy and the Environment, 30(4), 2021-2037. https://doi.org/10.1002/bse.2730

Fernando, Y., Chiappetta Jabbour, C. J., & Wah, W. (2019). Pursuing green growth in technology firms through the connections between environmental innovation and sustainable business performance: Does service capability matter? Resources, Conservation and Recycling, 141, 8-20. https://doi.org/10.1016/j.resconrec.2018.09.031

Ferrari, V. E., da Silveira, J. M. F. J., & Dal-Poz, M. E. S. (2019). Patent network analysis in agriculture: A case study of the development and protection of biotechnologies. Economics of Innovation and New Technology, 30(2), 111–133. https://doi.org/10.1080/10438599.2019.1684645

Fiala, D., & Tutoky, G. (2017). PageRank-based prediction of award-winning researchers and the impact of citations. Journal of Informetrics, 11(4), 1044–1068. https://doi.org/10.1016/j.joi.2017.09.008

Finco, A., & Nijkamp, P. (2001). Pathways to urban sustainability. Journal of Environmental Policy & Planning, 3(4), 289–302. https://doi.org/10.1002/jepp.94

for bibliometric mapping. Scientometrics, 84(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Fornell, C., & Larcker, D. F. (1981). Evaluating Structural Equation Models with Unobservable Variables and Measurement Error. Journal of Marketing Research, 18(1), 39–50. https://doi.org/10.2307/3151312

Frisio, D. G., & Ventura, V. (2021). Global Innovation Trends for Plant-Based Vaccines Production: A Patent Analysis. Plants, 10(12), 2558. https://doi.org/10.3390/plants10122558

Fuglie, K. O., Hertel, T. W., Lobell, D. B., & Villoria, N. B. (2024). Agricultural productivity and climate mitigation. Annual Review of Resource Economics, 16(1), 21–40. https://doi.org/10.1146/annurev-resource-101323-094349

Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., ... & Takahashi, K. (2022). Land-based climate change mitigation measures can affect agricultural markets and food security. Nature Food, 3(2), 110-121. https://doi.org/10.1038/s43016-022-00449-6

Gallego-Ramírez, C., Chica, E., & Rubio-Clemente, A. (2023). Life Cycle Assessment of Raw and Fe-Modified Biochars: Contributing to Circular Economy. Materials, 16(17), Article 17. https://doi.org/10.3390/ma16176059

Garfield, E. (1988). Announcing the SCI compact disk edition: CD-ROM-cd-rom gigabyte storage technology, novel software, and bibliographic coupling make desk-top research and discovery a reality. Current Contents, 22, 3–13;

Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Ghosh, D., & Shah, J. (2012). A comparative analysis of greening policies across supply chain structures. International Journal of Production Economics, 135(2), 568-583. https://doi.org/10.1016/j.ijpe.2011.05.027

Ghosh, D., & Shah, J. (2015). Supply chain analysis under green sensitive consumer demand and cost sharing contract. International Journal of Production Economics, 164, 319-329. https://doi.org/10.1016/j.ijpe.2014.11.005

Giannone, D., & Santaniello, M. (2018). Governance by indicators: the case of the Digital Agenda for Europe. Information, Communication & Society, 22(13), 1889–1902. https://doi.org/10.1080/1369118X.2018.1469655

Glaeser, S., & Lang, M. (2024). Measuring innovation and navigating its unique information issues: A review of the accounting literature on innovation. Journal of Accounting and Economics, 78(2-3), 101720. https://doi.org/10.1016/j.jacceco.2024.101720

Goyal, S., Chauhan, S., & Mishra, P. (2021). Circular economy research: A bibliometric analysis (2000–2019) and future research insights. Journal of cleaner production, 287, 125011. https://doi.org/10.1016/j.jclepro.2020.125011

Green, K., & Vergragt, P. (2002). Towards sustainable households: A methodology for developing sustainable technological and social innovations. Futures, 34(5), 381-400. https://doi.org/10.1016/S0016-3287(01)00066-0

Grigorieva, E., Livenets, A., & Stelmakh, E. (2023). Adaptation of Agriculture to Climate Change: A Scoping Review. Climate, 11(10), 202. https://doi.org/10.3390/cli11100202

Gross, A., Bromm, T., & Glaser, B. (2021). Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis. Agronomy, 11(12), Article 12. https://doi.org/10.3390/agronomy11122474

Guo, X. (2022). A bibliometric analysis of child language during 1900–2021. Frontiers in Psychology, 13. https://doi.org/10.3389/fpsyg.2022.862042

Gurzki, H., & Woisetschläger, D. M. (2017). Mapping the luxury research landscape: A bibliometric citation analysis. Journal of Business Research, 77, 147–166. http://dx.doi.org/10.1016/j.jbusres.2016.11.009

Habib-ur-Rahman, M., Ahmad, A., Raza, A., Hasnain, M. U., Alharby, H. F., Alzahrani, Y. M., ... & El Sabagh, A. (2022). Impact of climate change on agricultural production; Issues, challenges, and opportunities in Asia. Frontiers in Plant Science, 13, 925548. https://doi.org/10.3389/fpls.2022.925548

Hall, J., Matos, S. & Bachor, V. (2019). From green technology development to green innovation: inducing regulatory adoption of pathogen detection technology for sustainable forestry. Small Bus Econ 52, 877–889. https://doi.org/10.1007/s11187-017-9940-0

Hall, J., Matos, S., Gold, S., & Severino, L. S. (2018). The paradox of sustainable innovation: The 'Eroom' effect (Moore's law backwards). Journal of Cleaner Production, 172, 3487-3497. https://doi.org/10.1016/j.jclepro.2017.07.162

Hao Tan, Jialing Li, Min He, Jiayu Li, Dan Zhi, Fanzhi Qin, Chen Zhang (2021). Global evolution of research on green energy and environmental technologies:A bibliometric study. Journal of Environmental Management, 297. https://doi.org/10.1016/j.jenvman.2021.113382

Hart, S. L. (1995). A Natural-Resource-Based View of the Firm. The Academy of Management Review, 20(4), 986–1014. https://doi.org/10.2307/258963

Hart, S. L. (1997). Beyond Greening: Strategies for a Sustainable World. Harvard Business Review. https://hbr.org/1997/01/beyond-greening-strategies-for-a-sustainable-world

Harzing, AW., Alakangas, S. Google Scholar, Scopus and the Web of Science: a longitudinal and cross-disciplinary comparison. Scientometrics 106, 787–804 (2016). https://doi.org/10.1007/s11192-015-1798-9

Hegde, D., Herkenhoff, K., & Zhu, C. (2023). Patent Publication and Innovation. Journal of Political Economy. https://doi.org/10.1086/723636

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., & Smits, R. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change, 74(4), 413-432. https://doi.org/10.1016/j.techfore.2006.03.002

Hindle, R. L. (2024). Y02 as Climate Praxis. Technology|Architecture + Design, 8(1), 48–59. https://doi.org/10.1080/24751448.2024.2313440

Hockerts, K., & Wüstenhagen, R. (2010). Greening Goliaths versus emerging Davids — Theorizing about the role of incumbents and new entrants in sustainable entrepreneurship. Journal of Business Venturing, 25(5), 481-492. https://doi.org/10.1016/j.jbusvent.2009.07.005

Holton, G. J. (2000). Einstein, History, and Other Passions: The Rebellion Against Science at the End of the Twentieth Century. USA: Harvard University Press;

Hong, Z., & Guo, X. (2019). Green product supply chain contracts considering environmental responsibilities. Omega, 83, 155-166. https://doi.org/10.1016/j.omega.2018.02.010

Horbach, J. (2008). Determinants of environmental innovation—New evidence from German panel data sources. Research Policy, 37(1), 163-173. https://doi.org/10.1016/j.respol.2007.08.006

Horbach, J., Rammer, C. and Rennings, K., (2012), Determinants of eco-innovations by type of environmental impact — The role of regulatory push/pull, technology push and market pull, Ecological Economics, 78, issue C, p. 112-122, https://EconPapers.repec.org/RePEc:eee:ecolec:v:78:y:2012:i:c:p:112-122

Hou, R., Li, S., Chen, H., Ren, G., Gao, W., & Liu, L. (2021). Coupling mechanism and development prospect of innovative ecosystem of clean energy in smart agriculture based on blockchain. Journal of Cleaner Production, 319, 128466. https://doi.org/10.1016/j.jclepro.2021.128466

Hrovatin, N., Dolšak, N., & Zorić, J. (2016). Factors impacting investments in energy efficiency and clean technologies: Empirical evidence from Slovenian manufacturing firms. Journal of Cleaner Production, 127, 475-486. https://doi.org/10.1016/j.jclepro.2016.04.039

Hsu, D. H., Hsu, P., Zhou, T., & Ziedonis, A. A. (2020). Benchmarking U.S. University patent value and commercialization efforts: A new approach. Research Policy, 50(1), 104076. https://doi.org/10.1016/j.respol.2020.104076

http://dx.doi.org/10.2307/257052

Ikram, M., Sroufe, R., Awan, U., & Abid, N. (2021). Enabling Progress in Developing Economies: A Novel Hybrid Decision-Making Model for Green Technology Planning. Sustainability, 14(1), 258. https://doi.org/10.3390/su14010258

Ilić, N. (2024). Determining Economic Impact of Patents: Innovation and Competition. In: Law and Economics of Patents. SpringerBriefs in Law. Springer, Cham. https://doi.org/10.1007/978-3-031-62860-3_4

Islam, M., Fremeth, A., & Marcus, A. (2017). Signaling by early stage startups: US government research grants and venture capital funding. Journal of Business Venturing, 33(1), 35-51. https://doi.org/10.1016/j.jbusvent.2017.10.001

Islam, M.T. (2023), "Newly developed green technology innovations in business: paving the way toward sustainability", Technological Sustainability, Vol. 2 No. 3, pp. 295-319. https://doi.org/10.1108/TECHS-02-2023-0008

Jaffe, A., & Stavins, R. (1995). Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion. Journal of Environmental Economics and Management, 29(3), S43-S63. https://doi.org/10.1006/jeem.1995.1060

Jaffe, A., Palmer, K. (1997). Environmental Regulation and Innovation: A Panel Data Study. The Review of Economics and Statistics; 79 (4): 610–619. doi: https://doi.org/10.1162/003465397557196

Jiang, L., Zou, F., Qiao, Y., & Huang, Y. (2022). Patent analysis for generating the technology landscape and competition situation of renewable energy. Journal of Cleaner Production, 378, 134264. https://doi.org/10.1016/j.jclepro.2022.134264

Joyce, A., & Paquin, R. L. (2016). The triple layered business model canvas: A tool to design more sustainable business models. Journal of Cleaner Production, 135, 1474-1486. https://doi.org/10.1016/j.jclepro.2016.06.067

Joyce, A., & Paquin, R. L. (2016). The triple layered business model canvas: A tool to design more sustainable business models. Journal of Cleaner Production, 135, 1474–1486. https://doi.org/10.1016/j.jclepro.2016.06.067

Kabil, M., Priatmoko, S., Magda, R., & Dávid, L. D. (2021). Blue economy and coastal tourism: a comprehensive visualization bibliometric analysis. Sustainability, 13(7), 3650. https://doi.org/10.3390/su13073650

Kadlec, V., Květoň, V., Vlčková, J. et al. Contrasting patterns and dynamics of patent offshoring in European regions. J Technol Transf 48, 1300–1326 (2023). https://doi.org/10.1007/s10961-022-09968-4

Kang, J., Zhang, Y., & Chen, W. (2022). Delivering negative emissions innovation on the right track: A patent analysis. Renewable and Sustainable Energy Reviews, 158, 112169. https://doi.org/10.1016/j.rser.2022.112169

Kang, Y., Ma, X., Xie, M., & Zhong, N. (2025). Innovation's false spring: U.S. Export controls and Chinese patent quality. Journal of International Money and Finance, 150, 103229. https://doi.org/10.1016/j.jimonfin.2024.103229

Karataş, A. R., Kazak, H., Akcan, A. T., Akkaş, E., & Arık, M. (2024). A bibliometric mapping analysis of the literature on patent analysis. World Patent Information, 77, 102266. https://doi.org/10.1016/j.wpi.2024.102266

Kemp, R., Schot, J., & Hoogma, R. (1998). Regime Shifts to Sustainability Through Processes of Niche Formation: The Approach of Strategic Niche Management. Technology analysis & strategic management, 10(2), 175-195. https://doi.org/10.1080/09537329808524310

Khan, S. J., Kaur, P., Jabeen, F., & Dhir, A. (2021). Green process innovation: Where we are and where we are going. Business Strategy and the Environment, 30(7), 3273-3296. https://doi.org/10.1002/bse.2802

Khanh Chi, N. T. (2022). Driving factors for green innovation in agricultural production: An empirical study in an emerging economy. Journal of Cleaner Production, 368, 132965. https://doi.org/10.1016/j.jclepro.2022.132965

Kiefer, C. P., Río González, P. D., & Carrillo-Hermosilla, J. (2018). Drivers and barriers of eco-innovation types for sustainable transitions: A quantitative perspective. Business Strategy and the Environment, 28(1), 155-172. https://doi.org/10.1002/bse.2246

Kim, H. (2013). Deregulation and differentiation: Incumbent investment in green technologies. Strategic Management Journal, 34(10), 1162-1185. https://doi.org/10.1002/smj.2067

Kim, I., Pantzalis, C., & Zhang, Z. (2021). Multinationality and the value of green innovation. Journal of Corporate Finance, 69, 101996. https://doi.org/10.1016/j.jcorpfin.2021.101996

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kong, S., Tang, J., Ouyang, F., & Chen, M. (2021). Research on the treatment of heavy metal pollution in urban soil based on biochar technology. Environmental Technology & Innovation, 23, 101670. https://doi.org/10.1016/j.eti.2021.101670

Körner, MF., Leinauer, C., Ströher, T. et al. Digital Measuring, Reporting, and Verification (dMRV) for Decarbonization. Bus Inf Syst Eng (2025). https://doi.org/10.1007/s12599-025-00953-3

Krass, D., Nedorezov, T., & Ovchinnikov, A. (2013). Environmental Taxes and the Choice of Green Technology. Production and Operations Management, 22(5), 1035-1055. https://doi.org/10.1111/poms.12023

Kreft, C., Huber, R., Wuepper, D., & Finger, R. (2021). The role of non-cognitive skills in farmers' adoption of climate change mitigation measures. Ecological Economics, 189, 107169. https://doi.org/10.1016/j.ecolecon.2021.107169

Kumar, S., & Sindhu, S. S. (2023). Drought stress mitigation through bioengineering of microbes and crop varieties for sustainable agriculture and food security. Current Research in Microbial Sciences, 7, 100285. https://doi.org/10.1016/j.crmicr.2024.100285

Kurniawan, T. A., Othman, M. H. D., Liang, X., Goh, H. H., Gikas, P., Chong, K.-K., & Chew, K. W. (2023). Challenges and opportunities for biochar to promote circular economy and carbon neutrality. Journal of Environmental Management, 332, 117429. https://doi.org/10.1016/j.jenvman.2023.117429

Laborde, D., Mamun, A., Martin, W., Piñeiro, V., & Vos, R. (2021). Agricultural subsidies and global greenhouse gas emissions. Nature Communications, 12(1), 1-9. https://doi.org/10.1038/s41467-021-22703-1

Lam, P. T., Chan, E. H., Poon, C., Chau, C., & Chun, K. (2009). Factors affecting the implementation of green specifications in construction. Journal of Environmental Management, 91(3), 654-661. https://doi.org/10.1016/j.jenvman.2009.09.029

Leal Filho, W., Wall, T., Rui Mucova, S. A., Nagy, G. J., Balogun, A., Luetz, J. M., Ng, A. W., Kovaleva, M., Safiul Azam, F. M., Alves, F., Guevara, Z., Matandirotya, N. R., Skouloudis, A., Tzachor, A., Malakar, K., & Gandhi, O. (2022). Deploying artificial intelligence for climate change adaptation. Technological Forecasting and Social Change, 180, 121662. https://doi.org/10.1016/j.techfore.2022.121662

Leal, L. A., Ángel-Ospina, A. C., Ramos, J. A. L., & Machuca-Martínez, F. (2025). Aquaculture sector in Colombia: Uncovering sustainability, transformative potential, and trends through bibliometric and patent analysis. Aquaculture, 598, 742068. https://doi.org/10.1016/j.aquaculture.2024.742068

Lewandowski, M. (2016). Designing the Business Models for Circular Economy—Towards the Conceptual Framework. Sustainability, 8(1), Article 1. https://doi.org/10.3390/su8010043

Li, G., & Branstetter, L. G. (2024). Does "Made in China 2025" work for China? Evidence from Chinese listed firms. Research Policy, 53(6), 105009. https://doi.org/10.1016/j.respol.2024.105009

Li, J., Xiong, W., Casady, C. B., Liu, B., & Wang, F. (2023). Advancing Urban Sustainability through Public–Private Partnerships: Case Study of the Gu'An New Industry City in China. Journal of Management in Engineering, 39(1), 05022016. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001103

Li, L. M., Liu, Y. H., & Zhang, Y. F. (2023). The U-shaped relationship between patent age and patent value: evidence from assigned patents in China. Economics of Innovation and New Technology, 33(6), 830–852. https://doi.org/10.1080/10438599.2023.2255978

Li, L., Msaad, H., Sun, H., Tan, M., Lu, Y., & Lau, A. (2020). Green innovation and business sustainability: new evidence from energy intensive industry in china. International Journal of Environmental Research and Public Health, 17(21), 7826. https://doi.org/10.3390/ijerph17217826

Li, L., Zhu, X. The Impact of Digital Agriculture on Green Productivity in Agriculture: Evidence from China. J Knowl Econ (2024). https://doi.org/10.1007/s13132-024-02502-x

Li, M.; Wang, X.; Wang, Z.; Maqbool, B.; Hussain, A.; Khan, W.A. (2022). Bibliometric Analysis of the Research on the Impact of Environmental Regulation on Green Technology Innovation Based on CiteSpace. Int. J. Environ. Res. Public Health, 19. https://doi.org/10.3390/ijerph192013273

Li, S., Chan, C. Y., Sharbatmaleki, M., Trejo, H., & Delagah, S. (2020). Engineered Biochar Production and Its Potential Benefits in a Closed-Loop Water-Reuse Agriculture System. Water, 12(10), Article 10. https://doi.org/10.3390/w12102847

Li, Y., Herzog, F., Levers, C., et al. (2024). Agricultural technology as a driver of sustainable intensification: Insights from the diffusion and focus of patents. Agronomy for Sustainable Development, 44, 14. https://doi.org/10.1007/s13593-024-00949-5

Li, Y., Hu, S., Chen, J., Müller, K., Li, Y., Fu, W., Lin, Z., & Wang, H. (2018). Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: A review. Journal of Soils and Sediments, 18(2), 546–563. https://doi.org/10.1007/s11368-017-1906-y

Li, Y., Xu, X., & Duan, Z. (2025). The impact of digital technologies on eco-efficiency: Evidence from ICT patents. Environmental and Sustainability Indicators, 26, 100675. https://doi.org/10.1016/j.indic.2025.100675

Li, Z., & Lin, B. (2024). Quantity or quality? The impact assessment of environmental regulation on green innovation. Environmental Impact Assessment Review, 110, 107726. https://doi.org/10.1016/j.eiar.2024.107726

Li, Z., Huang, Z., & Su, Y. (2023). New media environment, environmental regulation and corporate green technology innovation:Evidence from China. Energy Economics, 119, 106545. https://doi.org/10.1016/j.eneco.2023.106545

Lian, G., Xu, A., & Zhu, Y. (2022). Substantive green innovation or symbolic green innovation? The impact of ER on enterprise green innovation based on the dual moderating effects. Journal of Innovation & Knowledge, 7(3), 100203. https://doi.org/10.1016/j.jik.2022.100203

Liao, Z., Hong, W., Wang, Y., & Zhang, X. (2024). Does the patent value of green technology affect its transfer? The moderating role of industry competition. Environmental Research, 241, 117620. https://doi.org/10.1016/j.envres.2023.117620

Lindgren, P., Knoth, N., Sureshkumar, S., Friedrich, M., & Adomaityte, R. (2021). “green multi business models” how to measure green business models and green business model innovation?. Wireless Personal Communications, 121(2), 1303-1323. https://doi.org/10.1007/s11277-021-09189-2

Linnenluecke, M., Marrone, M., & Singh, A. (2019). Conducting systematic literature reviews and bibliometric analyses. Australian Journal of Management, 45(2), 175-194. https://doi.org/10.1177/0312896219877678

Liu, M., Guo, J., & Bi, D. (2023). Comparison of administrative and regulatory green technologies development between China and the U.S. Based on patent analysis. Data Science and Management, 6(1), 34-45. https://doi.org/10.1016/j.dsm.2023.01.001

Liu, S., Xu, R. & Chen, X. (2019). Does green credit affect the green innovation performance of high-polluting and energy-intensive enterprises? Evidence from a quasi-natural experiment. Environ Sci Pollut Res 28, 65265–65277. https://doi.org/10.1007/s11356-021-15217-2

Liu, T., Mostafa, S., Mohamed, S., & Nguyen, T. S. (2020). Emerging themes of public-private partnership application in developing smart city projects: A conceptual framework. Built Environment Project and Asset Management, 11(1), 138–156. https://doi.org/10.1108/BEPAM-12-2019-0142

Liu, Y., Xing, Y., Vendrell-Herrero, F., & Bustinza, O. F. (2024). Setting contextual conditions to resolve grand challenges through responsible innovation: A comparative patent analysis in the circular economy. Journal of Product Innovation Management, 41(2), 449-472. https://doi.org/10.1111/jpim.12659

Liu, Z., Anderson, T. D., & Cruz, J. M. (2012). Consumer environmental awareness and competition in two-stage supply chains. European Journal of Operational Research, 218(3), 602-613. https://doi.org/10.1016/j.ejor.2011.11.027

Loet L. & Félix de Moya-Anegón & Vicente P. Guerrero-Bote, 2010. “Journal maps on the basis of Scopus data: A comparison with the Journal Citation Reports of the ISI”, Journal of the American Society for Information Science and Technology, Association for Information Science & Technology, vol. 61(2), pages 352-369. https://ideas.repec.org/a/bla/jamist/v61y2010i2p352-369.html

Losacker, S. (2022). ‘License to green’: Regional patent licensing networks and green technology diffusion in China. Technological Forecasting and Social Change, 175, 121336. https://doi.org/10.1016/j.techfore.2021.121336

Lu, C., Yang, C., & Yen, H. (2020). Stackelberg game approach for sustainable production-inventory model with collaborative investment in technology for reducing carbon emissions. Journal of Cleaner Production, 270, 121963. https://doi.org/10.1016/j.jclepro.2020.121963

Lubik, S., & Garnsey, E. (2016). Early Business Model Evolution in Science-based Ventures: The Case of Advanced Materials. Long Range Planning, 49(3), 393-408. https://doi.org/10.1016/j.lrp.2015.03.001

Luo, Q., Miao, C., Sun, L., Meng, X., & Duan, M. (2019). Efficiency evaluation of green technology innovation of China’s strategic emerging industries: An empirical analysis based on

Malmquist-data envelopment analysis index. Journal of Cleaner Production, 238, 117782. https://doi.org/10.1016/j.jclepro.2019.117782

Luo, Z., Chen, X., & Wang, X. (2016). The role of co-opetition in low carbon manufacturing. European Journal of Operational Research, 253(2), 392-403. https://doi.org/10.1016/j.ejor.2016.02.030

Lv, C., Shao, C., & Lee, C. (2021). Green technology innovation and financial development: Do environmental regulation and innovation output matter? Energy Economics, 98, 105237. https://doi.org/10.1016/j.eneco.2021.105237

Ma, S., He, Y., Gu, R., & Li, S. (2021b). Sustainable supply chain management considering technology investments and government intervention. Transportation Research Part E: Logistics and Transportation Review, 149, 102290. https://doi.org/10.1016/j.tre.2021.102290

Ma, Y., Zhang, Q., & Yin, Q. (2021a). Top management team faultlines, green technology innovation and firm financial performance. Journal of Environmental Management, 285, 112095. https://doi.org/10.1016/j.jenvman.2021.112095

MacArthur, E. (2013). Towards the circular economy. Journal of Industrial Ecology, 2(1), 23–44.

Maja, M. M., & Ayano, S. F. (2021). The impact of population growth on natural resources and farmers' capacity to adapt to climate change in low-income countries. Earth Systems and Environment, 5(2), 271-283. https://doi.org/10.1007/s41748-021-00224-5

Malhi, G. S., Kaur, M., & Kaushik, P. (2021). Impact of climate change on agriculture and its mitigation strategies: A review. Sustainability, 13(3), 1318. https://doi.org/10.3390/su13031318

Mansoor, S., Iqbal, S., Popescu, S. M., Kim, S. L., Chung, Y. S., & Baek, J. (2025). Integration of smart sensors and IOT in precision agriculture: Trends, challenges and future prospectives. Frontiers in Plant Science, 16, 1587869. https://doi.org/10.3389/fpls.2025.1587869

Mashud, A. H. M., Roy, D., Daryanto, Y., Chakrabortty, R. K., & Tseng, M. (2021a). A sustainable inventory model with controllable carbon emissions, deterioration and advance payments. Journal of Cleaner Production, 296, 126608. https://doi.org/10.1016/j.jclepro.2021.126608

Mashud, A. H., Pervin, M., Mishra, U., Daryanto, Y., Tseng, M., & Lim, M. K. (2021b). A sustainable inventory model with controllable carbon emissions in green-warehouse farms. Journal of Cleaner Production, 298, 126777. https://doi.org/10.1016/j.jclepro.2021.126777

Masupha, T. E., Moeletsi, M. E., & Tsubo, M. (2025). Employing a metric to quantify the effectiveness of an agricultural drought early warning system during the fourth industrial revolution. Computers and Electronics in Agriculture, 230, 109906. https://doi.org/10.1016/j.compag.2025.109906

Matuštík, J., Hnátková, T., & Kočí, V. (2020). Life cycle assessment of biochar-to-soil systems: A review. Journal of Cleaner Production, 259, 120998. https://doi.org/10.1016/j.jclepro.2020.120998

Mazzocchi, C., Orsi, L., Ferrazzi, G., & Corsi, S. (2020). The Dimensions of Agricultural Diversification: A Spatial Analysis of Italian Municipalities. Rural Sociology, 85(2), 316–345. https://doi.org/10.1111/ruso.12291

McNeely, J.A. Nature and COVID-19: The pandemic, the environment, and the way ahead. Ambio 50, 767–781 (2021). https://doi.org/10.1007/s13280-020-01447-0

Meuleman, L., & Niestroy, I. (2015). Common But Differentiated Governance: A Metagovernance Approach to Make the SDGs Work. Sustainability, 7(9), Article 9. https://doi.org/10.3390/su70912295

Meyskens, M., Carsrud, A.L. Nascent green-technology ventures: a study assessing the role of partnership diversity in firm success. Small Bus Econ 40, 739–759 (2013). https://doi.org/10.1007/s11187-011-9400-1

Mezzacapo, E. (2024). Mind the Gap: Assessing Member States' Implementation of Farm to Farm-to-Fork Targets within the 2023–2027 Common Agricultural Policy. European Journal of Risk Regulation, 15(2), 265–279. https://doi.org/10.1017/err.2024.44

Mignon, I., & Bergek, A. (2016). System- and actor-level challenges for diffusion of renewable electricity technologies: An international comparison. Journal of Cleaner Production, 128, 105-115. https://doi.org/10.1016/j.jclepro.2015.09.048

Mishra, U., Wu, J., & Sarkar, B. (2020). A sustainable production-inventory model for a controllable carbon emissions rate under shortages. Journal of Cleaner Production, 256, 120268. https://doi.org/10.1016/j.jclepro.2020.120268

Mishra, U., Wu, J., & Sarkar, B. (2021a). Optimum sustainable inventory management with backorder and deterioration under controllable carbon emissions. Journal of Cleaner Production, 279, 123699. https://doi.org/10.1016/j.jclepro.2020.123699

Mongeon, P., Paul-Hus, A., (2016), The journal coverage of Web of Science and Scopus: a comparative analysis, Scientometrics, 106, issue 1, p. 213-228, https://EconPapers.repec.org/RePEc:spr:scient:v:106:y:2016:i:1:d:10.1007_s11192-015-1765-5

Montalvo, C. (2007). General wisdom concerning the factors affecting the adoption of cleaner technologies: A survey 1990–2007. Journal of Cleaner Production, 16(1), S7-S13. https://doi.org/10.1016/j.jclepro.2007.10.002

Muangprathub, J., Boonnam, N., Kajornkasirat, S., Lekbangpong, N., Wanichsombat, A., & Nillaor, P. (2018). IoT and agriculture data analysis for smart farm. Computers and Electronics in Agriculture, 156, 467-474. https://doi.org/10.1016/j.compag.2018.12.011

Mubeen, A., Nisar, Q.A., Patwary, A.K. et al. Greening your business: nexus of green dynamic capabilities, green innovation and sustainable performance. Environ Dev Sustain 26, 22747–22773 (2024). https://doi.org/10.1007/s10668-023-03574-6

Mukherjee, A., & Lal, R. (2013). Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. Agronomy, 3(2), Article 2. https://doi.org/10.3390/agronomy3020313

Mukherjee, A., Singh, R.K., Mishra, R. et al. Application of blockchain technology for sustainability development in agricultural supply chain: justification framework. Oper Manag Res 15, 46–61 (2022). https://doi.org/10.1007/s12063-021-00180-5

Müller, S., Backhaus, N., Nagabovanalli, P., & Abiven, S. (2019). A social-ecological system evaluation to implement sustainably a biochar system in South India. Agronomy for Sustainable Development, 39(4), 43. https://doi.org/10.1007/s13593-019-0586-y

Mumtaz, M., & Puppim de Oliveira, J. A. (2023). A framework for analyzing the implementation of climate adaptation policies in the agriculture sector at the subnational level. Environmental Science & Policy, 147, 126-137. https://doi.org/10.1016/j.envsci.2023.06.002

Muscas, D., Orlandi, F., Petrucci, R., Proietti, C., Ruga, L., & Fornaciari, M. (2024). Effects of urban tree pruning on ecosystem services performance. Trees, Forests and People, 15, 100503. https://doi.org/10.1016/j.tfp.2024.100503

Musiolik, J., Markard, J., & Hekkert, M. (2012). Networks and network resources in technological innovation systems: Towards a conceptual framework for system building. Technological Forecasting and Social Change, 79(6), 1032-1048. https://doi.org/10.1016/j.techfore.2012.01.003

Myshko, A., Checchinato, F., Colapinto, C., Finotto, V., & Mauracher, C. (2024). Towards the twin transition in the agri-food sector? Framing the current debate on sustainability and digitalisation. Journal of Cleaner Production, 452, 142063. https://doi.org/10.1016/j.jclepro.2024.142063

Nelson, K. P., Parton, L. C., & Brown, Z. S. (2022). Biofuels policy and innovation impacts: Evidence from biofuels and agricultural patent indicators. Energy Policy, 162, 112767. https://doi.org/10.1016/j.enpol.2021.112767

Nematian, M., Keske, C., & Ng'ombe, J. N. (2021). A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. Waste Management, 135, 467–477. https://doi.org/10.1016/j.wasman.2021.09.014

Nematian, M., Ng'ombe, J. N., & Keske, C. (2023). Sustaining agricultural economies: Regional economic impacts of biochar production from waste orchard biomass in California's Central Valley. Environment, Development and Sustainability. https://doi.org/10.1007/s10668-023-03984-6

Niknejad, N., Ismail, W., Bahari, M., Hendradi, R., & Salleh, A. Z. (2021). Mapping the research trends on blockchain technology in food and agriculture industry: A bibliometric analysis. Environmental Technology & Innovation, 21, 101272. https://doi.org/10.1016/j.eti.2020.101272

Niknejad, N., Nazari, B., Foroutani, S. et al. (2023). A bibliometric analysis of green technologies applied to water and wastewater treatment. Environ Sci Pollut Res 30, 71849–71863. https://doi.org/10.1007/s11356-022-18705-1

Novotný, M., Marković, M., Raček, J., Šipka, M., Chorazy, T., Tošić, I., & Hlavínek, P. (2023). The use of biochar made from biomass and biosolids as a substrate for green infrastructure: A review. Sustainable Chemistry and Pharmacy, 32, 100999. https://doi.org/10.1016/j.scp.2023.100999

Ojo, T. O., Adetoro, A. A., Ogundeji, A. A., & Belle, J. A. (2021). Quantifying the determinants of climate change adaptation strategies and farmers' access to credit in South Africa. Science of the Total Environment, 792, 148499. https://doi.org/10.1016/j.scitotenv.2021.148499

Oldfield, T. L., Sikirica, N., Mondini, C., López, G., Kuikman, P. J., & Holden, N. M. (2018). Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon. Journal of Environmental Management, 218, 465–476. https://doi.org/10.1016/j.jenvman.2018.04.061

Orlando, B., Ballestra, L. V., Scuotto, V., Pironti, M., & Di Giudice, M. (2022). The impact of R&D investments on eco-innovation: A cross-cultural perspective of green technology management. IEEE Transactions on Engineering Management, 69(5), 2275-2284. https://doi.org/10.1109/TEM.2020.3005525

Orsatti, G., Quatraro, F., & Pezzoni, M. (2020). The antecedents of green technologies: The role of team-level recombinant capabilities. Research Policy, 49(3), 103919. https://doi.org/10.1016/j.respol.2019.103919

Ortiz, A. M., Ortiz, D., Outhwaite, C., Dalin, C., & Newbold, T. (2021). A review of the interactions between biodiversity, agriculture, climate change and international trade: Research and policy priorities. One Earth, 4(1), 88-101. https://doi.org/10.1016/j.oneear.2020.12.008

Osman, A. I., Farghali, M., & Rashwan, A. K. (2024). Life cycle assessment of biochar as a green sorbent for soil remediation. Current Opinion in Green and Sustainable Chemistry, 46, 100882. https://doi.org/10.1016/j.cogsc.2024.100882

Osterwalder, A., & Pigneur, Y. (2010). Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. John Wiley & Sons.

overview of different approaches and an empirical comparison. Scientometrics, 96(3), Paes, L. A. B., Bezerra, B. S., Deus, R. M., Jugend, D., & Battistelle, R. A. G. (2019). Organic solid waste management in a circular economy perspective – A systematic review and SWOT analysis. Journal of Cleaner Production, 239, 118086. https://doi.org/10.1016/j.jclepro.2019.118086

Pages 611-620. https://doi.org/10.1016/j.jclepro.2019.05.024

Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., & Ok, Y. S. (2019). Response of microbial communities to biochar-amended soils: A critical review. Biochar, 1(1), 3-22. https://doi.org/10.1007/s42773-019-00009-2

Pan, L., Xu, Z., & Skare, M. (2023). Sustainable business model innovation literature: a bibliometrics analysis. Review of Managerial Science, 17(3), 757-785. https://doi.org/10.1007/s11846-022-00548-2

Pan, S., He, K., Lin, K., Fan, C., & Chang, C. (2022). Addressing nitrogenous gases from croplands toward low-emission agriculture. Npj Climate and Atmospheric Science, 5(1), 1-18. https://doi.org/10.1038/s41612-022-00265-3

Pandey, N., & Sagar, A. D. (2022). Beyond technology transfer: Innovation cooperation to advance sustainable development in developing countries. Wiley Interdisciplinary Reviews: Energy and Environment, 11(2), e422. https://doi.org/10.1002/wene.422

Park, H. (2004). Design science in information systems research. Mis Quarterly, 28(1), 75. https://doi.org/10.2307/25148625

Parra-López, C., Ben Abdallah, S., Garcia-Garcia, G., Hassoun, A., Sánchez-Zamora, P., Trollman, H., Jagtap, S., & Carmona-Torres, C. (2024). Integrating digital technologies in agriculture for climate change adaptation and mitigation: State of the art and future perspectives. Computers and Electronics in Agriculture, 226, 109412. https://doi.org/10.1016/j.compag.2024.109412

Patel, M. R., & Panwar, N. L. (2024). Evaluating the agronomic and economic viability of biochar in sustainable crop production. Biomass and Bioenergy, 188, 107328. https://doi.org/10.1016/j.biombioe.2024.107328

Patel, P. C. (2025). Prevention Is Better Than Cure? Climate Mitigation and Adaptation Patents and Firm Performance. Business Strategy and the Environment, 34(5), 5576-5600. https://doi.org/10.1002/bse.4260

patterns in scientific literature. Journal of the Association for Information Science and

Pavesi, R., Orsi, L., & Zanderighi, L. (2024). Enhancing Circularity in Urban Waste Management: A Case Study on Biochar from Urban Pruning. Environments, 12(1), 5. https://doi.org/10.3390/environments12010005

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), Article 12. https://doi.org/10.24294/jipd.v8i12.9051

Perey, R., Benn, S., Agarwal, R., & Edwards, M. (2018). The place of waste: Changing business value for the circular economy. Business Strategy and the Environment, 27(5), 631–642. https://doi.org/10.1002/bse.2068

Perot, E. (2023). Technology transfer, climate change, and the developing countries: The difficulties posed by green patents. Journal of Intellectual Property Law & Practice, 18(5), 397-406. https://doi.org/10.1093/jiplp/jpad039

Phdungsilp, A. (2011). Futures studies' backcasting method used for strategic sustainable city planning. Futures, 43(7), 707-714. https://doi.org/10.1016/j.futures.2011.05.012

Pieroni, M. P. P., McAloone, T. C., & Pigosso, D. C. A. (2019). Business model innovation for circular economy and sustainability: A review of approaches. Journal of Cleaner Production, 215, 198–216. https://doi.org/10.1016/j.jclepro.2019.01.036

Podsakoff, P. M., MacKenzie, S. B., Lee, J.-Y., & Podsakoff, N. P. (2003). Common method biases in behavioral research: A critical review of the literature and recommended remedies. Journal of Applied Psychology, 88(5), 879–903. https://doi.org/10.1037/0021-9010.88.5.879

Ponta, L., Puliga, G., Manzini, R., & Cincotti, S. (2022). Sustainability-oriented innovation and co-patenting role in agri-food sector: Empirical analysis with patents. Technological Forecasting and Social Change, 178, 121595. https://doi.org/10.1016/j.techfore.2022.121595

Porter, M. E. (1991). Essay. Scientific American, 264(4), 168-168.

Porter, M. E., Van der Linde, C. (1995). “Toward a New Conception of the Environment-Competitiveness Relationship”. Journal of Economic Perspectives, 9 (4): 97-118. https://doi.org/10.1257/jep.9.4.97

Porter, M., & Van der Linde, C. (1995a). Green and competitive: ending the stalemate. The Dynamics of the eco-efficient economy: environmental regulation and competitive advantage, 33, 120-134.

Pranckutė, R. (2021). Web of science (wos) and scopus: the titans of bibliographic information in today’s academic world. Publications, 9(1), 12. https://doi.org/10.3390/publications9010012

Priore, R. (2024). Cobalt recycling patents dataset selected using ‘green’ classification codes: Focus on the nickel manganese cobalt (NMC) batteries recycling. Data in Brief, 54, 110320. https://doi.org/10.1016/j.dib.2024.110320

Puertas, R., Marti, L., & Calafat, C. (2023). Agricultural and innovation policies aimed at mitigating climate change. Environmental Science & Pollution Research, 30, 47299–47310. https://doi.org/10.1007/s11356-023-25663-9

Qi, G., Jia, Y., & Zou, H. (2020). Is institutional pressure the mother of green innovation? Examining the moderating effect of absorptive capacity. Journal of Cleaner Production, 278, 123957. https://doi.org/10.1016/j.jclepro.2020.123957

Qiu, R., Hou, S., Chen, X., & Meng, Z. (2021). Green aviation industry sustainable development towards an integrated support system. Business Strategy and the Environment, 30(5), 2441-2452. https://doi.org/10.1002/bse.2756

Quandt, A., Grafton, D., Gorman, K. et al. Mitigation and adaptation to climate change in San Diego County, California. Mitig Adapt Strateg Glob Change 28, 7 (2023). https://doi.org/10.1007/s11027-022-10041-6

Rainville, A., Dikker, I., & Buggenhagen, M. (2024). Tracking innovation via green patent classification systems: Are we truly capturing circular economy progress? Journal of Cleaner Production, 486, 144385. https://doi.org/10.1016/j.jclepro.2024.144385

Ramezanzadeh, H., Zarehaghi, D., Baybordi, A., Bouket, A. C., Oszako, T., Alenezi, F. N., & Belbahri, L. (2023). The Impacts of Biochar-Assisted Factors on the Hydrophysical Characteristics of Amended Soils: A Review. Sustainability, 15(11), Article 11. https://doi.org/10.3390/su15118700

Rattalino, F. (2018). Circular advantage anyone? Sustainability-driven innovation and circularity at Patagonia, Inc. Thunderbird International Business Review, 60(5), 747–755. https://doi.org/10.1002/tie.21917

Regmi, A., Singh, S., Moustaid-Moussa, N., Coldren, C., & Simpson, C. (2022). The Negative Effects of High Rates of Biochar on Violas Can Be Counteracted with Fertilizer. Plants, 11(4), Article 4. https://doi.org/10.3390/plants11040491

Reichstein, M., Benson, V., Blunk, J., Creutzig, F., Fearnley, C. J., Han, B., Kornhuber, K., Rahaman, N., Schölkopf, B., Tárraga, J. M., Vinuesa, R., Dall, K., Denzler, J., Frank, D., Martini, G., Nganga, N., Maddix, D. C., & Weldemariam, K. (2025). Early warning of complex climate risk with integrated artificial intelligence. Nature Communications, 16(1), 1-13. https://doi.org/10.1038/s41467-025-57640-w

Ren, J., Liang, H., & Chan, F. T. (2017). Urban sewage sludge, sustainability, and transition for Eco-City: Multi-criteria sustainability assessment of technologies based on best-worst method. Technological Forecasting and Social Change, 116, 29-39. https://doi.org/10.1016/j.techfore.2016.10.070

Rennings, K. (2000). Redefining innovation — Eco-innovation research and the contribution from ecological economics. Ecological Economics, 32(2), 319-332. https://doi.org/10.1016/S0921-8009(99)00112-3

Rossa-Roccor, V., Acheson, E. S., Andrade-Rivas, F., Coombe, M., Ogura, S., Super, L., … & Hong, A. (2020). Scoping review and bibliometric analysis of the term “planetary health” in the peer-reviewed literature. Frontiers in Public Health, 8. https://doi.org/10.3389/fpubh.2020.00343

Russo, M.V. and Fouts, P.A. (1997) A Resource-Based Perspective on Corporate Environmental Performance and Profitability. Academy of Management Journal, 40, 534-559.

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2018). Blockchain technology and its relationships to sustainable supply chain management. International Journal of Production Research, 57(7), 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Saha, A., Raut, R., & Kumar, M. (2025). Digital technology adoption challenges in the agri-food supply chain from the perspective of attaining sustainable development goals. The International Journal of Logistics Management, 36(2), 556-588. https://doi.org/10.1108/IJLM-09-2023-0412

Sahoo, S., Kumar, A., & Upadhyay, A. (2022). How do green knowledge management and green technology innovation impact corporate environmental performance? Understanding the role of green knowledge acquisition. Business Strategy and the Environment, 32(1), 551-569. https://doi.org/10.1002/bse.3160

Sajja, G. S., Rane, K. P., Phasinam, K., Kassanuk, T., Okoronkwo, E., & Prabhu, P. (2022). Towards applicability of blockchain in agriculture sector. Materials Today: Proceedings, 80, 3705-3708. https://doi.org/10.1016/j.matpr.2021.07.366

Salam, A. (2024). Internet of Things in Agricultural Innovation and Security. In: Internet of Things for Sustainable Community Development. Internet of Things. Springer, Cham. https://doi.org/10.1007/978-3-031-62162-8_3

Salvador, R. W., & Doong, R.-A. (2024). Simultaneous achievement of energy recovery and carbon sequestration through municipal solid waste management: A review. Chemosphere, 361, 142478. https://doi.org/10.1016/j.chemosphere.2024.142478

Salvioni, D. M., & Almici, A. (2020). Transitioning Toward a Circular Economy: The Impact of Stakeholder Engagement on Sustainability Culture. Sustainability, 12(20), Article 20. https://doi.org/10.3390/su12208641

Sánchez-Monedero, M. A., Cayuela, M. L., Sánchez-García, M., Vandecasteele, B., D’Hose, T., López, G., Martínez-Gaitán, C., Kuikman, P. J., Sinicco, T., & Mondini, C. (2019). Agronomic Evaluation of Biochar, Compost and Biochar-Blended Compost across Different Cropping Systems: Perspective from the European Project FERTIPLUS. Agronomy, 9(5), Article 5. https://doi.org/10.3390/agronomy9050225

Sandström, U. (2009). Combining curriculum vitae and bibliometric analysis: mobility, gender and research performance. Research Evaluation, 18(2), 135–142. https://doi.org/10.3152/095820209X441790;

Sarfraz, S., Ali, F., Hameed, A., Ahmad, Z., & Riaz, K. (2023). Sustainable agriculture through technological innovations. In Prakash, C.S., Fiaz, S., Nadeem, M.A., Baloch, F.S., & Qayyum, A. (Eds.), Sustainable Agriculture in the Era of the OMICs Revolution. Springer, Cham. https://doi.org/10.1007/978-3-031-15568-0_10

Savari, M., & Shokati Amghani, M. (2021). Factors influencing farmers' adaptation strategies in confronting the drought in Iran. Environment, Development & Sustainability, 23(4). https://doi.org/10.1007/s10668-020-00798-8

Schaltegger, S., Lüdeke-Freund, F., & Hansen, E. G. (2012). Business cases for sustainability: The role of business model innovation for corporate sustainability. International Journal of Innovation and Sustainable Development, 6(2), 95-119. https://doi.org/10.1504/IJISD.2012.046944

Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., & Cayuela, M. L. (2021). Biochar in agriculture – A systematic review of 26 global meta-analyses. GCB Bioenergy, 13(11), 1708–1730. https://doi.org/10.1111/gcbb.12889

Sedighi, M. (2016). Application of word co-occurrence analysis method in mapping of the scientific fields (case study: the field of Informetrics). Library Review, 65(1/2), 52-64. https://doi.org/10.1108/LR-07-2015-0075

Şener, İ. and Artar, M. (2024). How green strategy research is evolving a systematic literature review. Journal of Global Strategic Management. https://doi.org/10.20460/jgsm.2023.317

Sharma, K., & Shivandu, S. K. (2024). Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture. Sensors International, 5, 100292. https://doi.org/10.1016/j.sintl.2024.100292

Sharma, S., & Vredenburg, H. (1998). Proactive corporate environmental strategy and the development of competitively valuable organizational capabilities. Strategic Management Journal, 19(8), 729-753. https://doi.org/10.1002/(SICI)1097-0266(199808)19:8<729::AID-SMJ967>3.0.CO;2-4

Singh, E., Mishra, R., Kumar, A., Shukla, S. K., Lo, S.-L., & Kumar, S. (2022). Circular economy-based environmental management using biochar: Driving towards sustainability. Process Safety and Environmental Protection, 163, 585–600. https://doi.org/10.1016/j.psep.2022.05.056

Singh, V.K., Singh, P., Karmakar, M. et al. The journal coverage of Web of Science, Scopus and Dimensions: A comparative analysis. Scientometrics 126, 5113–5142 (2021). https://doi.org/10.1007/s11192-021-03948-5

Skevas, T., Massey, R. & Grashuis, J. Farmer adoption and intensity of use of extreme weather adaptation and mitigation strategies: evidence from a sample of Missouri farmers. Climatic Change 174, 18 (2022). https://doi.org/10.1007/s10584-022-03439-3

Small, H. (1999). Visualizing science by citation mapping. Journal of the American Society for Information Science, 50(9), 799–813. https://doi.org/10.1002/(SICI)1097-4571(1999)50:9%3C799::AID-ASI9%3E3.0.CO;2-G

Smolenaars, W.J., Jamil, M.K., Dhaubanjar, S. et al. Exploring the potential of agricultural system change as an integrated adaptation strategy for water and food security in the Indus basin. Environ Dev Sustain 26, 15177–15212 (2024). https://doi.org/10.1007/s10668-023-03245-6

Söderholm, P., Hellsmark, H., Frishammar, J., Hansson, J., Mossberg, J., & Sandström, A. (2018). Technological development for sustainability: The role of network management in the innovation policy mix. Technological Forecasting and Social Change, 138, 309-323. https://doi.org/10.1016/j.techfore.2018.10.010

Spreafico, C., Thonemann, N., Pizzol, M. et al. Using patents to support prospective life cycle assessment: opportunities and limitations. Int J Life Cycle Assess 30, 201–220 (2025). https://doi.org/10.1007/s11367-024-02404-9

Suchek, N., Fernandes, C. I., Kraus, S., Filser, M., & Sjögrén, H. (2021). Innovation and the circular economy: A systematic literature review. Business Strategy and the Environment, 30(8), 3686–3702. https://doi.org/10.1002/bse.2834

Sun, L., Miao, C., & Yang, L. (2017). Ecological-economic efficiency evaluation of green technology innovation in strategic emerging industries based on entropy weighted TOPSIS method. Ecological Indicators, 73, 554-558. https://doi.org/10.1016/j.ecolind.2016.10.018

Sun, Y., Gao, P., Tian, W., & Guan, W. (2023). Green innovation for resource efficiency and sustainability: Empirical analysis and policy. Resources Policy, 81, 103369. https://doi.org/10.1016/j.resourpol.2023.103369

Supunsala Senadheera, S., Amasha Withana, P., Yau Lim, J., You, S., X. Chang, S., Wang, F., Hyuk Rhee, J., & Sik Ok, Y. (2024). Carbon negative biochar systems contribute to sustainable urban green infrastructure: A critical review. Green Chemistry, 26(21), 10634–10660. https://doi.org/10.1039/D4GC03071K

Swinkels, L. (2024). Trading carbon credit tokens on the blockchain. International Review of Economics & Finance, 91, 720-733. https://doi.org/10.1016/j.iref.2024.01.012

Tabares, S., Parida, V., & Chirumalla, K. (2025). Twin transition in industrial organizations: Conceptualization, implementation framework, and research agenda. Technological Forecasting and Social Change, 213, 123995. https://doi.org/10.1016/j.techfore.2025.123995

Tang, C., Xu, Y., Hao, Y., Wu, H., & Xue, Y. (2021). What is the role of telecommunications infrastructure construction in green technology innovation? A firm-level analysis for China. Energy Economics, 103, 105576. https://doi.org/10.1016/j.eneco.2021.105576

Tarei, P. K., Chand, P., & Gupta, H. (2021). Barriers to the adoption of electric vehicles: Evidence from India. Journal of Cleaner Production, 291, 125847. https://doi.org/10.1016/j.jclepro.2021.125847

Teece, D. J. (2010). Business Models, Business Strategy and Innovation. Long Range Planning, 43(2-3), 172-194. https://doi.org/10.1016/j.lrp.2009.07.003

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. Strategic Management Journal, 18(7), 509-533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z

Tseng, M., Tan, R. R., & Siriban-Manalang, A. B. (2013). Sustainable consumption and production for Asia: Sustainability through green design and practice. Journal of Cleaner Production, 40, 1-5. https://doi.org/10.1016/j.jclepro.2012.07.015

Usigbe, M.J., Asem-Hiablie, S., Uyeh, D.D. et al. Enhancing resilience in agricultural production systems with AI-based technologies. Environ Dev Sustain 26, 21955–21983 (2024). https://doi.org/10.1007/s10668-023-03588-0

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program

Van Eck, N.J., & Waltman, L. (2009). How to normalize cooccurrence data? An analysis of some well-known similarity measures. Journal of the American Society for Information Science and Technology, 60(8), 1635–1651. https://doi.org/10.1002/asi.21075

Van Holm, E.J., Jung, H. & Welch, E.W. The impacts of foreignness and cultural distance on commercialization of patents. J Technol Transf 46, 29–61 (2021). https://doi.org/10.1007/s10961-020-09775-9

Van Tilburg, A. J., & Hudson, P. F. (2022). Extreme weather events and farmer adaptation in Zeeland, the Netherlands: A European climate change case study from the Rhine delta. Science of The Total Environment, 844, 157212. https://doi.org/10.1016/j.scitotenv.2022.157212

Vanapalli, K. R., Sharma, H. B., Ranjan, V. P., Samal, B., Bhattacharya, J., Dubey, B. K., & Goel, S. (2021). Challenges and strategies for effective plastic waste management during and post COVID-19 pandemic. The Science of the total environment, 750, 141514. https://doi.org/10.1016/j.scitotenv.2020.141514

Vaverková, M. D., Adamcová, D., Winkler, J., Koda, E., Petrželová, L., & Maxianová, A. (2020). Alternative method of composting on a reclaimed municipal waste landfill in accordance with the circular economy: Benefits and risks. Science of The Total Environment, 723, 137971. https://doi.org/10.1016/j.scitotenv.2020.137971

Vela Almeida, D., Kolinjivadi, V., Ferrando, T., Roy, B., Herrera, H., Vecchione Gonçalves, M., & Van Hecken, G. (2023). The “Greening” of Empire: The European Green Deal as the EU first agenda. Political Geography, 105, 102925. https://doi.org/10.1016/j.polgeo.2023.102925

Vizinho, A., Avelar, D., Branquinho, C., Capela Lourenco, T., Carvalho, S., Nunes, A., ... & Penha-Lopes, G. (2021). Framework for climate change adaptation of agriculture and forestry in Mediterranean climate regions. Land, 10(2), 161. https://doi.org/10.3390/land10020161

Vogel, R., Güttel, W. H. (2013). The dynamic capability view in strategic management: A bibliometric review. International Journal of Management Reviews, 15(4), 426–446. https://doi.org/10.1111/ijmr.12000

Von Bertalanffy, L. (1968). General system theory: Foundations, development, applications. George Braziller.

Wadin, J. L., Ahlgren, K., & Bengtsson, L. (2017). Joint business model innovation for sustainable transformation of industries – A large multinational utility in alliance with a small solar energy company. Journal of Cleaner Production, 160, 139-150. https://doi.org/10.1016/j.jclepro.2017.03.151

Waheed, A., Xu, H., Qiao, X., et al. (2025). Biochar in sustainable agriculture and climate mitigation: Mechanisms, challenges, and applications in the circular bioeconomy. Biomass and Bioenergy, 193, 107531. https://doi.org/10.1016/j.biombioe.2024.107531

Wakweya, R. B. (2023). Challenges and prospects of adopting climate-smart agricultural practices and technologies: Implications for food security. Journal of Agriculture and Food Research, 14, 100698. https://doi.org/10.1016/j.jafr.2023.100698

Walsh, P., Murphy, E., & Horan, D. (2020). The role of science, technology and innovation in the UN 2030 agenda. Technological Forecasting and Social Change, 154, 119957. https://doi.org/10.1016/j.techfore.2020.119957

Waltman, L., & van Eck, N. J. (2013). Source normalized indicators of citation impact: an

Wang, H., Li, M., Wang, Z., Deng, W., & Zhang, Z. (2024). Technological innovation strategies of information and communication technology enterprises: A comparative study of China, US, and Europe. Finance Research Letters, 61, 105023. https://doi.org/10.1016/j.frl.2024.105023

Wang, L., Wu, Y., Huang, Z., & Wang, Y. (2022). How big data drives green economic development: Evidence from China. Frontiers in Environmental Science, 10, 1055162. https://doi.org/10.3389/fenvs.2022.1055162

Wang, N., & Ma, M. (2021). Public–private partnership as a tool for sustainable development – What literatures say? Sustainable Development, 29(1), 243–258. https://doi.org/10.1002/sd.2127

Wang, Q. R., & Zheng, Y. (2022). Nest without birds: Inventor mobility and the left-behind patents. Research Policy, 51(4), 104485. https://doi.org/10.1016/j.respol.2022.104485

Wang, S., Abbas, J., Sial, M. S., Álvarez-Otero, S., & Cioca, L. (2022b). Achieving green innovation and sustainable development goals through green knowledge management: Moderating role of organizational green culture. Journal of Innovation & Knowledge, 7(4), 100272. https://doi.org/10.1016/j.jik.2022.100272

Wang, X., Cho, S.-H., & Scheller-Wolf, A. (2020). Green technology development and adoption: Competition, regulation, and uncertainty—A global game approach. Management Science, 67(1), 201-219. https://doi.org/10.1287/mnsc.2019.3538

Wang, X., Gan, Y., Zhou, S., & Wang, X. (2024). Digital technology adoption, absorptive capacity, CEO green experience and the quality of green innovation: Evidence from China. Finance Research Letters, 63, 105271. https://doi.org/10.1016/j.frl.2024.105271

Wang, X., & Zhong, X. (2024). Digital transformation and green innovation: Firm-level evidence from China. Frontiers in Environmental Science, 12, 1389255. https://doi.org/10.3389/fenvs.2024.1389255

Wang, Y., Lo, F., & Huarng, K. (2024). What shapes innovative firms' performance? A multi-level analysis. Journal of Innovation & Knowledge, 9(4), 100599. https://doi.org/10.1016/j.jik.2024.100599

Weber, K., & Quicker, P. (2018). Properties of biochar. Fuel, 217, 240–261. https://doi.org/10.1016/j.fuel.2017.12.054

Weigelt, C., & Shittu, E. (2015). Competition, Regulatory Policy, and Firms' Resource Investments: The Case of Renewable Energy Technologies. Academy of Management Journal, 59(2). https://doi.org/10.5465/amj.2013.0661

Wu, B., Monfort, A., Jin, C., & Shen, X. (2021). Substantial response or impression management? Compliance strategies for sustainable development responsibility in family firms. Technological Forecasting and Social Change, 174, 121214. https://doi.org/10.1016/j.techfore.2021.121214

Wu, H., Lin, J., & Wu, H. (2022). Investigating the real effect of China's patent surge: New evidence from firm-level patent quality data. Journal of Economic Behavior & Organization, 204, 422-442. https://doi.org/10.1016/j.jebo.2022.10.004

Wu, Y., Li, X., Zhang, C. et al. The impact of government subsidies on technological innovation of new energy vehicle enterprises: from the perspective of industry chain. Environ Dev Sustain 26, 25589–25607 (2024). https://doi.org/10.1007/s10668-023-03697-w

Wu, Y., Wang, H., Wang, Z., Zhang, B., & Meyer, B. C. (2019). Knowledge Mapping Analysis of Rural Landscape Using CiteSpace. Sustainability, 12(1), 66. https://doi.org/10.3390/su12010066

Xia, D., Yu, Q., Gao, Q., & Cheng, G. (2017). Sustainable technology selection decision-making model for enterprise in supply chain: Based on a modified strategic balanced scorecard. Journal of Cleaner Production, 141, 1337-1348. https://doi.org/10.1016/j.jclepro.2016.09.083

Xia, D., Zhang, M., Yu, Q., & Tu, Y. (2019). Developing a framework to identify barriers of Green technology adoption for enterprises. Resources, Conservation and Recycling, 143, 99-110. https://doi.org/10.1016/j.resconrec.2018.12.022

Xie, R., & Teo, T. S. (2022). Green technology innovation, environmental externality, and the cleaner upgrading of industrial structure in China — Considering the moderating effect of environmental regulation. Technological Forecasting and Social Change, 184, 122020. https://doi.org/10.1016/j.techfore.2022.122020

Xie, X., Huo, J., & Zou, H. (2019). Green process innovation, green product innovation, and corporate financial performance: A content analysis method. Journal of Business Research, 101, 697-706. https://doi.org/10.1016/j.jbusres.2019.01.010

Xing, Y., & Wang, X. (2023). Precision Agriculture and Water Conservation Strategies for Sustainable Crop Production in Arid Regions. Plants, 13(22), 3184. https://doi.org/10.3390/plants13223184

Xu, A., Zhu, Y., & Wang, W. (2023). Micro green technology innovation effects of green finance pilot policy—From the perspectives of action points and green value. Journal of Business Research, 159, 113724. https://doi.org/10.1016/j.jbusres.2023.113724

Yaashikaa, P. R., Kumar, P. S., Varjani, S., & Saravanan, A. (2020). A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. Biotechnology Reports, 28, e00570. https://doi.org/10.1016/j.btre.2020.e00570

Yacob, P., Wong, L.S. and Khor, S.C. (2019), "An empirical investigation of green initiatives and environmental sustainability for manufacturing SMEs", Journal of Manufacturing Technology Management, Vol. 30 No. 1, pp. 2-25. https://doi.org/10.1108/JMTM-08-2017-0153

Yang, D., Lee, J., Song, N. C., Lee, S., Kim, S., Lee, S., & Choi, S. (2023). Patent analysis on green hydrogen technology for future promising technologies. International Journal of Hydrogen Energy, 48(83), 32241-32260. https://doi.org/10.1016/j.ijhydene.2023.04.317

Yang, W., Pan, Y., Ma, J., Yang, T., & Ke, X. (2020). Effects of allowance allocation rules on green technology investment and product pricing under the cap-and-trade mechanism. Energy Policy, 139, 111333. https://doi.org/10.1016/j.enpol.2020.111333

Yang, Z., Chen, H., Du, L., Lin, C., & Lu, W. (2021). How does alliance-based government-university-industry foster cleantech innovation in a green innovation ecosystem? Journal of Cleaner Production, 283, 124559. https://doi.org/10.1016/j.jclepro.2020.124559

Yang, Z., Liu, P., & Luo, L. (2024). How Does Environmental Regulation Affect Corporate Green Innovation: A Comparative Study between Voluntary and Mandatory Environmental Regulations. Journal of Comparative Policy Analysis: Research and Practice, 26(2), 130–158. https://doi.org/10.1080/13876988.2024.2328602

Ye, L. (2025). Digital economy and high-quality agricultural development. International Review of Economics & Finance, 99, 104028. https://doi.org/10.1016/j.iref.2025.104028

Yigitcanlar, T., & Kamruzzaman, M. (2015). Planning, Development and Management of Sustainable Cities: A Commentary from the Guest Editors. Sustainability, 7(11), Article 11. https://doi.org/10.3390/su71114677

Yin, R. K. (2015). Qualitative research from start to finish (2nd ed.). The Guilford Press.

Yong Qin, Zeshui Xu, Xinxin Wang, Marinko Škare (2022). Green energy adoption and its determinants: A bibliometric analysis. Renewable and Sustainable Energy Reviews, 153. https://doi.org/10.1016/j.rser.2021.111780

Yousaf, M. (2022). Labour productivity and firm performance: evidence from certified firms from the EFQM excellence model. Total Quality Management & Business Excellence, 34(3–4), 312–325. https://doi.org/10.1080/14783363.2022.2054319

Zhang, H., Zhang, X., Tan, H., & Tu, Y. (2024). Government subsidies, market competition and firms' technological innovation efficiency. International Review of Economics & Finance, 96, 103567. https://doi.org/10.1016/j.iref.2024.103567

Zhang, W., Zhang, M., Wu, S., & Liu, F. (2021b). A complex path model for low-carbon sustainable development of enterprise based on system dynamics. Journal of Cleaner Production, 321, 128934. https://doi.org/10.1016/j.jclepro.2021.128934

Zhang, Z., & Fujii, H. (2024). A Global Analysis of Patent Invention Strategies in Automotive Technologies for Environmental Sustainability. Sustainability, 17(2), 696. https://doi.org/10.3390/su17020696

Zhao, X., Guo, Y., & Mi, J. (2023). Value creation and value capture from patents: Theory and implications for patent strategies. Journal of Innovation & Knowledge, 8(3), 100397. https://doi.org/10.1016/j.jik.2023.100397

Zhao, X. and Pan, W. (2021). The characteristics and evolution of business model for green buildings: a bibliometric approach. Engineering Construction & Architectural Management, 29(10), 4241-4266. https://doi.org/10.1108/ecam-08-2020-0657

Zhao, Y., Tan, J., Fang, L., & Jiang, L. (2025). Leveraging gene editing to combat methane emissions in ruminant agriculture. Trends in Biotechnology. https://doi.org/10.1016/j.tibtech.2025.05.020

Zheng, X.-J., Chen, M., Wang, J.-F., Liu, Y., Liao, Y.-Q., & Liu, Y.-C. (2020). Assessment of Zeolite, Biochar, and Their Combination for Stabilization of Multimetal-Contaminated Soil. ACS Omega, 5(42), 27374–27382. https://doi.org/10.1021/acsomega.0c03710

Zhou, F., & Wang, X. (2022). The carbon emissions trading scheme and green technology innovation in China: A new structural economics perspective. Economic Analysis and Policy, 74, 365-381. https://doi.org/10.1016/j.eap.2022.03.007

Zhou, X., & Du, J. (2021). Does environmental regulation induce improved financial development for green technological innovation in China? Journal of Environmental Management, 300, 113685. https://doi.org/10.1016/j.jenvman.2021.113685

Zhu, K., Zhang, F., Wu, F., & Feng, Y. (2024). Governing innovation-driven development under state entrepreneurialism in China. Cities, 152, 105194. https://doi.org/10.1016/j.cities.2024.105194

Zhu, Y., Zhang, H., Siddik, A. B., Zheng, Y., & Sobhani, F. A. (2023). Understanding Corporate Green Competitive Advantage through Green Technology Adoption and Green Dynamic Capabilities: Does Green Product Innovation Matter? Systems, 11(9), 461. https://doi.org/10.3390/systems11090461

Zott, C., & Amit, R. (2010). Business Model Design: An Activity System Perspective. Long Range Planning, 43(2-3), 216-226. https://doi.org/10.1016/j.lrp.2009.07.004