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Lifecycle Dynamics of Agricultural Green Patents in China and the Global Context

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ABSTRACT: Agriculture is both a major source of greenhouse gas emissions and highly vulnerable to climate change. While green patents are widely used to track sustainability-oriented innovation, limited research examines how agricultural climate technologies evolve across their full patent lifecycle. This study analyzes agricultural climate-related patent families using Orbit Intelligence data until 2025. Although global patterns are mapped for context, the empirical focus centers on China, which dominates worldwide filings. Using CPC and IPC classifications to identify adaptation and mitigation technologies, we examine temporal dynamics, technological composition, institutional ownership, collaboration networks, legal status, and forward citation outcomes. Results show a strong predominance of adaptation-oriented, product-based technologies, particularly in soil management and irrigation, with limited representation of digital or service-oriented solutions. Within China, patenting exhibits a compressed innovation cycle: a sharp expansion in the mid-2010s followed by substantial attrition. Nearly two-thirds of patent families are inactive. Econometric evidence indicates that inactive patents receive significantly fewer forward citations, especially those owned by universities, suggesting weaker technological visibility and limited integration into cumulative innovation trajectories. By shifting attention from patent counts to patent lifecycles, this study highlights structural features of state-driven innovation systems and provides a foundation for future research on commercialization, institutional design and climate-oriented agricultural policy.

KEYWORDS: *Green patents; Agricultural innovation; Climate adaptation; Climate mitigation; Patent analysis*

1. INTRODUCTION

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 using a global dataset. While the scope of the data is worldwide, the empirical strategy deliberately adopts a China-centered analytical focus, using global temporal and geographical patterns primarily as contextual benchmarks. The core 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 within different innovation systems. Specifically, this paper makes three main contributions. First, it introduces a sector-specific patent analysis using a dual classification system to identify agricultural climate adaptation and mitigation technologies. Second, it incorporates legal status and co-assignment data to assess the longevity and collaborative nature of innovation at the patent-family level. Third, and most centrally, it evaluates how national innovation models, with particular emphasis on China's state-led strategy, align with long-term climate resilience goals, shedding light on the institutional structures that shape patenting behavior, commercialization potential, and technology diffusion. By situating China's patenting dynamics within the broader global landscape, this research offers critical insights for policymakers and managers. In particular, it informs the design of adaptation-oriented innovation policies in regions highly vulnerable to climate change, where technology transfer mechanisms and commercialization support are urgently needed to transform patented inventions into accessible, context-sensitive solutions.

While this study develops a China-centered analytical perspective and incorporates lifecycle indicators such as legal status and forward citations, its primary objective is to provide a structured empirical mapping of agricultural climate patent dynamics rather than a causal evaluation of individual policy instruments. By documenting technological orientation, institutional configurations, and retention outcomes, the study establishes a foundation upon which more granular and policy-specific investigations can be developed. In this sense, the analysis is intended to clarify structural patterns and tensions within the agricultural climate innovation system, thereby paving the way for subsequent research to explore causal mechanisms, regional heterogeneity, and commercialization pathways in greater depth.

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, clarifying the distinction between global contextual analyses and China-focused empirical investigation. The Results section first presents global temporal and geographical patterns, and then examines China’s patenting dynamics across assignee activity, technological focus, collaboration, and legal status. The Discussion interprets these findings through the lens of state-driven innovation systems and climate policy objectives, highlighting institutional dominance, adaptation–mitigation trade-offs, and commercialization challenges. Managerial implications are also outlined, emphasizing strategic considerations for policymakers, firms, and research institutions. Finally, the Conclusion summarizes the key insights, acknowledges study limitations, and suggests directions for future research.

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, with China representing the most prominent and policy-intensive example of a state-driven approach to green agricultural innovation, 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 and provides the conceptual lens through which China's agricultural climate patenting dynamics are examined in the empirical analysis. 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 descriptive patent counts, this study examines patent lifecycles, institutional origins, collaborative structures, and retention outcomes. This framework is applied to a global dataset but operationalized through a China-centered analysis, allowing us to assess how a state-driven innovation model shapes the development, protection, and abandonment of agricultural climate technologies.

3. METHODOLOGY

3.1. Data collection & scope

This study is based on patent families, which group together multiple patents protecting the same invention across jurisdictions and are used as the unit of analysis to avoid multiple counting. 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, 2025, 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. Accordingly, the analysis captures the observable stock and evolution of green patenting activity rather than the original timing of inventive events. The empirical strategy follows a two-step analytical design. First, the full global dataset is used to map overall temporal dynamics and geographical distribution of agricultural climate-related patenting activity. Second, the analysis progressively narrows its focus to China, which emerges endogenously from the global dataset as the dominant patenting actor. China is therefore not treated as one case among many, but as the primary empirical phenomenon, while non-Chinese patent families serve as a comparative benchmark rather than as co-equal analytical units.

China-focused analyses are based on a subset of patent families for which both the priority country and the publication country are China. This restriction ensures that the observed patenting activity reflects domestically generated and domestically protected innovation, excluding patents with offshore priority filings or purely strategic extensions to the Chinese market. This sub-sample definition allows for a more accurate assessment of China's state-driven innovation system and its institutional characteristics. Accordingly, the dataset is intentionally not rebalanced or weighted across countries, as the objective of the study is to observe real-world asymmetries in agricultural climate-related patenting activity rather than to construct a normalized cross-country comparison. Standardized data-cleaning procedures are applied uniformly across the dataset to ensure internal consistency, without altering its technological or geographical scope. As such, the prominence of specific countries, most notably China, reflects an empirical outcome of the data rather than a methodological artifact.

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 patent classification tools for large-scale patent-based research. Orbit has been extensively used across multiple disciplines to examine innovation trends, technological diffusion, and commercialization dynamics. For example, Da Silveira et al. (2021) employed Orbit to analyze agricultural machinery patents in Brazil, while Frisio & Ventura (2021) used it to track global innovation trends in plant-based vaccine production. The platform enables the integration of key analytical dimensions, including priority and application year trends, assignee activity, geographical distribution, and patent classification mapping, and has been applied in diverse contexts ranging from healthcare business methods (Da Veiga et al., 2024) to sustainability trends in aquaculture (Leal et al., 2025).

A key feature of Orbit is its legal status tracking, which distinguishes between active and inactive patents and allows for the assessment of patent retention, abandonment, and potential commercialization. This functionality is particularly relevant for evaluating whether green innovations remain confined to institutional research or are sustained over time. Orbit aggregates data from the European Patent Office's PATSTAT database together with direct information feeds from other major patent offices, establishing it as a standard tool for innovation research (Priore, 2024; Kadlec et al., 2023). As with all patent databases, limitations remain, including heterogeneous data coverage, reporting lags across jurisdictions, and differences in national legal frameworks and classification practices, as well as the fact that patent data capture only patented inventions and may reflect strategic choices between patenting and trade secrecy. These limitations are acknowledged in the interpretation of the results (Karataş et al., 2024).

3.2. Patent classification codes & search strategy

Patent classification schemes organize patent documents into standardized technological categories to enable systematic retrieval, mapping, and quantitative analysis. The International Patent Classification (IPC) is a hierarchical taxonomy used to assign patents to broad and nested technology fields and forms the basis of most patent analytics; its coverage includes most patent offices worldwide. The Cooperative Patent Classification (CPC), jointly developed by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO), extends IPC by providing much higher granularity, additional subdivisions, and more frequent documentation updates, which enhances the analytical resolution and timeliness of patent landscapes (Van Rijn & Timmis, 2023; Degroote & Held, 2018). Furthermore, Leydesdorff, Kogler, and Yan (2017) demonstrate how CPC supports more robust portfolio and statistical analysis compared to IPC due to its refined structure. In the context of climate and green technologies, the CPC includes cross-cutting classes (e.g., Y-tags) specifically designed to capture environmental innovations that might otherwise be scattered across unrelated technical silos in the traditional IPC. In this study, we use CPC Y02 codes to identify climate-relevant technologies and restrict our analysis to agricultural and soil-related fields using IPC/CPC classes in categories A01, C09K, and E02D.

Although IPC and CPC schemes are shared across major databases, their implementation varies due to differences in indexing depth, data cleaning protocols, and family grouping logics. To ensure data consistency this study utilizes Orbit Intelligence. A detailed comparison of patent databases, addressing the "Fampat" grouping logic and the rationale for selecting Orbit over other platforms, is provided in Appendix A.

To systematically identify agricultural climate adaptation and mitigation technologies, we constructed an advanced search query using International Patent Classification and Cooperative Patent Classification 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 < 2025-12-31))

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. This search query defines the global baseline dataset used throughout the study. It is intentionally designed to be technology-driven rather than country-specific, allowing major patenting actors to emerge endogenously from the data rather than being selected ex ante.

Building on this global query, China-focused analyses are conducted on a restricted subset of patent families identified by both priority country and publication country equal to China. This operational definition ensures that the China sub-sample reflects domestically generated inventions that are also protected within the Chinese patent system. The use of this restriction avoids conflating domestic innovation with patents that merely extend protection to the Chinese market through secondary filings.

Table 1 – CPC and IPC codes used in the Orbit search query. Source: Authors' elaboration.

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 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 methodological transparency and reproducibility, data management followed a structured and non-destructive protocol applied to the full global dataset extracted from Orbit Intelligence. The initial search query yielded 15,168 patent families filed up to 2025, representing the complete observable population of agricultural climate-related patenting activity identified through the classification strategy described above.

Data preparation was designed to preserve the original sample composition while ensuring internal consistency and replicability. First, patent families were defined using Orbit Intelligence’s Fampat logic, which consolidates multiple patent documents related to the same invention, such as priority filings, national applications, and granted patents, into a single family-level record. This procedure eliminates technical duplication arising from multi-jurisdictional filing strategies without excluding valid inventions. Second, assignee name standardization was performed through entity resolution procedures that harmonize spelling variants, transliterations, and organizational inconsistencies, preventing artificial inflation of actor counts. Third, legal status information was validated by mapping heterogeneous national legal event codes into two harmonized macro-categories, ALIVE and DEAD, providing an economically meaningful distinction for analyzing patent lifecycles and innovation persistence. These procedures did not result in the exclusion of patent families. Instead, they ensured a consistent analytical structure across the full population of 15,168 families. Within this dataset, missing values are limited and concentrated in non-core bibliographic fields. Specifically, 116 patent families lack assignee name information, and a single record is missing the application date. As a result, 15,051 patent families, corresponding to over 99 percent of the global sample, exhibit complete bibliographic and legal information. Core variables used in the empirical analysis, including patent family identifiers, publication year, forward citation counts, and legal status, are effectively complete for the entire dataset.

China-focused analyses are conducted on a sub-sample of 11,345 patent families identified by both priority country and publication country equal to China. This operational definition ensures that the Chinese sub-sample reflects domestically generated inventions that are also protected within the Chinese patent system. Importantly, the Chinese sub-sample was kept fully intact throughout all stages of data preparation, and no rebalancing or selective filtering was applied. Overall, data management emphasizes minimal intervention, ensuring that empirical results reflect observed innovation patterns rather than artifacts of data cleaning choices.

3.3. Patent analysis dimensions

The empirical analysis follows Orbit Intelligence's structured methodology from the "Analysis Module" and is organized along five analytical dimensions. Consistent with the two-step empirical design outlined above, selected dimensions are first examined on the full global dataset and subsequently analyzed in greater depth for the China-focused sub-sample. Specifically, the analysis covers:

1. Temporal trends: tracking publication years to identify innovation waves at the global level, followed by China-specific temporal and cohort-based analyses;
2. Geographical distribution: mapping patenting activity across countries in the global sample, with a focused comparison between China and non-China patent families;
3. Assignees and inventors: examining the institutional composition of patenting activity, with particular attention to the dominance of academic institutions and the structure of innovation actors within the Chinese system;
4. Technological landscape: categorizing patent families by broad and specialized technical domains to compare the technological focus of Chinese and non-Chinese innovations;
5. Patent lifecycle and legal status: assessing enforcement outcomes by distinguishing between active and inactive patent families, with specific emphasis on retention and abandonment patterns in China.

This structured approach enables a systematic assessment of global patenting activity while supporting an in-depth investigation of China's state-driven innovation model within the broader international landscape of agricultural climate adaptation and mitigation technologies.

3.4. Econometric strategy

To assess the effect of patent expiration on technological relevance, we analyze the forward citation outcomes of dead and alive patents (see section 4.5.2). Since citation data are non-negative, highly skewed, and characterized by a substantial mass of zeros, standard linear models are inappropriate. Therefore, our main specification relies on a hurdle model (Cameron & Trivedi, 2013), which distinguishes between two processes: the extensive margin (probability of receiving at least one citation) and the intensive margin (citation count conditional on being cited). The first stage uses a logit model for the binary outcome, while the second stage employs a truncated negative binomial distribution to account for overdispersion. This approach is particularly well-suited for innovation studies, where the determinants of being cited may differ from those driving citation intensity (Hall et al., 2005). All models include priority year fixed effects to control for truncation bias, cohort effects, and temporal shifts in citation practices (Guellec & van Pottelsberghe, 2007). Standard errors are clustered at the assignee level to account for within-organization correlation in inventive activity (Czarnitzki et al., 2011). As a robustness check, we also estimate a conventional negative binomial model. Consistency across specifications ensures that results are not driven by functional form assumptions or excess zeros, confirming that patent status is a robust predictor of technological impact (Bessen & Meurer, 2008).

4. RESULTS

4.1. Temporal trends: a global overview

The global evolution of patenting activity in agricultural climate adaptation and mitigation technologies shows a clear long-term expansion over the past three decades. Across priority, application, and publication year indicators, patent family counts remain relatively low and stable throughout the 1990s and early 2000s, followed by a gradual increase after the mid-2000s and a pronounced acceleration after 2010. This growth culminates around 2017, when patenting activity reaches its highest observed levels across all three temporal indicators. In the most recent years, counts appear lower, particularly for 2024 and 2025; however, these observations are affected by reporting lags and truncation effects inherent to patent databases and should therefore be interpreted with caution. Overall, the global temporal pattern is characterized by a prolonged phase of moderate activity, a sustained expansion during the 2010s, and a high-intensity plateau in the early 2020s. This global overview provides a contextual benchmark for the subsequent analysis, which examines how these aggregate trends are distributed across countries and institutional settings

4.1.1. Priority year

Figure 1 reports the distribution of agricultural climate-related patent families by first priority year over the period 1990–2025. Priority year captures the timing of the initial inventive act and therefore provides insight into when new technological ideas entered the patent system, independently of subsequent filing and publication lags. For most of the 1990s, patenting activity remains very limited, with annual counts fluctuating between approximately 40 and 60 patent families. A modest increase becomes visible in the early 2000s, though priority filings remain below 200 families per year until the mid-2000s, indicating a prolonged phase of low inventive intensity in agricultural climate technologies.

A clear structural break emerges after 2010. Priority filings increase sharply from fewer than 300 patent families in 2010 to more than 500 by 2015, signaling the beginning of a rapid expansion phase. This upward trajectory culminates in a pronounced peak in 2017, when 1,557 patent families record their first priority filing, representing the highest value observed in the entire time series. This peak reflects an intense wave of inventive activity concentrated within a short time window, consistent with the expansion of climate-oriented agricultural innovation policies and R&D incentives during the mid-2010s.

Following the 2017 peak, priority-year counts decline but remain elevated relative to pre-2010 levels. Between 2018 and 2022, annual priority filings consistently exceed 900 patent families, reaching 1,311 in 2022. More recent years show a marked decrease, with 869 priority filings in 2023, 733 in 2024, and 509 in 2025. Unlike publication-year trends, this decline is less affected by disclosure lags and likely reflects a genuine slowdown in new inventive activity rather than a data truncation artifact. Overall, the priority-year evidence depicted in Figure 1 identifies a three-phase pattern: a long period of low activity prior to 2010, a rapid expansion culminating in a sharp peak in 2017, and a subsequent phase of contraction combined with sustained but lower inventive intensity in the early 2020s.

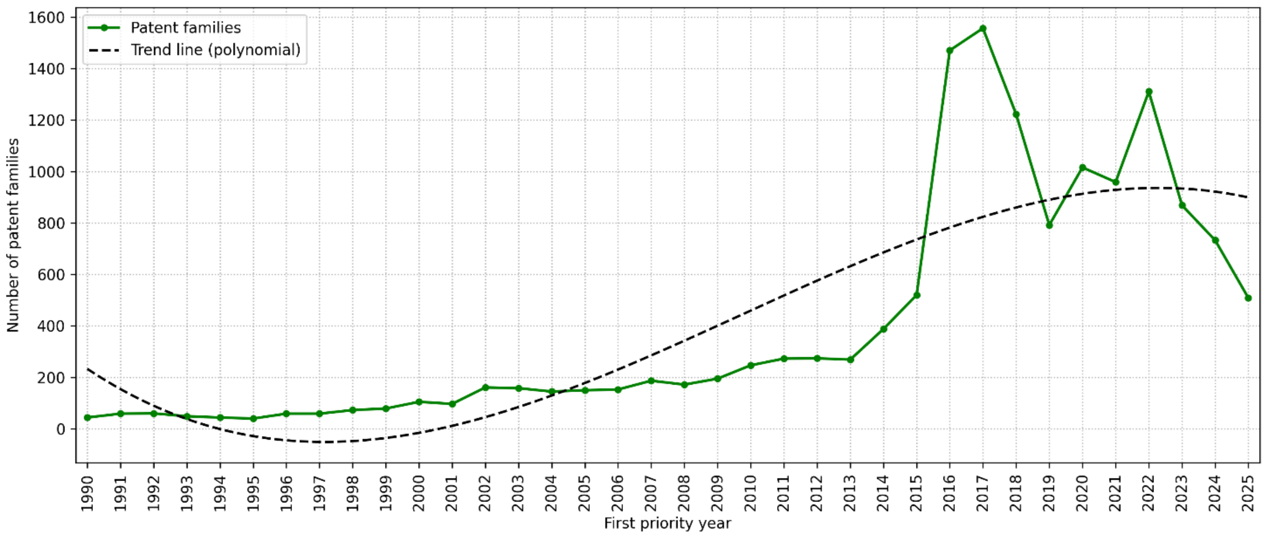

Figure 1 – First Priority Year. Source: Authors' elaboration on Orbit data.

4.1.2. Application and publication year

Patent application and publication years capture the progression of inventions from initial filing to formal legal processing and public disclosure. While closely related to priority filings, these stages typically exhibit short temporal lags reflecting examination procedures and disclosure rules. Analyzing application and publication years therefore provides insight into the consolidation and diffusion phases of agricultural climate-related innovation.

Consistent with the priority-year dynamics discussed above, application filings display a pronounced acceleration after 2010. In 2010, the dataset records 253 patent families by application year, increasing to 512 families in 2015. Application activity then rises sharply, peaking in 2017 with 1,569 patent families, the highest value observed in the entire time series. This peak closely mirrors the surge in priority filings and indicates a period in which a large share of inventions rapidly progressed from conception to formal application, likely supported by favorable policy incentives and increased R&D funding in climate-related agricultural technologies. Following the 2017 peak, application counts remain elevated but more volatile. Applications decline to 1,006 families in 2020, before rebounding to 1,335 families in 2022. More recent years show a clear downward trend, with 877 applications in 2023, 737 in 2024, and 512 in 2025. The decline observed after 2022 should be interpreted with caution, as later years are more likely to be affected by reporting lags and incomplete processing, particularly for the most recent application cohorts.

Publication-year trends largely mirror application dynamics, confirming the presence of a short but visible lag between filing and disclosure. In 2010, 197 patent families are recorded by publication year, increasing to 398 in 2015. Publications reach their maximum in 2017 with 1,482 families, closely aligned with the peak in applications and priorities. This concentration confirms that the mid-2010s represent the height of innovation disclosure in agricultural climate technologies. After 2017, publication activity remains substantial, with 921 families in 2020 and a renewed increase to 1,305 families in 2022. Publications remain comparatively high in 2023 (1,147 families) before declining sharply in 2024 (564 families). The apparent rebound to 921 publications in 2025 reflects the delayed disclosure of applications filed in earlier years and should not be interpreted as a renewed surge in inventive activity.

Taken together, application and publication trends reinforce the three-phase temporal structure identified in priority filings: a prolonged period of low activity prior to 2010, a rapid expansion culminating in 2017, and a subsequent phase of stabilization followed by decline in the most recent years. Importantly, the persistence of high application and publication counts after the priority peak indicates that a substantial share of innovations initiated during the mid-2010s continued to move through the patent system, even as new inventive activity began to slow.

4.2. Geographical distribution of green innovation in agriculture

The geographical distribution of patent families provides insight into where agricultural climate-related innovations originate, where they are disclosed, and where inventors choose to maintain legal protection. Building on the temporal dynamics described in Section 4.1, this section examines the spatial structure of green innovation using priority, publication, and protection country information derived from the global patent family dataset covering filings up to 2025. Consistent with the two-step empirical strategy outlined in the methodology, global patterns are first described to establish context, followed by a focused interpretation of China's role as the dominant patenting actor.

4.2.1. Priority country

The priority country identifies the jurisdiction in which a patent family was first filed and therefore captures the geographical origin of inventive activity. Figure 2 reports the distribution of patent families by priority country, while Figure 3 visualizes the same information through a spatial heatmap.

The results reveal a highly concentrated innovation landscape. China accounts for 11,447 patent families, representing by far the largest share of global priority filings in agricultural climate-related technologies. This volume is almost an order of magnitude larger than that of the second-ranked country, the United States, which records 1,235 patent families. A similar magnitude is observed for international filings through the World Intellectual Property Organization (1,227 families), followed closely by Japan (1,139 families) and South Korea (289 families). Beyond these leading actors, priority filings are distributed across a diverse but comparatively small group of countries, including the European Patent Office (EP), Germany, Russia, Australia, India, and several emerging economies. However, none of these jurisdictions individually exceed a few hundred priority filings. Overall, the priority-country distribution clearly establishes China as the primary source of inventive activity in agricultural climate technologies. This dominance reflects the scale and intensity of China's state-led innovation strategy and provides the empirical justification for treating China not as one case among many, but as the primary empirical focus of the analysis.; the observed asymmetry therefore reflects actual patenting outcomes rather than a methodological artifact.

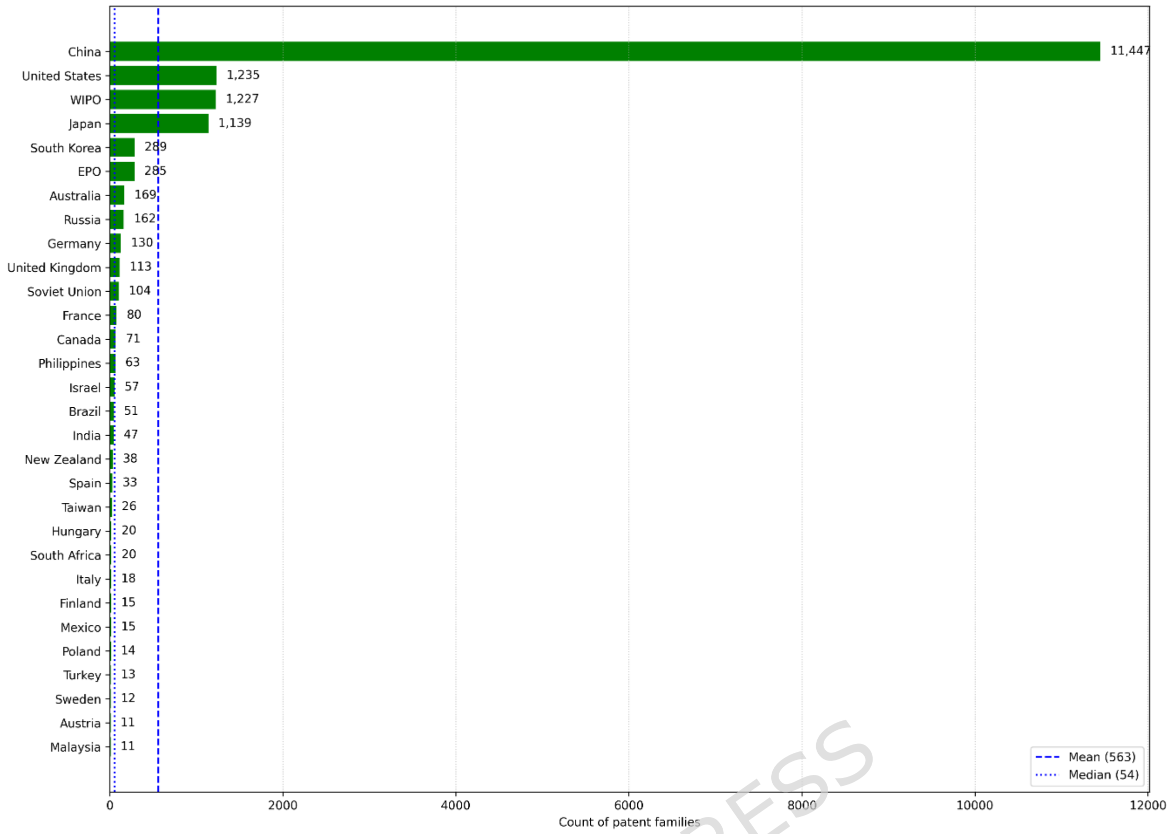

Figure 2 – Top 30 Priority Countries. Source: Authors' elaboration on Orbit data.

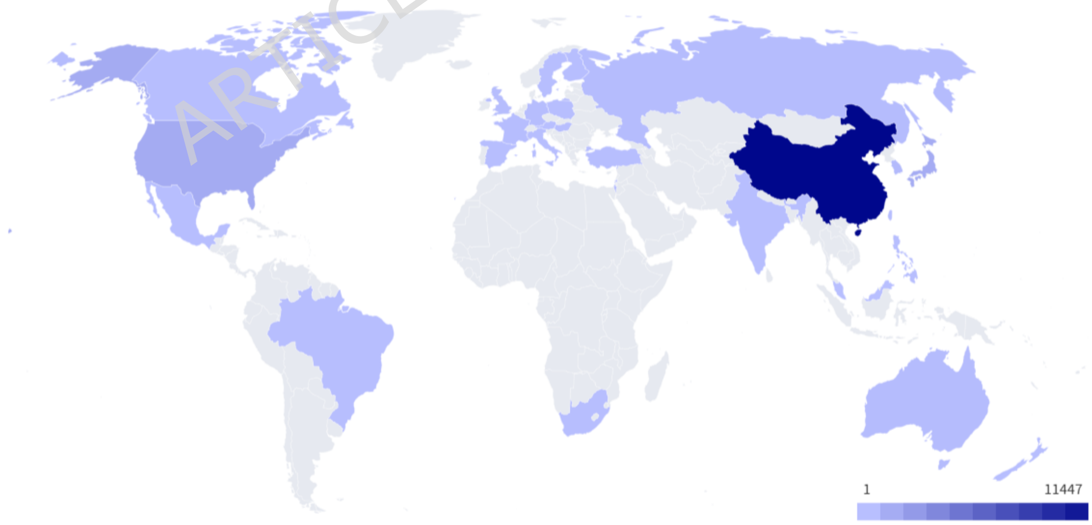

Figure 3 – Heat Map of the Top 30 Priority Countries. Source: Orbit.

4.2.2. Where are agricultural climate patents protected and published?

Patent publication and protection provide complementary perspectives on innovation dynamics, capturing respectively the diffusion of technological knowledge and the jurisdictions in which patent holders actively seek to enforce intellectual property rights. While publication reflects disclosure and potential knowledge spillovers, protection signals strategic expectations regarding market relevance and commercial value.

The publication-country distribution confirms and further amplifies the dominance observed in priority filings. China remains the central node of global knowledge disclosure, with 12,040 published patent families, far exceeding all other jurisdictions. Japan (1,605 families) and the United States (1,525 families) follow at a considerable distance, while international filings through the World Intellectual Property Organization account for 1,424 families, highlighting the role of the PCT route in disseminating agricultural climate technologies across multiple jurisdictions. The European Patent Office also emerges as a major publication venue (1,017 families), followed by Canada (784), Australia (779), Brazil (581), and South Korea (565). Overall, the publication landscape remains highly skewed, with China alone accounting for the majority of disclosed patent families, indicating both the scale of its inventive activity and the strong emphasis placed on formal disclosure within its innovation system. The protection-country distribution, however, reveals a markedly different pattern. Although China still ranks first, with 4,231 protected patent families, the gap between China and other jurisdictions narrows substantially when compared to priority and publication counts. The United States records 566 protected families, followed by the European Patent Office (366), Japan (331), Mexico (321), and Canada (317). A broader set of countries, including India (294), South Korea (237), Germany (220), Brazil (213), and Australia (205), also display significant protection activity. This more dispersed pattern suggests that firms and institutions selectively maintain patent rights in jurisdictions perceived as commercially or strategically relevant, rather than uniformly extending protection across all possible markets.

The contrast between publication and protection patterns is particularly informative in the Chinese case. While China dominates both priority and publication stages, the sharp reduction observed at the protection stage indicates that a substantial share of disclosed patents is not actively maintained through long-term legal enforcement. This divergence points to a patenting strategy characterized by high-volume filing and disclosure, but more limited downstream commitment to patent maintenance. In contrast, countries such as the United States, Japan, and several European jurisdictions display a higher relative balance between publication and protection, consistent with more selective and market-oriented intellectual property strategies. Taken together, the publication and protection evidence reinforces the view that China’s leadership in agricultural climate patenting is primarily driven by scale and policy-induced filing incentives, whereas other innovation systems emphasize strategic protection and enforcement. These differences in patenting behavior provide a critical backdrop for the subsequent analysis of legal status, abandonment, and institutional dynamics, particularly within China’s state-driven innovation model.

4.3. Top assignees: who leads in agricultural climate innovation?

From this section onward, the empirical analysis focuses exclusively on the China-only sub-sample, defined as patent families for which both the priority country and the publication country are China. This sub-sample comprises 11,345 patent families and represents the full population of domestically generated and domestically disclosed agricultural climate-related patents within the Chinese patent system.

In patent analysis, the assignee identifies the entity that holds the intellectual property rights and therefore captures how innovation activity is institutionally distributed. Figure 4 reports the top 30 assignees within this Chinese sub-sample, ranked by the number of patent families. The assignee distribution reveals a highly fragmented ownership structure. The most active assignee, the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, holds 50 patent families, followed by the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (47 families) and Shandong Sunway Garden Technology (46 families). Other leading assignees include Northwest Agriculture & Forestry University (42), Guangxi University (39), Beijing Forestry University (37), and South China Agricultural University (37). Across the top-30 ranking, patent family counts range from 15 to 50, with a mean of approximately 25 patent families per assignee. Even the most prolific institution accounts for less than 0.5 percent of the total 11,345 patent families, indicating that patent ownership is widely dispersed across a large number of organizations rather than concentrated in a small group of dominant actors.

The institutional composition of the top assignees is overwhelmingly public-sector driven. Universities and public research institutes dominate the ranking, particularly those affiliated with the Chinese Academy of Sciences, the Chinese Academy of Agricultural Sciences, and provincial agricultural and forestry research systems. These institutions are strongly represented in applied research areas such as soil restoration, water-saving irrigation, desertification control, ecological agriculture, and climate-resilient crop systems, all of which are central to China's agricultural and environmental policy agenda. Private firms are present but remain secondary in scale. Companies such as Shandong Sunway Garden Technology, Zhengzhou Sibian Technology, Qingdao Yuebang Agricultural Seed Industry, and Hefei Longbin Chemical Technology appear among the top assignees, typically holding between 19 and 46 patent families. Their patenting activity is comparable to that of individual universities or research institutes rather than indicating strong concentration of proprietary technological assets within the corporate sector.

Overall, the top-assignee analysis highlights three key features of China's agricultural climate innovation system. First, patent ownership is highly fragmented, with no single organization exerting structural dominance. Second, innovation activity is anchored primarily in public universities and state-affiliated research institutes, reflecting a research-driven model of technological development. Third, corporate participation exists but remains limited in scale and dispersed, suggesting that patenting in this domain is not concentrated within a small set of industrial champions. These characteristics of assignee structure provide an essential empirical foundation for interpreting subsequent analyses of collaboration patterns, legal status, and patent retention within the Chinese system.

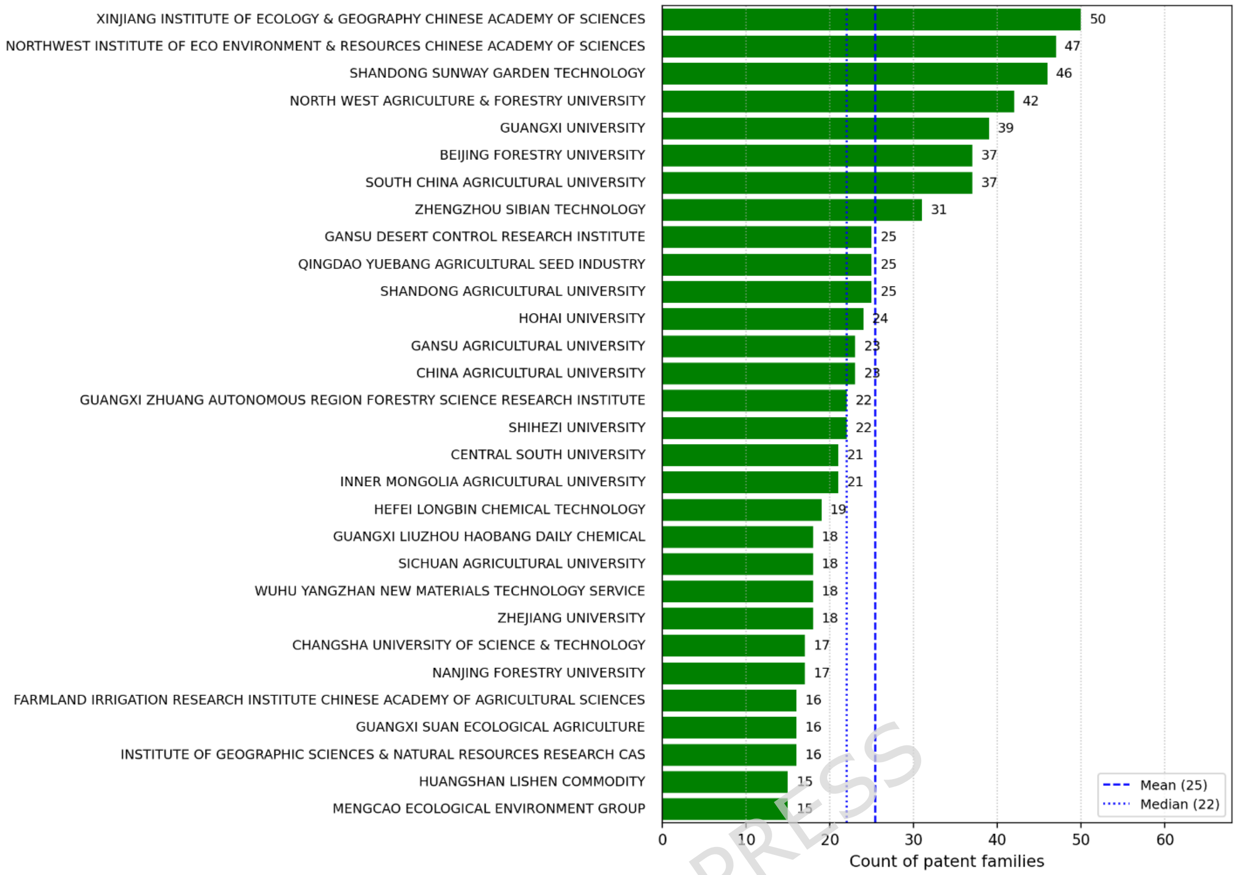

Figure 4 – Top 30 Assignees. Source: Authors' elaboration on Orbit data.

4.3.1. Temporal trends: when did these assignees emerge?

To link the assignee structure to the temporal dynamics discussed in Section 4.1, this subsection examines when the top 30 Chinese assignees emerged within the patenting trajectory of agricultural climate technologies, as pictured in Figure 5. A clear and consistent temporal pattern emerges. Virtually none of the top 30 assignees exhibit patenting activity before the early 2000s, and for most of them, systematic patenting begins only after 2010. Early sporadic filings are observed for a limited number of public research institutions, such as Beijing Forestry University, Xinjiang Institute of Ecology and Geography, and Northwest Agriculture & Forestry University, but these remain isolated and low in volume. The decisive structural break occurs in the mid-2010s, closely aligning with the aggregate surge in patenting activity identified in Section 4.1. For many assignees, patenting activity is heavily concentrated in a short and intense window between 2015 and 2022.

Several organizations display abrupt entry patterns characterized by a single-year or two-year burst of filings. For example, Shandong Sunway Garden Technology, Zhengzhou Sibian Technology, Qingdao Yuebang Agricultural Seed Industry, Hefei Longbin Chemical Technology, and Guangxi S□an Ecological Agriculture concentrate nearly all of their patent families in a single year, typically 2016 or 2017. Public universities and research institutes show a more gradual and persistent accumulation of patent families over time. Institutions such as Xinjiang Institute of Ecology and Geography (CAS), Northwest Institute of Eco-Environment and Resources, South China Agricultural University, Beijing Forestry University, and Northwest Agriculture & Forestry University exhibit repeated filings across multiple consecutive years, particularly from 2015 onward, indicating sustained participation in the innovation system rather than opportunistic patenting.

Overall, the temporal emergence of the top assignees confirms that leadership within China’s agricultural climate patent landscape is a relatively recent phenomenon. The dominance of these institutions is not the result of long-term cumulative advantage since the 1990s, but rather of rapid scaling during the same period in which aggregate patenting peaked nationally. This tight synchronization between assignee emergence and the mid-2010s patenting boom reinforces the interpretation of China’s agricultural climate innovation as a policy-driven and time-compressed innovation wave, rather than a slow, path-dependent accumulation of technological leadership.

Figure 5 – Top 30 Assignees 1990-2025. Source: Authors’ elaboration on Orbit data.

4.3.2. Co-assignment trends

This section examines collaboration patterns among patent assignees within the China-focused subsample. Collaboration is identified through co-assignment, indicating joint ownership of patent families by two or more institutions.

Figure 6 visualizes the assignee collaboration network after applying minimum thresholds to ensure analytical readability. Only assignees with at least 10 patent families and collaboration links based on a minimum of two co-assigned patent families are displayed. Under these conditions, the resulting network is sparse and fragmented, indicating a limited incidence of co-assignment among leading Chinese innovators in agricultural climate technologies.

The collaborations that do emerge are highly localized and institutionally homogeneous. A first identifiable cluster involves institutes affiliated with the Chinese

Academy of Sciences, including the Xinjiang Institute of Ecology & Geography, the Northwest Institute of Eco-Environment & Resources, and the Institute of Geographic Sciences & Natural Resources Research. These linkages are concentrated in north-western China and reflect coordinated research activity in arid and semi-arid environments, where ecological restoration, soil management, and climate adaptation represent shared scientific priorities. A second, weaker set of connections links regional agricultural universities operating within the same macro-regions, such as North West Agriculture & Forestry University, Gansu Agricultural University, and Shihezi University. These collaborations remain limited in scope and do not extend beyond regional boundaries. A small number of additional links are observed among forestry-oriented institutions in southern China, including Beijing Forestry University and South China Agricultural University, but these ties are sporadic and do not form a cohesive network. Notably, the network does not exhibit any national-level hubs or bridging institutions. No assignee connects multiple regional clusters, and there is no evidence of dense inter-regional collaboration. Moreover, collaborations between universities and firms are largely absent, indicating that co-assignment in this domain is predominantly confined to public research institutions operating within geographically proximate areas.

Overall, the assignee collaboration network highlights a pattern of territorially segmented innovation, where joint patenting activity mirrors regional ecological challenges rather than a nationally integrated collaborative structure. While patenting activity in agricultural climate technologies is highly concentrated in China, co-assignment remains limited and localized, suggesting that innovation efforts are coordinated primarily at the regional and institutional level rather than through broad, system-wide collaboration.

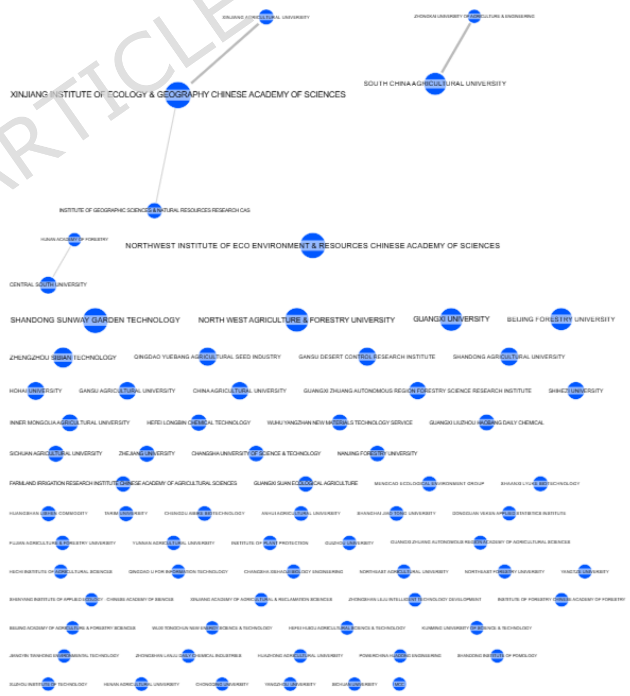

Figure 6 – Assignee Collaborations. Source: Orbit.

4.4. Technological trends: what types of innovations are being patented?

This section analyzes the technological composition of agricultural climate-related patents within the China-only patent families, classified according to broad technology domains. The objective is to identify which technological areas dominate climate-related innovation and to assess the structural orientation of China's patenting activity in this field.

The distribution of patent families across technology domains reveals a strong concentration in engineering- and chemistry-intensive fields. The largest domain by a wide margin is Other Special Machines, which accounts for 6,493 patent families. This category includes specialized agricultural machinery, irrigation equipment, soil treatment devices, and climate-adaptive mechanical systems. Its dominance indicates that China's agricultural climate innovation is primarily hardware- and equipment-oriented, reflecting a strong emphasis on tangible, deployable technologies.

The second most prominent domain is Basic Materials Chemistry, with 5,217 patent families, followed by Civil Engineering with 3,652 families. Together, these domains highlight the central role of chemical inputs, soil amendments, fertilizers, stabilizing compounds, and infrastructure-related solutions in China's climate-oriented agricultural patenting. These technologies are closely linked to soil conditioning, erosion control, water management, and land restoration, which are key priorities in climate adaptation strategies. A second tier of domains includes Chemical Engineering (905 families) and Environmental Technology (468 families). These categories capture process-oriented innovations related to treatment methods, emissions reduction, waste valorization, and environmental remediation. While substantial in absolute terms, their scale remains significantly smaller than that of core mechanical and materials-based domains.

By contrast, digital and information-related domains play a marginal role. Computer Technology accounts for only 44 patent families, IT Methods for Management for 75 families, Digital Communication for 18 families, and Telecommunications for 33 families. Similarly, Control and Measurement technologies jointly account for 156 families. This limited presence suggests that digital, data-driven, and software-based solutions are weakly represented in the patent landscape of agricultural climate technologies in China.

Life-science-oriented domains, including Biotechnology (102 families), Pharmaceuticals (256 families), and Food Chemistry (235 families), also represent a relatively small share of the total portfolio. Their lower weight indicates that biological and genetic approaches to climate adaptation and mitigation remain secondary compared to engineering-based solutions.

Overall, the technological domain analysis reveals a structurally unbalanced innovation profile, heavily skewed toward mechanical, chemical, and civil-engineering technologies. This pattern is consistent with an innovation system that prioritizes codifiable, infrastructure-intensive, and product-based solutions, while comparatively underinvesting in digital, systemic, and service-oriented technologies. These findings provide important context for interpreting subsequent results on patent lifecycles and legal status, as different technological domains exhibit inherently different commercialization dynamics and retention incentives.

4.4.1. Conceptual orientation of technological activity among leading Chinese assignees

To further qualify the technological domain analysis, this section examines the conceptual focus of patenting activity among the top 30 Chinese assignees, based on recurring technological concepts extracted from patent families. This allows a more granular interpretation of how dominant technology domains translate into concrete problem-oriented innovation strategies, as displayed in Figure 7.

Across leading institutions, the most pervasive concepts are ground and soil-related technologies, irrigation systems, and planting practices, confirming that China's agricultural climate innovation is strongly centered on land-based adaptation rather than downstream or digital solutions. For instance, the Xinjiang Institute of Ecology and Geography, the single largest assignee, shows a pronounced emphasis on ground (30 occurrences), irrigation (23), and planting (21), reflecting its focus on soil management, desertification control, and water-scarce agro-ecosystems in arid regions. A similar pattern is observed among other CAS-affiliated institutes. The Northwest Institute of Eco-Environment and Resources concentrates on ground, irrigation, and rainwater concepts, alongside a non-negligible presence of contamination-related technologies, indicating an integrated approach to land restoration and environmental remediation. Universities with a strong agro-environmental orientation, such as North West Agriculture and Forestry University, China Agricultural University, and Gansu Agricultural University, display balanced portfolios combining irrigation, planting, ground, and insect pest control, consistent with applied agronomic research targeting climate resilience.

Private firms, by contrast, exhibit narrower and more input-specific conceptual profiles. Shandong Sunway Garden Technology shows high concentrations in irrigation (23), pesticides (14), and insect pest control (10), pointing to a product-oriented strategy focused on deployable agro-technologies. Similarly, Zhengzhou Sibian Technology and Qingdao Yuebang Agricultural Seed Industry are heavily specialized in raw materials, pesticides, and contamination-related concepts, suggesting a chemical-input and formulation-driven innovation model rather than systemic adaptation solutions.

Water-related concepts cut across nearly all major assignees but with different emphases. While irrigation dominates most portfolios, rainwater and water storage concepts are particularly prominent in institutions such as Hohai University and Nanjing Forestry University, reflecting expertise in hydrology, water engineering, and infrastructure-based adaptation. The Farmland Irrigation Research Institute stands out for its strong focus on irrigation and water pump technologies, reinforcing the centrality of mechanical water management solutions in China's climate-oriented agricultural innovation system.

Notably, concepts associated with digital monitoring, sensing, or data-driven decision support are largely absent across the top assignees. Even where environmental or contamination-related technologies appear, they are predominantly framed in chemical or engineering terms rather than information-based control systems. This conceptual structure mirrors the technological-domain results and confirms a broader pattern: innovation efforts prioritize physical control of natural processes (soil, water, pests) through machinery, chemicals, and infrastructure, rather than through digital coordination or service-based solutions.

Overall, the concept-level analysis reinforces the view that China's agricultural climate innovation is problem-driven but technologically conservative, centered on tangible interventions in land and water systems. This orientation aligns with state priorities related to food security, land stability, and environmental control, while also helping to explain the dominance of mechanical and chemical domains observed at the aggregate level.

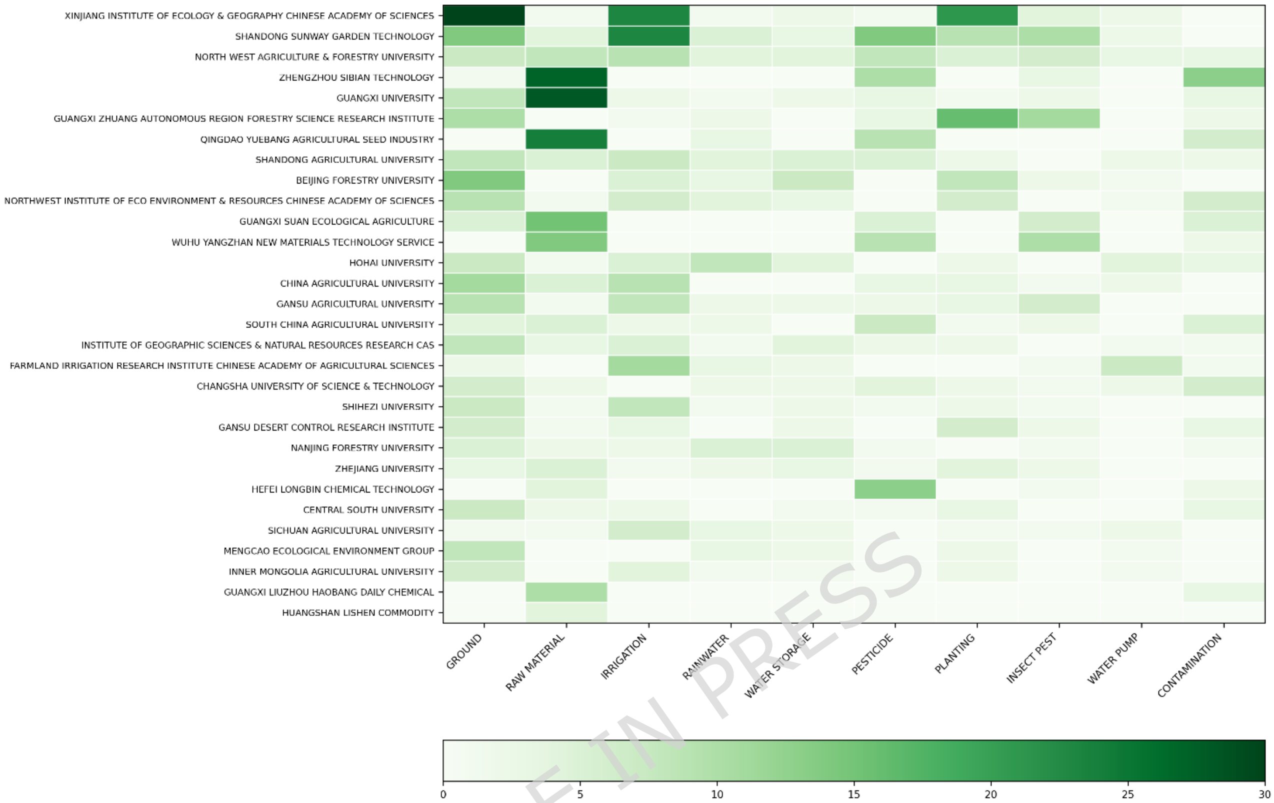

Figure 7 – Concept intensity across top 30 assignees. Source: Authors' elaboration on Orbit data.

4.5. Legal status: are agricultural climate patents being maintained?

This section examines the legal state and legal status of agricultural climate-related patent families within the Chinese sub-sample. The analysis of legal outcomes provides insight into the persistence, abandonment, and enforceability of patented technologies, offering an indirect measure of their economic relevance and institutional sustainability. Figure 8 reports the distribution of patent families by legal state, distinguishing between patents that remain active within the intellectual property system (ALIVE) and those that are no longer in force (DEAD). The results reveal a strongly asymmetric pattern. 7,365 patent families (64.9%) are classified as DEAD, while only 3,989 families (35.1%) remain ALIVE. This indicates that nearly two-thirds of agricultural climate patents filed and published in China are no longer legally active, pointing to a high rate of attrition within the patent stock.

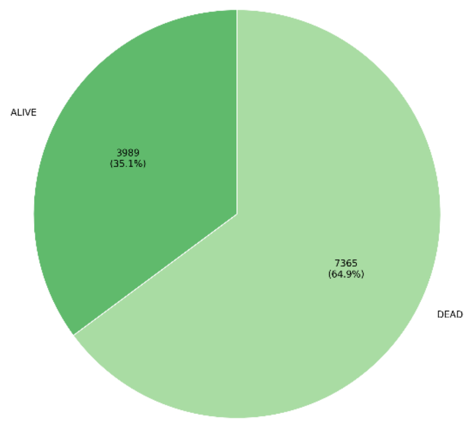

Figure 8 – Legal State. Source: Authors' elaboration on Orbit data.

To unpack this pattern in greater detail, Table 2 presents a breakdown by legal status, disaggregating patent families into granted, pending, lapsed, revoked, and expired categories. Among active patents, 2,913 families (25.7% of the total sample) are granted, representing inventions that are legally enforceable and actively maintained. An additional 1,076 families (9.5%) are pending, indicating technologies that are still under examination and may enter the active stock in the near future. Together, these categories constitute the ALIVE population reported in Figure 9. The DEAD category is dominated by patents that were abandoned before reaching or maintaining full legal protection. Lapsed patents account for 4,806 families (42.3%), representing the largest single status group in the dataset. These patents were discontinued due to non-payment of renewal fees, suggesting limited commercial prospects or strategic disengagement by assignees. A further 2,501 families (22.0%) are classified as revoked, typically reflecting invalidation during examination or post-grant challenges, often due to lack of novelty, inventive step, or conflicts with prior art. Only 58 families (0.5%) are expired, having reached the end of the statutory protection period, indicating that very few agricultural climate technologies in the Chinese sample have completed a full twenty-year patent lifecycle.

Table 2 – Legal Status breakdown. Source: Authors' elaboration.

Category	Subcategory	Patent Families	% of Total	Description
Alive Patents	Granted	2,913	25.7%	Actively maintained and legally enforceable, indicating commercial viability or strategic protection.
	Pending	1,076	9.5%	Still under examination, representing the next wave of potential agricultural climate innovations.
Dead Patents	Lapsed	4806	42.3%	Abandoned due to non-payment of maintenance fees, suggesting either a lack of commercial viability

				or strategic withdrawal by the assignees.
	Revoked	2,501	22%	Challenged and invalidated, typically due to prior art conflicts, lack of novelty, or opposition proceedings.
	Expired	58	0.5%	Reached the end of the 20-year protection term, meaning their technologies are now in the public domain and freely available for use.

Overall, the legal-state and legal-status distributions reveal a patent landscape characterized by high filing volumes but limited long-term retention. The predominance of lapsed and revoked patents suggests that a substantial share of agricultural climate inventions does not translate into sustained legal protection. Rather than reflecting technological obsolescence alone, this pattern is consistent with a system in which patenting activity is encouraged at early stages, while downstream selection mechanisms, through maintenance costs, examination outcomes, and strategic reassessment, lead to rapid contraction of the active patent stock. These dynamics are explored further in the discussion, where legal outcomes are interpreted in relation to China's state-driven innovation model and its implications for commercialization and technological diffusion.

4.5.1. Patent inactivity among top Chinese assignees

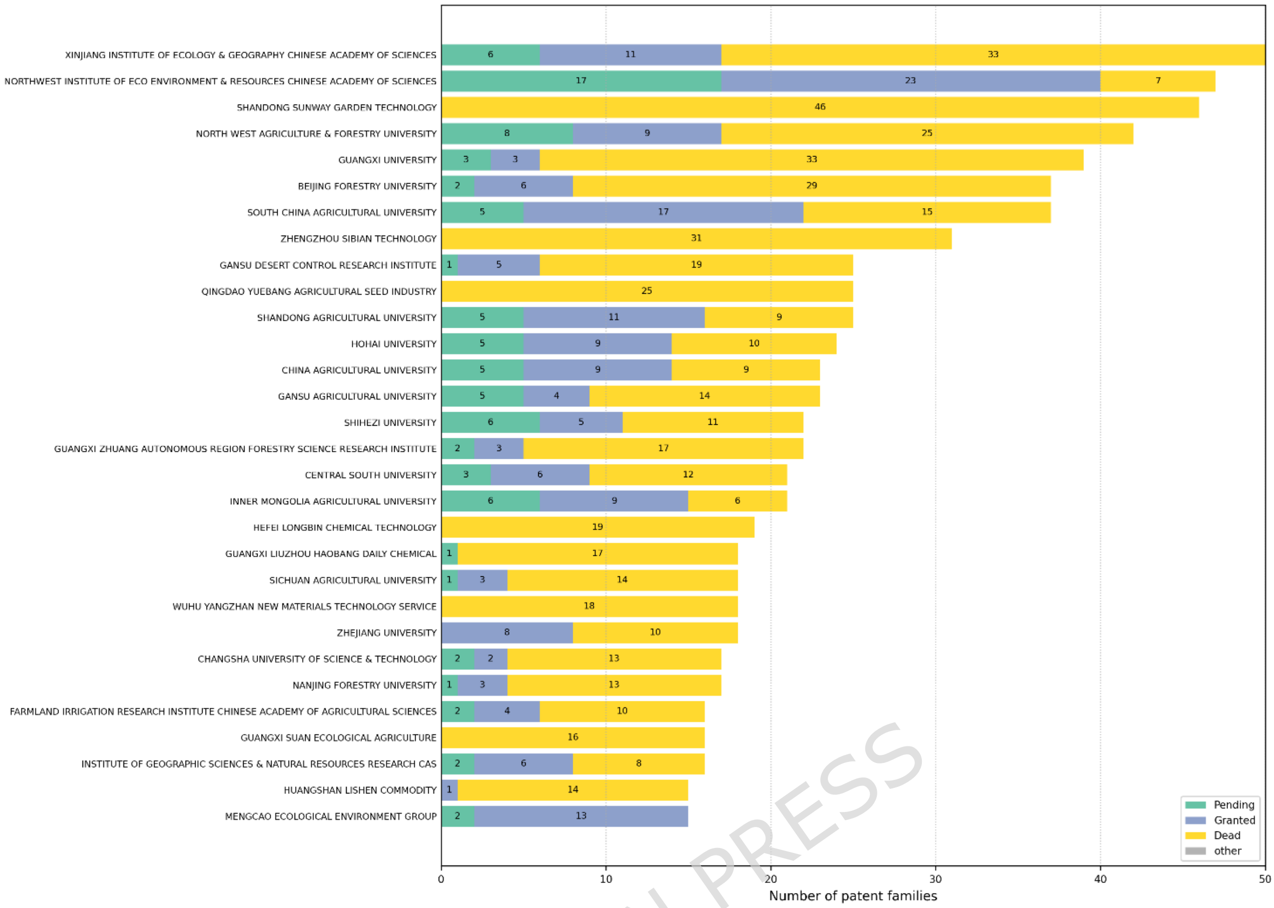

Figure 9 - Legal status composition of patent families by assignee. Source: Authors' elaboration on Orbit data.

Figure 9 reports the legal state composition of patent portfolios held by the top 30 Chinese assignees, covering a total of approximately 960 patent families within the China-only sample. The distribution reveals a pronounced dominance of inactive patents across virtually all major assignees, though with marked heterogeneity in the balance between granted, pending, and dead patents. Several assignees exhibit entirely inactive portfolios. Shandong Sunway Garden Technology holds 46 patent families, all classified as dead, with no granted or pending patents. A similar pattern is observed for Zhengzhou Sibian Technology (31 dead patents), Qingdao Yuebang Agricultural Seed Industry (25 dead patents), Hefei Longbin Chemical Technology (19 dead patents), Wuhu Yangzhan New Materials Technology Service (18 dead patents), and Guangxi Suan Ecological Agriculture (16 dead patents). In these cases, patenting activity appears concentrated in short, intense filing episodes followed by complete abandonment.

Among large public research institutions and universities, inactivity remains dominant but is accompanied by a non-negligible stock of active patents. The Xinjiang Institute of Ecology & Geography holds 33 dead patents, compared to 11 granted and 6 pending, implying that roughly two-thirds of its portfolio is inactive. The Northwest Institute of Eco-Environment & Resources shows a comparatively stronger retention profile, with 23 granted and 17 pending patents, against only 7 dead, making it one of the few top assignees where active patents clearly dominate. Most universities display an intermediate pattern. North West Agriculture & Forestry University holds 25 dead, 9 granted, and 8 pending patents, while Guangxi University records 33 dead patents versus only 6 active ones. Beijing Forestry University shows 29 dead, 6 granted, and 2 pending patents, again indicating a strong skew toward inactivity. By contrast, South China Agricultural University stands out with 22 active patents (17 granted and 5 pending) and 15 dead, representing one of the more balanced portfolios among academic institutions.

Overall, the legal status composition of top assignees highlights three empirical regularities. First, patent inactivity is pervasive even among the largest and most research-intensive organizations, confirming that abandonment is not confined to marginal or low-quality assignees. Second, universities and public research institutes systematically hold mixed portfolios, combining a limited stock of granted and pending patents with a much larger mass of inactive ones. Third, private firms among the top assignees tend to display more polarized strategies, with either fully inactive portfolios or highly concentrated bursts of patenting followed by rapid exit. These patterns provide the empirical backdrop for the subsequent analysis, which examines whether patent inactivity is associated with weaker technological relevance as measured by forward citation outcomes.

4.5.2. Patent inactivity and forward citations

Within the Chinese sample of 11,345 patent families, 2,322 patents (20.5%) are owned by universities or public research institutions, while the remaining 9,023 patents (79.5%) are held by non-university entities. Although university-owned patents account for a minority of the overall patent stock, these assignees are prominently represented among the largest patent holders, underscoring the central role of public research organizations within the Chinese innovation system. Building on the previous section, we examine whether patent inactivity is systematically associated with differences in technological relevance, proxied by forward citation counts. Table 3 reports estimates from hurdle models and negative binomial regressions, allowing us to distinguish between the extensive margin, whether a patent receives any forward citation, and the intensive margin, i.e. the number of citations conditional on being cited at least once.

Across the full Chinese sample (Mod. 1a), patent inactivity is robustly associated with weaker forward citation performance. Results from the binary component of the hurdle model indicate that inactive patent families exhibit a positive and statistically significant coefficient, implying substantially higher odds of receiving zero forward citations relative to active patents. Conditional on being cited, inactive patents receive significantly fewer forward citations, as indicated by the negative coefficient in the truncated count equation. Consistent with these findings, estimates from the unconditional negative binomial model (Mod. 2a) confirm that inactive patents are associated with a sizable reduction in expected citation counts.

When the analysis is restricted to university-owned patent families (Mod. 1b), the negative association between inactivity and forward citation outcomes becomes more pronounced, particularly along the extensive margin. Inactive university patents display a positive and highly significant coefficient in the binary hurdle equation, indicating a markedly higher likelihood of remaining uncited compared to active university patents. Conditional on being cited, the truncated count model points to a substantially lower citation intensity for inactive patents. The negative binomial estimates (Mod. 2b) corroborate this pattern, showing a strong reduction in expected citation counts for inactive university-owned patents. For non-university patent families (Mod. 1c), inactivity is likewise associated with poorer citation outcomes, although the magnitude of the effects is consistently smaller. Inactive non-university patents exhibit higher odds of receiving zero citations in the binary hurdle equation and lower citation intensity conditional on being cited. The unconditional negative binomial model (Mod. 2c) confirms a reduction in total expected citation counts for inactive patents in this group

Overall, the results reported in Table 3 document a robust and economically meaningful negative association between patent inactivity and forward citation outcomes across all specifications. The effects are systematically stronger for patents owned by universities and public research institutions, especially with respect to the probability of receiving any forward citation, suggesting that inactivity is particularly detrimental to the technological visibility of public-sector inventions.

Table 3 – Patent Expiration and Forward Citations: Hurdle and Negative Binomial Estimates

	Mod.1a Hurdle (all pat.)	Mod. 1b Hurdle (uni pat.)	Mod. 1c Hurdle (non uni pat.)	Mod.2a NegBin (all pat.)	Mod. 2b NegBin (uni pat.)	Mod. 2c NegBin (non uni pat.)
Parameters of the count model equation						
(Intercept)	0.680	1.247***	0.550	1.336***	1.602***	1.269***
	(0.593)	(0.115)	(0.612)	(0.336)	(0.077)	(0.338)
Dead Pat.	-0.522***	-0.529***	-0.476***	-0.420***	-0.503***	-0.353***
	(0.069)	(0.113)	(0.085)	(0.052)	(0.077)	(0.066)
Parameters of the binary hurdle equation						
(Intercept)	-0.726***	-0.505***	-0.817***			
	(0.036)	(0.067)	(0.042)			
Dead Pat.	1.183***	1.211***	1.228***			
	(0.046)	(0.091)	(0.053)			
Year (dummy)	Yes	Yes	Yes	Yes	Yes	Yes
Obs.	11345	2322	9023	11345	2322	9023
AIC	36818.5	7782.9	28982.1	34919.2	7165.1	27604.3
BIC	37133.9	7961.1	29280.5	35219.9	7331.9	27888.5
Log Lik	-18366.251	-3860.444	-14449.054	-17418.6	-3553.6	-13762.1

*Notes: Significance levels: *** p < 0.01, ** p < 0.05, * p < 0.10. The dependent variable is the number of forward citations. Columns 1a–1c report hurdle models that separately estimate (i) a zero-truncated negative binomial equation modeling the number of forward citations conditional on being cited at least once, and (ii) a binary equation modeling the probability of receiving zero versus positive forward citations. Columns 2a–2c report standard negative binomial models estimating unconditional citation counts. Columns 2a–2c report negative binomial regressions as a robustness check. In all specifications, the key regressor is a dead patent, an indicator equal to 1 for patents that are dead (expired/lapsed) and 0 for patents that are alive. Priority-year fixed effects are included in all models using year dummies constructed from the patent priority date (priority year). Standard errors are cluster-robust at the assignee level.*

5. DISCUSSION

5.1. Institutional dynamics and lifecycle patterns in China's agricultural climate innovation

This study was designed to move beyond descriptive mappings of green patenting activity by examining how agricultural climate innovations evolve over their full lifecycle, from filing and institutional ownership to retention, abandonment, and technological visibility. While the global patent landscape provides an important contextual benchmark (Section 4.1 and Section 4.2), the empirical evidence consistently identifies China as the dominant and analytically central case. The discussion therefore interprets the results through the lens of China's state-driven innovation system. Three interrelated insights emerge. First, the dominance of adaptation-oriented patents reflects institutional incentives and classification mechanisms rather than purely technological priorities. Second, China's agricultural climate patenting follows a compressed, policy-aligned and institutionally reinforced innovation cycle characterized by front-loaded filing and extensive ex post selection through abandonment. Third, patent inactivity is not neutral: it is systematically associated with weaker technological visibility, particularly for university-owned inventions. Together, these findings help clarify the nature of the innovation–policy disconnect in agricultural climate technologies.

5.1.1. Adaptation versus mitigation: technological orientation or institutional artifact?

The results reported in Sections 4.4 and 4.4.1 show a clear predominance of adaptation-oriented technologies within China's agricultural climate patent portfolio. Patents are heavily concentrated in domains related to soil management, irrigation systems, water control, and land restoration, as reflected both in the technological-domain analysis (Section 4.4) and in the concept-level mapping of leading assignees (Figure 7). By contrast, explicitly mitigation-oriented technologies, such as carbon sequestration, methane reduction, or low-emission input systems, are comparatively underrepresented.

At face value, this pattern could be interpreted as evidence that agricultural innovation naturally prioritizes adaptation over mitigation. However, the findings suggest a more nuanced interpretation. First, the distinction between adaptation and mitigation technologies is analytically useful but technologically imperfect. Many agricultural innovations, such as biochar, soil-conditioning practices, and precision input management, simultaneously enhance resilience while reducing emissions. As discussed in Section 3.2, the CPC Y02A and Y02P classifications capture the primary intended function of a technology rather than its full range of environmental effects. As a result, some dual-use technologies are conservatively coded as adaptation-focused, contributing to an apparent imbalance that partly reflects classification conventions rather than innovation priorities alone. Second, and more importantly, the adaptation bias appears to be institutionally shaped. The dominance of universities and public research institutes among Chinese assignees (Section 4.3; Figure 4) aligns with an innovation model that favors applied, engineering-based solutions addressing immediate environmental constraints, such as water scarcity, soil degradation, and desertification. These challenges are regionally salient and politically salient within China's agricultural policy agenda, making adaptation-oriented technologies more compatible with short-term research funding cycles and institutional performance metrics. In contrast, mitigation technologies often require systemic coordination and longer time horizons. They are also more dependent on market-based incentives, such as carbon pricing, which remain weak or absent in the agricultural sector. Taken together, these findings suggest that the observed dominance of adaptation-oriented patents is not simply a reflection of technological necessity, but an outcome of how agricultural innovation is institutionally organized, evaluated, and incentivized. This distinction matters for policy interpretation, as it implies that current innovation portfolios may be structurally biased toward reactive resilience solutions, potentially at the expense of longer-term decarbonization strategies.

Patent-based evidence does not capture all forms of innovation equally, as different innovation typologies exhibit markedly different propensities for patenting (OECD/Eurostat, 2018). In agriculture, product-oriented technologies, such as crop varieties, irrigation equipment, soil-conditioning inputs, or mechanical treatment systems, are generally more amenable to patent protection because their technical features are embodied in tangible artefacts and can be clearly specified in legal claims. This structural characteristic aligns closely with the technological profile observed in Section 4.4, where mechanical and materials-based domains dominate China’s agricultural climate patent portfolio. By contrast, many process innovations, including agronomic practices, soil management protocols, cultivation techniques, or emission-reduction strategies, while in principle patentable, are often protected through tacit knowledge, learning-by-doing, or trade secrecy. In open-field agricultural settings, monitoring unauthorized use of such practices is difficult, reducing the incentives to rely on formal intellectual property protection. Service-based and organizational innovations, such as advisory systems, decision-support platforms, insurance mechanisms, or farm-management models, are even less likely to be captured by patent statistics, particularly in contexts where legal barriers to software or business-method patenting apply or where innovation resides primarily in organizational routines rather than technical artefacts. Accordingly, patent data should be interpreted as an indicator of codified, technologically embodied innovation rather than as a comprehensive measure of all climate-related innovation in agriculture. This patentability bias helps explain the dominance of engineering- and input-intensive solutions documented in Section 4.4 and Figure 7, as well as the relatively marginal presence of digital and service-oriented technologies. In state-driven innovation systems such as China’s, where institutional incentives explicitly reward formalized and countable outputs, this bias is likely to be amplified. From an analytical perspective, this feature is therefore not merely a limitation but an integral characteristic of the innovation system under investigation, shedding light on how policy incentives shape the types of agricultural climate technologies that are developed, protected, and ultimately retained over time.

5.1.2. Compressed innovation cycles and ex post selection in China’s patenting system

The temporal patterns documented in Section 4.1 reveal a highly compressed innovation cycle in China’s agricultural climate patenting. Patent families surge rapidly during the mid-2010s, peaking around 2017 across priority, application, and publication years (Figure 1), followed by a sustained decline in new inventive activity. This concentration contrasts with the more gradual and persistent patenting trajectories observed in other major innovation systems and suggests that China’s leadership in agricultural climate patents is the result of a time-bound policy-driven expansion rather than long-term cumulative technological dominance. Rather than interpreting this pattern as a simple boom-and-bust cycle, the legal-status evidence in Section 4.5 indicates that China’s patenting system operates through a form of delayed selection. High filing volumes are followed by extensive attrition, with nearly two-thirds of patent families classified as inactive (Figure 8; Table 2). The predominance of lapsed and revoked patents, combined with the very small share of patents reaching full statutory expiration, indicates that most inventions are screened out relatively early in their lifecycle.

This pattern is consistent with an innovation model in which patent filing is incentivized ex ante, often as an output metric tied to funding, evaluation, or institutional prestige, while economic relevance is assessed ex post through maintenance decisions and examination outcomes. In this sense, abandonment does not simply signal failure, but functions as a selection mechanism that concentrates legal protection on a smaller subset of inventions deemed worth sustaining. However, the scale of attrition observed in China suggests that this selection occurs late and at considerable systemic cost, raising questions about the efficiency of front-loaded patenting strategies in resource-constrained policy environments.

5.1.3. Institutional dominance, weak transfer, and why patent inactivity matters

A distinctive feature of China's agricultural climate patent landscape is the overwhelming dominance of universities and public research institutes among leading assignees (Section 4.3). While public-sector leadership in early-stage innovation is not inherently problematic, the results indicate that this institutional configuration has important implications for technology diffusion and persistence. Collaboration through co-assignment is sparse and geographically localized (Section 4.3.2; Figure 6), and partnerships between academic institutions and firms are notably rare. As a result, many patents appear to be generated within institutional silos rather than embedded in broader commercialization networks. The forward-citation analysis reported in Section 4.5.2 provides critical evidence on the consequences of this structure. Across all specifications, inactive patent families are significantly more likely to receive zero forward citations and, conditional on being cited, receive fewer citations than active patents (Table 3). Importantly, these effects are substantially stronger for university-owned patents than for those held by non-university assignees. This finding indicates that patent inactivity is not merely a legal or administrative outcome, but is systematically associated with reduced technological visibility and weaker integration into subsequent innovation trajectories.

These results address a key concern raised in the literature regarding whether abandoned patents nonetheless contribute to knowledge diffusion through informal channels. While such diffusion cannot be ruled out, the citation evidence suggests that inactivity is correlated with diminished recognition within the formal innovation system. In the case of public research institutions, abandonment appears to sever the link between research output and cumulative technological development, reinforcing the interpretation of many patents as short-lived institutional outputs rather than durable innovation assets.

Moreover, the limited incidence of co-assignment among Chinese assignees further reinforces this interpretation. As shown in Figure 6, collaboration networks are fragmented, regionally bounded, and largely confined to public-sector actors facing similar ecological challenges. The absence of national hubs or bridging institutions suggests that innovation remains territorially segmented rather than systemically integrated. From an innovation-systems perspective, this structure reduces opportunities for cross-regional learning, industrial scaling, and sustained patent maintenance. In contrast to innovation systems where co-assignment reflects shared investment and risk among universities and firms, the Chinese case suggests that patents are often owned by single institutions with limited incentives to internalize long-term value. This helps explain why abandonment is pervasive even among the most active assignees (Section 4.5.1; Figure 9) and why inactivity is closely linked to weaker citation outcomes. Fragmentation thus reinforces attrition, creating localized innovation traps in which research output accumulates rapidly but dissipates just as quickly.

5.2. Implications beyond China: conditional lessons for climate-vulnerable regions

Building directly on the empirical patterns observed in Sections 4.3, 4.5, and 4.5.2, the Chinese case provides conditional insights for climate-vulnerable innovation systems. While China represents an extreme case in terms of scale, institutional configuration, and state involvement, its experience provides analytically relevant lessons for climate-vulnerable regions beyond East Asia. These lessons should not be interpreted as prescriptive models, but as conditional insights regarding how institutional incentives shape the structure, durability, and visibility of agricultural climate innovation.

First, the Chinese case illustrates the risks associated with quantity-driven patent incentives. As shown in Section 4.5, high filing volumes combined with elevated abandonment rates generate impressive short-term innovation statistics but limited long-term technological persistence. For lower-income or resource-constrained countries, replicating such front-loaded patenting strategies would likely impose high fiscal and administrative costs without guaranteeing durable technological accumulation. The key insight is not that patenting is ineffective, but that innovation policy must extend beyond filing incentives to encompass retention, collaboration, and downstream deployment mechanisms. Second, the dominance of universities and public research institutes in China (Section 4.3) highlights both the strengths and limitations of state-centered innovation systems. Public institutions can mobilize rapid knowledge production in response to urgent climate challenges, particularly in adaptation-related domains. However, as the forward-citation results demonstrate (Section 4.5.2), weak integration with industry reduces the likelihood that inventions remain technologically visible and cumulative over time. For many countries in Sub-Saharan Africa, South Asia, and parts of Latin America, where public agricultural research institutions play a central role, this finding underscores the importance of building commercialization bridges rather than expanding patent output alone. Third, the patentability bias discussed in Section 4.1 has particular relevance for climate-vulnerable regions. Agricultural innovation in such contexts often takes the form of process-based, organizational, or community-driven solutions that are less amenable to formal intellectual property protection. Reliance on patent statistics as the primary indicator of innovation performance may therefore systematically undervalue locally embedded and practice-based adaptation strategies. Innovation metrics that incorporate extension systems, adoption rates, and field-level performance may be more appropriate complements to patent-based indicators in these settings.

At the same time, the high rate of patent expiration and lapse observed in China generates a growing body of publicly accessible technological knowledge. For latecomer innovation systems, this represents a strategic opportunity. Rather than investing heavily in duplicative R&D, governments and regional organizations could establish patent intelligence programs that identify relevant expired or abandoned technologies for adaptation to local agro-ecological conditions. In this sense, the Chinese case offers not only cautionary evidence about quantity-driven patenting, but also a dynamic knowledge reservoir that can be leveraged through second-mover strategies.

Overall, the transferability of China's experience depends on institutional capacity, market structure, and policy design. The central lesson is not that state-driven patenting is inherently inefficient, nor that market-driven systems are inherently superior. Rather, the evidence suggests that agricultural climate innovation systems are most effective when incentives are aligned across the full lifecycle of technological development, from research and patenting to maintenance, collaboration, diffusion, and sustained use. For climate-vulnerable regions seeking to accelerate resilience and mitigation, lifecycle-oriented innovation governance may be more consequential than patent volume per se.

5.3. Toward lifecycle-oriented agricultural innovation

The empirical evidence presented in this study suggests that the effectiveness of agricultural climate innovation systems cannot be evaluated solely by the volume of patents generated. Instead, innovation performance depends on how inventions are retained, connected, and translated into cumulative technological trajectories. Building on the lifecycle perspective developed in Sections 4.5 and 5.1, this section outlines implications for firms, research institutions, and policymakers seeking to strengthen the durability and systemic impact of agricultural climate technologies.

5.3.1. Managerial implications

For firms operating in agricultural inputs, biotechnology, irrigation systems, and climate-related technologies, the Chinese case reveals both risk and opportunity. The high share of inactive patent families (Section 4.5) indicates that a substantial proportion of inventions fail to remain legally protected or technologically visible over time. For established firms with commercialization capacity, this represents a strategic opportunity to identify, acquire, or adapt underutilized technologies, particularly those originating from universities or public research institutes. Expired or lapsed patents may contain technically viable solutions that were not sustained due to institutional misalignment rather than intrinsic technological weakness. At the same time, the forward-citation evidence (Section 4.5.2) demonstrates that patent inactivity is associated with significantly lower technological visibility, especially among university-owned patents. For private actors, this underscores the importance of early-stage engagement in collaborative research rather than ex post acquisition alone. Co-development agreements, joint patenting arrangements, and structured industry–university partnerships can help ensure that inventions are embedded within market-oriented innovation pathways from the outset, increasing the likelihood of maintenance, diffusion, and cumulative development. The technological composition of China's patent portfolio (Section 4.4) also suggests that innovation remains heavily concentrated in engineering- and input-intensive domains, with comparatively limited representation of digital, service-based, and system-integration solutions. Firms that integrate monitoring technologies, data analytics, or performance verification tools with physical adaptation technologies may therefore create differentiated value propositions. Hybrid innovation strategies, combining embodied technologies with digital infrastructures, may be particularly relevant in contexts where future climate policies increasingly require traceability and measurable environmental performance.

5.3.2. Implications for universities and public research institutions

The dominance of universities and public research institutes in China's agricultural climate patent landscape (Section 4.3) highlights the central role of public research in addressing climate-related agricultural challenges. However, the observed patterns of abandonment and limited citation visibility indicate that patent filing alone is insufficient as a measure of innovation impact. For research institutions, this suggests a need to recalibrate incentive structures. Rather than emphasizing patent counts as standalone performance metrics, evaluation systems could incorporate indicators related to patent maintenance duration, licensing agreements, co-assignment with industry, and documented downstream deployment. Strengthening technology transfer offices, fostering incubators linked to agricultural innovation, and encouraging longer-term industry partnerships may help align research outputs with sustained technological trajectories. Moreover, selective patenting strategies, prioritizing inventions with credible pathways to application, may be more effective than broad filing approaches. In state-driven systems where patents are easily incentivized, the absence of downstream filters can generate large portfolios with limited cumulative impact. Introducing lifecycle-oriented evaluation criteria may reduce attrition and improve knowledge persistence.

5.3.3. Implications for policymakers and innovation governance

For policymakers, particularly in climate-vulnerable regions, the Chinese case underscores the importance of aligning incentives across the entire innovation lifecycle. Front-loaded filing subsidies or patent-based evaluation metrics can rapidly expand patent output, but without parallel mechanisms supporting retention, collaboration, and deployment, such strategies risk generating high levels of attrition, as evidenced in Section 4.5.

Innovation policy in agriculture may therefore benefit from shifting from volume-based incentives toward durability-oriented instruments. These may include support for patent maintenance in strategically relevant domains, targeted funding for pilot deployment and scaling, and frameworks encouraging university–industry co-assignment. In sectors where mitigation technologies remain underrepresented, complementary policy instruments, such as carbon pricing, sustainability certification, or public procurement, may be necessary to create market signals that justify longer-term investment horizons. The patentability bias discussed in Section 5.1 also has policy implications. Because patent data primarily capture codified, product-oriented innovation, reliance on patent statistics as the sole indicator of climate innovation performance may undervalue process-based and organizational solutions. Policymakers should therefore complement patent indicators with adoption metrics, extension system performance, and field-level impact assessments to obtain a more comprehensive view of agricultural climate innovation.

Finally, the high share of expired and lapsed patents represents not only systemic inefficiency but also a potential knowledge resource. Governments and regional organizations could develop patent intelligence mechanisms to identify publicly available technologies suitable for local adaptation. For resource-constrained innovation systems, strategic absorption and contextual adaptation of such technologies may offer a cost-effective pathway to strengthening climate resilience without replicating high-volume patenting models.

Overall, the findings suggest that agricultural climate innovation systems are most effective when incentives are aligned across research, protection, collaboration, and deployment stages. Patent generation, retention, and technological visibility are interdependent processes rather than isolated events. Policies and managerial strategies that recognize this interdependence are more likely to produce durable, cumulative innovation trajectories capable of supporting both adaptation and mitigation goals.

6. CONCLUSION & LIMITATIONS

6.1. Main Findings and Contributions

This study examined agricultural climate innovation through a lifecycle-oriented patent analysis, integrating technological classification, institutional ownership, legal status, and forward citation indicators. While the dataset is global in scope, the empirical evidence identifies China as the dominant patenting actor, justifying the China-centered analytical focus adopted throughout the paper. Three core findings emerge. First, agricultural climate patenting is technologically concentrated in engineering- and input-based domains, with adaptation-oriented technologies prevailing over explicitly mitigation-focused ones. This pattern is observable both at the domain level and in the concept-level mapping of leading assignees. Second, China's agricultural climate innovation displays a temporally concentrated expansion phase followed by substantial attrition. Patent filings peaked in the mid-2010s, while legal status analysis shows that a majority of patent families are no longer active, indicating significant post-filing selection dynamics. Third, patent inactivity is systematically associated with weaker technological visibility. Inactive patents are significantly more likely to remain uncited and, conditional on citation, receive fewer forward citations, with stronger effects observed for university-owned patents.

By combining technological orientation, institutional structure, and lifecycle outcomes within a unified analytical framework, this study contributes a structured empirical mapping of agricultural climate patent dynamics and clarifies how innovation system configurations shape not only filing behavior but also retention and technological recognition over time.

6.2. Limitations

Several limitations define the analytical boundaries of this study. First, patent families are used as a proxy for technological innovation. While patent data provide structured, internationally comparable, and traceable information on codified inventions, they do not capture all forms of innovation equally. In agriculture, many climate-relevant innovations, asuch as agronomic practices, cultivation protocols, farm-management routines, advisory services, or inforl knowledge diffusion, may remain unpatented or protected through tacit knowledge and trade secrecy. Patent statistics therefore reflect formally codified and legally protected technological outputs rather than the full spectrum of climate-related innovation activities. As such, the findings should be interpreted as indicative of patterns in patent-based innovation, not as a comprehensive measure of agricultural transformation. Second, forward citations are employed as a proxy for technological visibility and integration into subsequent inventive activity. Although widely used in innovation research, citation counts do not directly measure commercialization success, farmer adoption, environmental effectiveness, or economic value. A patent may receive limited citations yet still have local practical relevance, while highly cited patents may not necessarily translate into widespread implementation. Citation-based evidence should therefore be interpreted as an indicator of formal knowledge diffusion within the patent system rather than as a direct measure of real-world impact.

Third, legal status indicators capture whether patents are maintained, lapsed, revoked, or expired, but they do not provide direct evidence of commercial exploitation. Abandonment may reflect low economic potential, strategic withdrawal, institutional incentives, or shifts in research priorities. Conversely, maintained patents are not guaranteed to generate market success. Legal status thus represents a proxy for strategic commitment to intellectual property protection, not a definitive measure of economic performance. Fourth, the temporal scope of the dataset introduces inherent truncation effects. While priority-year trends are less affected, application and publication-year counts for the most recent years (2024–2025) may be incomplete due to reporting lags and ongoing examination processes. Interpretation of recent declines in filing or publication activity should therefore remain cautious.

Fifth, the identification of adaptation and mitigation technologies relies on CPC and IPC classification schemes. Although internationally standardized, these coding systems assign patents based on primary intended function. Dual-purpose technologies may therefore be conservatively categorized, potentially understating overlaps between resilience-enhancing and emission-reducing innovations. Sixth, the empirical strategy adopts a China-centered analytical focus justified by China's empirical dominance in priority and publication counts. While global patterns are presented for contextualization, the study does not implement a fully symmetrical cross-country institutional comparison. The findings should therefore be interpreted primarily as an in-depth examination of a dominant state-driven innovation system rather than as a comprehensive comparative assessment of global agricultural climate innovation.

Finally, the empirical design is observational. Although temporal co-movements between patenting waves and policy cycles are documented, the study does not estimate causal policy effects. The results identify structural patterns and associations within the patent system but do not establish direct causal relationships between specific policy interventions and innovation outcomes. These limitations clarify the scope of the analysis while reinforcing its contribution as a structured, lifecycle-oriented mapping of agricultural climate patent dynamics. They also motivate the more granular and causal research directions outlined in the following section.

6.3. Future research directions

As anticipated in the Introduction, this study was conceived as a lifecycle-oriented mapping exercise designed to surface structural patterns, tensions, and blind spots within agricultural climate patenting. Rather than providing definitive causal claims, it establishes an empirical foundation upon which more targeted and theory-driven investigations can build. The patterns identified in the preceding sections suggest several directions for future research.

The temporal concentration of patent filings and the subsequent contraction of the active patent stock indicate the need for more explicit causal analysis of policy-innovation dynamics. Future studies could move beyond structural description by examining how specific policy instruments, funding regimes, or evaluation criteria influence not only filing intensity but also patent survival and technological persistence. Linking patent cohorts to identifiable policy phases would allow a clearer assessment of whether compressed innovation cycles are a structural feature of state-driven systems or the outcome of particular incentive configurations. The strong territorial clustering and limited co-assignment networks documented in Section 4.3.2 also point to the importance of subnational analysis. Provincial-level investigations could explore how regional institutional ecosystems shape collaboration intensity, retention behavior, and technological specialization. Such work would clarify whether the observed fragmentation reflects systemic constraints or localized governance structures.

In addition, the adaptation-mitigation imbalance identified in Sections 4.4 and 5.1 calls for more refined analytical tools capable of capturing dual-use technologies and cross-domain complementarities. Text-based semantic approaches, alternative classification strategies, or integration with emission-reduction performance indicators could provide a more nuanced understanding of how agricultural technologies simultaneously address resilience and decarbonization objectives. Another critical extension concerns commercialization and diffusion. While patent retention and forward citations offer proxies for technological visibility, they do not directly measure real-world adoption or economic impact. Integrating patent data with firm-level financial information, licensing records, venture capital flows, or agricultural uptake indicators would enable researchers to assess whether legally retained patents translate into scalable climate solutions or remain confined within institutional research systems. Finally, comparative research across other innovation systems, particularly in climate-vulnerable regions of the Global South, would help evaluate the generalizability of the patterns identified in the Chinese case. Understanding whether high-volume filing combined with rapid attrition represents a broader feature of policy-intensive green innovation would provide valuable guidance for countries seeking to design more sustainable intellectual property strategies.

By situating these research trajectories within the lifecycle perspective articulated at the outset of the paper, future work can move from structural mapping toward deeper institutional, economic, and environmental evaluation. In this sense, the present study provides not a final account of agricultural climate innovation dynamics, but a structured empirical starting point for more granular and impact-oriented inquiry.

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APPENDIX A

Patent databases that implement standardized classification systems such as IPC and CPC nonetheless differ substantially in how patent information is structured, consolidated, and prepared for analytical use. These differences are particularly relevant for large-scale quantitative patent landscape studies, where the unit of analysis is the patent family rather than the individual patent document, and where consistency across jurisdictions and time is essential for reliable inference. In the scientometric and innovation-economics literature, structured global databases such as PATSTAT (EPO Worldwide Patent Statistical Database) are widely recognized as reference sources for large-scale patent analysis due to their global coverage and standardized relational structure (Higham et al., 2021; Jefferson et al., 2017). However, PATSTAT primarily exposes patent records grouped through relatively simple family definitions (often based on shared priorities), which may lead to multiple records referring to the same underlying invention in contexts characterized by fragmented filing strategies. This limitation is particularly relevant in countries such as China, where incremental filings, utility models, and divisional applications are frequently used, increasing the risk of artificial inflation in document- or priority-based counts. Comparative research further shows that differences in database construction and coverage, such as those between PATSTAT and USPTO PatentsView, can result in substantial variation in patent counts, institutional representation, and longitudinal trends, even when identical classification codes are applied (Squicciarini et al., (2013). These findings highlight that database choice is not methodologically neutral and can materially affect empirical results. A comparative overview of the main patent databases discussed is provided in Table A1.

Table A1 – Comparison of the main patent databases

Database	Primary Purpose	Family Definition	Assignee Normalization	Legal Status Harmonization	Suitability for Large-Scale

					Quantitative Analysis
PATSTAT (EPO)	Statistical and econometric patent analysis	Simple / Priority-based families	Limited (requires extensive manual cleaning)	Raw national legal events	High, but requires significant user-side post-processing
USPTO PatentsView	U.S.-focused innovation analytics	Simple families	Partial (primarily U.S. entities)	Limited	Moderate (restricted by geographic scope)
Espacenet (EPO)	Exploratory search and prior-art investigation	Document-based / Simple families	None	Raw legal status data	Low for structured landscape analysis
PATENTSCOPE (WIPO)	Global patent search and documentation access	Document-based / Simple families	None	Raw legal status data	Low for structured landscape analysis
The Lens	Bibliometric and science–technology linkage	Mixed / Document-based	Limited	Limited	Moderate for exploratory and bibliometric studies
DWPI (Clarivate)	Document-level interpretation and patent review	Curated proprietary families	Partial	Partial	Moderate; requires alignment for CPC-based analysis
Orbit Intelligence (Questel)	Patent landscape and portfolio analytics	Fampat (family-per-invention)	Systematic entity resolution (Corporate Trees)	Fully harmonized analytical categories	High; designed for large-scale, reproducible analysis

Publicly accessible databases such as Espacenet (European Patent Office) and PATENTSCOPE (World Intellectual Property Organization) provide broad access to patent publications, family links, and full-text documents across jurisdictions. While indispensable for exploratory search and prior-art investigation, these platforms generally rely on document-based or simple family groupings and expose raw legal-status information, requiring extensive post-processing to support quantitative landscape analysis, particularly with respect to family consolidation, legal-status harmonization, and assignee normalization (de Rassenfosse et al., 2019; Jefferson et al., 2017). Similarly, The Lens integrates patent records with scholarly publications and citation networks and is increasingly used in bibliometric research to study science–technology linkages (Jefferson et al., 2017). However, its analytical focus is primarily exploratory and relational, and it lacks the degree of structured family consolidation and harmonized legal-status categorization required for reproducible, large-scale patent family–based analyses. Among commercial platforms, Derwent World Patents Index (DWPI) is well known for its editorially enhanced abstracts, standardized titles, and curated patent families, which are particularly valuable for document-level interpretation and legal analysis. Nevertheless, DWPI's proprietary classification layers and emphasis on document enrichment may require additional alignment when conducting CPC-based quantitative analyses that prioritize standardized technological taxonomies and lifecycle indicators.

In contrast, Orbit Intelligence was selected for its handling of patent families and portfolio analysis. Orbit integrates global patent data using its proprietary Fampat family grouping logic, which consolidates patents related to the same technical invention into a single family record. This "family-per-invention" approach goes beyond simple priority-based families and significantly reduces the risk of multiple counting, particularly in jurisdictions characterized by fragmented or strategic filing behaviour, such as China. A critical feature for the scope of this study is its systematic assignee entity resolution, including the normalization of Chinese institutional names and corporate hierarchies through structured corporate trees. This feature is crucial for analyses focusing on state-driven innovation systems, where universities, public research institutes, and state-owned enterprises often appear under multiple name variants, subsidiaries, or affiliated entities. Prior empirical studies relying on Orbit Intelligence have adopted these entity-resolution capabilities to conduct institutional- and assignee-level patent analyses across countries and sectors (e.g., Da Silveira et al., 2021; Frisio & Ventura, 2021). Without such normalization, analyses based on raw assignee names, as in PATSTAT or public databases, would require extensive manual cleaning and remain prone to classification errors.

Finally, Orbit Intelligence provides advanced legal-status harmonization, transforming hundreds of thousands of heterogeneous national legal event codes into standardized analytical categories (e.g., pending, granted, lapsed, expired). This architecture is particularly critical for the legal-status analysis conducted in this study, as it enables robust and comparable measurement of patent abandonment and retention rates across different patent offices, an essential dimension for interpreting the economic relevance and maturity of green technologies in the Chinese context. The analytical use of harmonized legal-status information to assess technological maturity and market relevance has been adopted in prior patent-based studies using Orbit Intelligence (e.g., Da Veiga et al., 2024; Leal et al., 2025).

In summary, while IPC and CPC classifications provide a common taxonomic foundation across patent databases, differences in family grouping logic, assignee normalization, and legal-status harmonization are analytically consequential. Given the study's objective to construct a family-level dataset of climate-relevant agricultural patents and analyse innovation dynamics in a state-driven system, the Fampat grouping logic was prioritized to mitigate the overestimation bias inherent in simple priority-based counts. This choice enhances cross-jurisdictional comparability and supports reproducible quantitative analysis, addressing well-documented sources of bias in large-scale patent studies.