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Review

The Transition of Postharvest Science Toward Predictive and AI-Driven Systems: A Bibliometric and Technological Review

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Abstract

This study presents a critical historical, bibliometric, and technological overview of the evolution of postharvest science, emphasizing the transition from classical physiology-based approaches to emerging predictive and technology-driven systems. Scientific production related to postharvest research was analyzed using the Scopus and Web of Science databases, while bibliometric mapping and co-occurrence networks were generated using VOSviewer to identify thematic trends, emerging research areas, and structural scientific clusters. In parallel, a technological foresight analysis was conducted through the Lens.org platform to investigate the temporal evolution of patent deposits, the geographical distribution of innovation, the leading institutional applicants, and the predominant technological domains according to the Cooperative Patent Classification (CPC). The results revealed a substantial global expansion of postharvest research over recent decades. This growth was accompanied by increasing technological diversification and stronger integration between scientific knowledge and intellectual property protection. The analysis also highlighted the progressive incorporation of advanced methodologies into postharvest science, including biochemical approaches, non-destructive technologies, artificial intelligence, predictive modeling, and digital tools for quality assessment and shelf-life management. Overall, the study demonstrates that postharvest science is undergoing a paradigmatic transition toward integrated, multidisciplinary, and data-driven systems aligned with current demands for sustainability, food security, innovation, and reduction of postharvest losses.

Keywords: postharvest science; bibliometric analysis; technological foresight; patents; artificial intelligence; predictive systems

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1. Introduction

Postharvest science plays a strategic role in modern food systems by preserving the physicochemical, nutritional, and sensory quality of fresh products between harvest and consumption. Reducing postharvest losses remains one of the major global challenges for food security and sustainability, particularly for highly perishable fruits and vegetables. It is estimated that approximately 30–40% of global fruit and vegetable production is lost throughout the supply chain due to inadequate handling, storage, transportation, and commercialization practices [1]. In Brazil, these losses may exceed 35% in highly perishable commodities, directly affecting producers' income, food availability, and the sustainability of agro-food systems [2].

Early studies were predominantly based on physicochemical quality evaluations and storage physiology. This methodological transition has enabled a more comprehensive

understanding of metabolic, physiological, and structural changes occurring in fruits and vegetables during storage and commercialization [3,4]. Advances in chromatographic techniques, biosensors, hyperspectral imaging, machine learning, and computational tools have progressively transformed the field, enabling more accurate, rapid, and non-invasive approaches for quality assessment and shelf-life prediction. More recently, deep learning, computer vision, digital twins, and multimodal sensing systems have emerged as promising tools for automated quality evaluation, defect detection, and predictive shelf-life modeling in horticultural products [5–7].

In parallel with these methodological transformations, scientific production in postharvest research has expanded substantially worldwide, driven by increasing demand for sustainable food systems, reduction of food waste, shelf-life extension, and higher quality standards in horticultural supply chains. Beyond its scientific relevance, the sector also has major economic importance. The global fruit and vegetable market exceeds US$ 1.5 trillion annually and represents a major source of employment and economic activity worldwide [8]. In Brazil, horticultural production accounts for approximately 25% of the national agricultural value, particularly in export-oriented crops such as mango, grape, papaya, melon, banana, and tomato, which require advanced postharvest and processing technologies [9].

Historically, the foundations of postharvest research emerged from classical studies in plant physiology and microbiology, particularly those related to respiration, senescence, ethylene metabolism, and tissue deterioration. Over time, postharvest science progressively incorporated advanced biochemical analyses, non-destructive technologies, mathematical modeling, and digital tools, becoming increasingly interconnected with biotechnology, computational sciences, precision agriculture, and food engineering.

Despite this rapid evolution, integrative studies combining historical analysis, bibliometric evaluation, and technological foresight in postharvest science remain limited. Most available studies focus either on specific technologies or isolated bibliometric assessments, lacking a broader understanding of how scientific development, technological innovation, and intellectual property protection interact within the field.

Unlike previous reviews that separately addressed historical developments, bibliometric trends, or emerging technologies in postharvest science, this study integrates historical, bibliometric, patent, and prospective technological analyses into a single framework. This approach not only enables a comprehensive understanding of the scientific evolution of postharvest research but also reveals the relationship between knowledge generation and technological innovation, highlighting the transition from conventional preservation techniques to predictive and AI-based systems.

Therefore, this study provides a critical overview of the evolution of postharvest science through historical, bibliometric, and technological perspectives. This study was designed as an integrative review combining historical analysis, bibliometric assessment, and technological foresight approaches to provide a comprehensive overview of the evolution of postharvest science. Additionally, technological foresight was conducted using the Lens.org database to investigate patent evolution, technological concentration, major applicants, and innovation trends associated with postharvest technologies. Bibliometric mapping tools, including VOSviewer, were employed to identify co-occurrence networks, thematic clusters, and emerging research areas. Furthermore, this review incorporates an analytical focus on Brazil as a representative case study of major emerging agricultural economies. Due to its status as a leading global food exporter operating in tropical and subtropical climates, Brazil illustrates the amplified challenges of postharvest losses driven by environmental degradation and logistical bottlenecks. Examining this specific ecosystem offers

critical insights into how developing countries navigate the balance between high academic scientific output and the effective translation of knowledge into patented technologies.

2. Materials and Methods

2.1. Bibliometric and Historical Analysis of Postharvest Science

A historical and bibliometric analysis of postharvest science was conducted to investigate the evolution of the field at both global and national levels. Scientific data were collected from the Scopus (Elsevier) and Web of Science (Clarivate Analytics) databases using Boolean search strategies designed to maximize the retrieval of relevant records, including the terms "pós-colheita" OR "postharvest".

All publication years available in the databases were considered, including original articles, review papers, conference proceedings, and other indexed scientific documents. The analysis aimed to provide a comprehensive overview of the temporal and thematic evolution of postharvest research. Bibliometric indicators included annual publication trends, geographical distribution by country pr region, leading institutions and authors, most productive journals, and keyword frequency analysis.

To further investigate thematic evolution and research structure, bibliometric mapping analyses were performed using VOSviewer software (version 1.6.20) [10]. Metadata from the complete dataset of publications extracted from Scopus and Web of Science were used to generate co-occurrence and overlay visualization maps via VOSviewer to capture comprehensive thematic networks, while the 100 most-cited publications were specifically isolated to analyze international impact dynamics. Co-occurrence networks were applied to identify thematic clusters based on keyword frequency and interrelationships, while overlay visualizations were used to evaluate the temporal evolution of research themes according to average publication year. Additionally, heat maps and bubble maps were generated to illustrate the geographical distribution and concentration of scientific production worldwide.

Keyword normalization was performed using a thesaurus file to eliminate duplicated or equivalent terms (e.g., "USA" and "United States"), improving consistency in network construction and visualization analyses. Countries and regions were identified based on the affiliation metadata associated with the corresponding publications.

Although the search strategy based on the terms "postharvest" and "pós-colheita" allowed the identification of the core scientific production in the field over a long historical period, the authors acknowledge that some interdisciplinary studies may not have been retrieved. Emerging research areas, particularly those published in engineering, computer science, and artificial intelligence journals, often employ terms such as "computer vision", "hyperspectral imaging", "fresh produce quality assessment", or "shelf-life modeling" without explicitly using the term "postharvest". Therefore, the bibliometric dataset presented in this study should be interpreted as representing the central scientific nucleus of postharvest research rather than the entirety of all interdisciplinary studies associated with fruit and vegetable preservation and quality assessment.

2.2. Technological Foresight and Patent Analysis

Technological foresight analysis was performed using the Lens.org database, an international platform integrating patent and scientific publication records. Search strategies were developed using Boolean operators (AND, OR) and keywords associated with postharvest science, applied to title, abstract, and claims fields.

Patent documents published between 1970 and early 2026 were considered, including patent applications, granted patents, and international patent records. After data extraction, quantitative and descriptive analyses were conducted to evaluate: (i) temporal evolution

of patent deposits; (ii) geographical distribution by jurisdiction; (iii) leading patent applicants; and (iv) technological domains according to the Cooperative Patent Classification (CPC) system.

The resulting data were organized into graphs, geographical maps, and heat maps generated using Lens.org analytical tools, allowing the identification of technological concentration patterns, emerging innovation trends, and major institutional actors involved in postharvest technological development.

The bibliometric and technological foresight analyses, including data collection, processing, and visualization procedures, were carried out between January and February 2026.

2.3. Analytical Framework

This study was based on the hypothesis that postharvest science has undergone progressive methodological and technological sophistication over recent decades, characterized by increasing integration between fundamental science, applied technologies, digital tools, and intellectual property protection. This trend confirms the consolidation of postharvest science as a strategic multidisciplinary field strongly associated with innovation, sustainability, and technological development in modern agri-food systems.

Figures 1 and 12 were conceptually designed by the authors and graphically refined using generative artificial intelligence resources. The AI-assisted illustrations were produced using ChatGPT (OpenAI, GPT-5) to improve visual organization and graphical aesthetics. All scientific content, conceptual structure, and final revisions were performed and validated by the authors.

3. Results and Discussion

3.1. Historical Evolution of Postharvest Science

The foundations of postharvest science emerged from classical studies in plant physiology and microbiology during the late nineteenth and early twentieth centuries.

Postharvest science became consolidated during the second half of the twentieth century through advances in storage technologies, quality preservation, and ripening management. Early studies were predominantly descriptive and centered on physicochemical analyses such as mass loss, soluble solids, titratable acidity, firmness, and color changes [11]. Simultaneously, pioneering studies on fruit preservation and processing, particularly those developed by Cruess [12], contributed to the technological advancement of freezing, dehydration, and industrial processing strategies for fruits and vegetables.

From the 1970s onward, postharvest research expanded substantially with the incorporation of refrigerated storage, controlled atmosphere (CA), modified atmosphere packaging (MAP), and biochemical analyses aimed at understanding ripening physiology and quality preservation [3,13,14]. From the 1990s onward, advances in chromatographic and instrumental techniques expanded the biochemical characterization of postharvest metabolism. The commercial adoption of 1-methylcyclopropene (1-MCP) further represented a major technological milestone in the management of climacteric fruits [4,15].

At the same time, postharvest research progressively incorporated enzymatic, biochemical, and molecular approaches associated with ripening regulation, oxidative metabolism, and tissue degradation [16–18]. In Brazil, public research institutions played a central role in adapting postharvest technologies to tropical production systems.

From the 2000s onward, postharvest science evolved into a highly interdisciplinary and technology-oriented field integrating physiology, biochemistry, engineering, digital sensing, non-destructive technologies, mathematical modeling, and artificial intelligence. Emerging approaches such as hyperspectral imaging, biosensors, computer vision, machine learning, and predictive systems have progressively transformed quality assessment and

shelf-life management into more rapid, accurate, and data-driven processes. Recent advances increasingly combine food science, engineering, digital agriculture, and predictive technologies. The overall transition of postharvest science from classical descriptive approaches to integrated predictive and technology-driven systems is summarized in Figure 1, highlighting the major methodological and technological milestones that have shaped the field over recent decades.

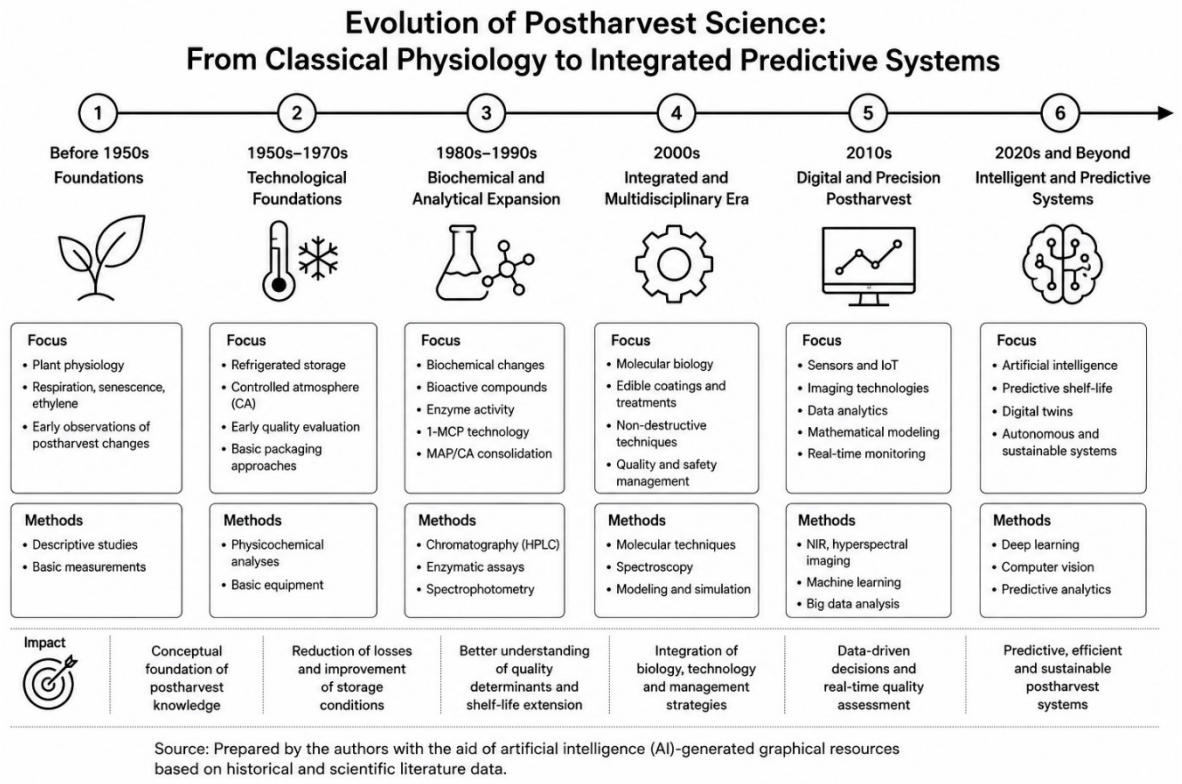


Figure 1. Chronological overview of the major scientific and technological advances in postharvest science, highlighting the transition from classical physiological approaches to integrated biochemical, instrumental, and predictive systems developed by leading international and Brazilian institutions. Source: Prepared by the authors with the aid of artificial intelligence (AI)-generated graphical resources based on historical and scientific literature data.

Recent studies have also demonstrated the increasing application of deep neural networks, explainable artificial intelligence (XAI), edge computing, and digital twin systems for real-time monitoring and autonomous decision-making in postharvest supply chains [7,19].

3.2. Bibliometric Analysis of Postharvest Research

Bibliometric data collected from the Scopus database using the descriptor "pós-colheita" OR "postharvest" identified 35,405 indexed documents published between 1952 and early 2026. The results revealed a substantial temporal expansion of postharvest research over recent decades. During the initial period (1950s–1980s), publication numbers remained relatively low, reflecting the emerging nature of the field. From the 1990s onward, publication rates increased progressively, coinciding with the consolidation of postharvest science and the expansion of analytical and technological methodologies.

This growth became more pronounced after the 2000s, with exponential increases in scientific production associated with the advancement of food security policies, sustainability concerns, reduction of postharvest losses, and the expansion of internationally indexed journals. The publication peak occurred between 2020 and 2022, exceeding 3000

documents per year in both Scopus and Web of Science (WoS) databases (Figure 2a,b). The slight reduction observed in the most recent years is likely associated with incomplete indexing of newly published records rather than an actual decline in scientific production, a common limitation in bibliometric analyses involving current years.

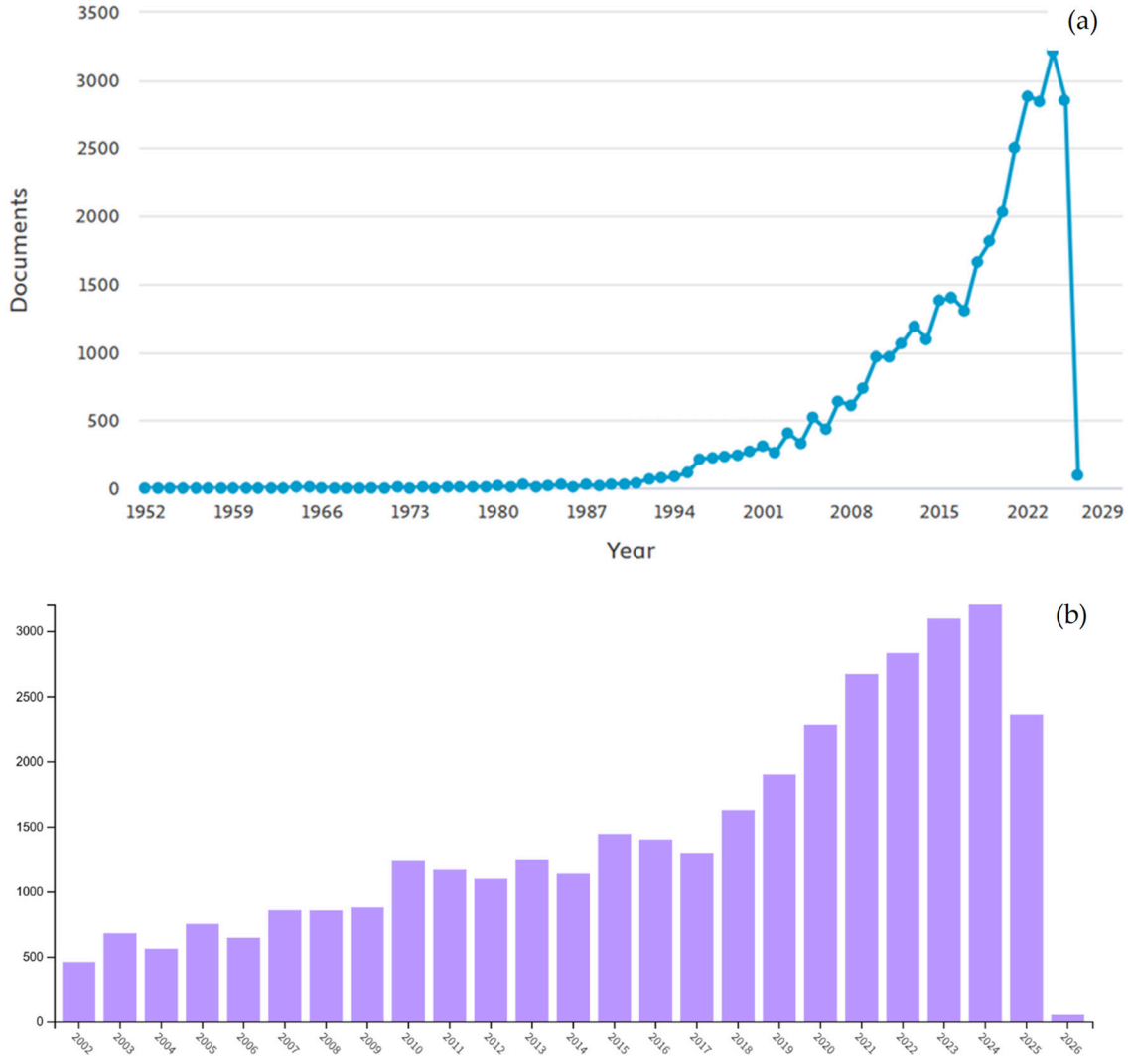


Figure 2. Temporal evolution of postharvest-related publications indexed in: (a) Scopus and (b) Web of Science databases. Source: Prepared by the authors based on data extracted from Scopus (Elsevier) and Web of Science (Clarivate) databases in January 2026.

Although publication growth reflects the increasing global relevance of postharvest science, the expansion of scientific output does not necessarily indicate disruptive innovation. A considerable proportion of studies remains focused on incremental advances, reinforcing the need for more integrative, predictive, and technology-oriented approaches capable of generating broader scientific and industrial impacts.

Geographical distribution analyses demonstrated that China currently leads global scientific production in postharvest research, followed by the United States and Brazil (Figure 3a). This pattern reflects the strategic investments made by these countries and regions in food security, agricultural innovation, and technological development. Countries and regions such as India, Spain, Italy, Iran, Mexico, Australia, and Canada also demonstrated significant participation, reinforcing the global and multidisciplinary nature of postharvest science.

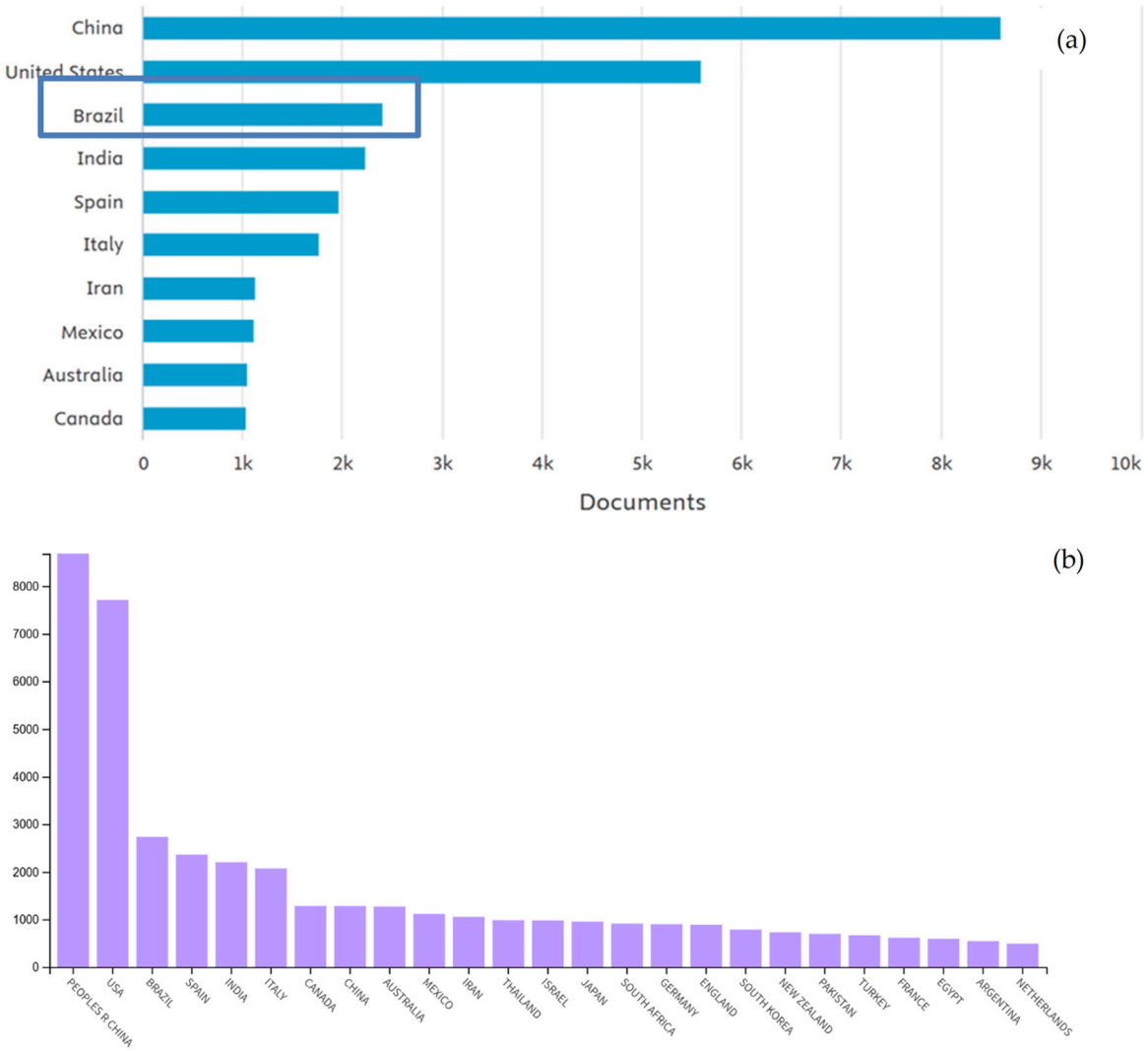


Figure 3. Geographical distribution of postharvest-related publications based on: (a) Scopus and (b) Web of Science databases. Source: Prepared by the authors based on data extracted from Scopus (Elsevier) and Web of Science (Clarivate) databases in January 2026.

The Web of Science database revealed a similar geographical and temporal distribution pattern, confirming the robustness and consistency of the identified trends (Figure 3b). The convergence between databases indicates strong alignment between scientific production and technological development in postharvest science worldwide.

Brazilian scientific production demonstrated consistent growth between 1996 and 2026 (Figure 4a,b). Publication rates increased substantially after the mid-2000s, coinciding with the expansion of graduate programs, strengthening of public funding agencies such as CAPES, CNPq, and FAPESP, and the consolidation of national scientific infrastructure.

The country reached publication peaks exceeding 160 documents per year after 2014, reflecting the internationalization of Brazilian agricultural and food science research. The apparent reduction in the most recent years should again be interpreted cautiously due to indexing delays in recently published records.

The results also demonstrated that Brazilian postharvest research is strongly supported by public universities and strategic research institutions. Empresa Brasileira de Pesquisa Agropecuária emerged as the leading national institution in terms of publication volume, followed by universities such as USP, UFV, UFLA, UNESP, UNICAMP, and UFSM (Figure 5). This distribution indicates a mature and collaborative scientific network integrating basic

science, applied research, and technological innovation, particularly in studies related to tropical fruits, food quality, and postharvest management.

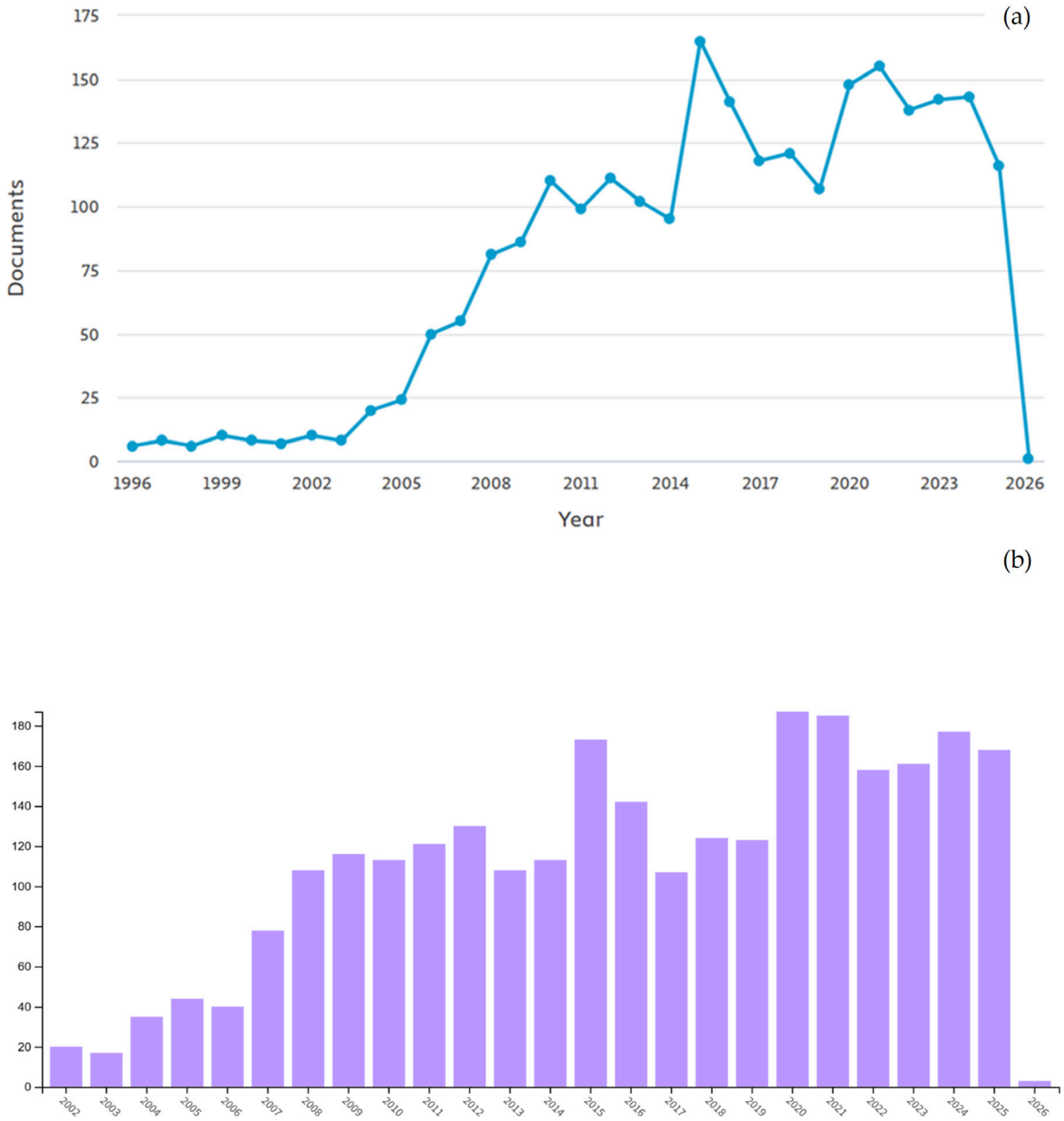


Figure 4. Temporal evolution of Brazilian postharvest-related publications indexed in: (a) Scopus and (b) Web of Science databases. Source: Prepared by the authors based on data extracted from Scopus (Elsevier) and Web of Science (Clarivate) databases in January 2026.

Altogether, the bibliometric results demonstrate that postharvest science has evolved into a globally distributed and rapidly expanding research field strongly associated with food security, sustainability, reduction of postharvest losses, and technological innovation. At the same time, the findings highlight the growing importance of multidisciplinary and predictive approaches integrating physiology, biochemistry, engineering, digital technologies, and artificial intelligence in modern postharvest systems.

The bibliometric analysis of the 100 most-cited publications revealed substantial thematic and geographical transformations in postharvest science over recent decades. Co-occurrence network analysis generated using VOSviewer identified major thematic

clusters associated with physiology, quality preservation, microbiology, food safety, and molecular approaches (Figure 6).

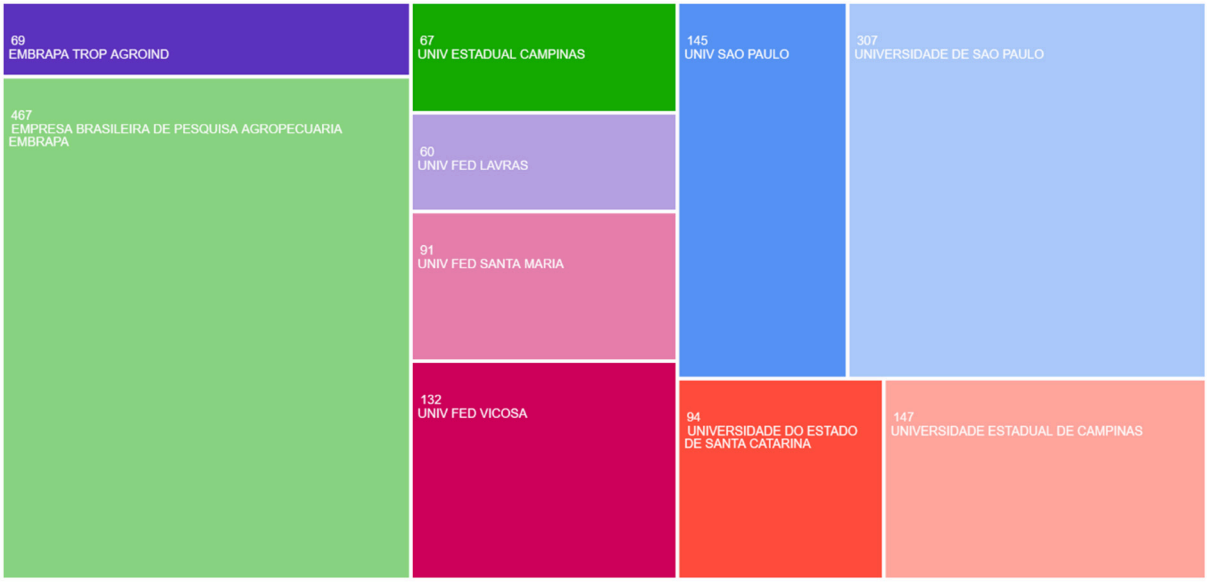


Figure 5. Main Brazilian institutions involved in postharvest research according to Web of Science data. Source: Data extracted from Web of Science (Clarivate) in January 2026; prepared by the authors.

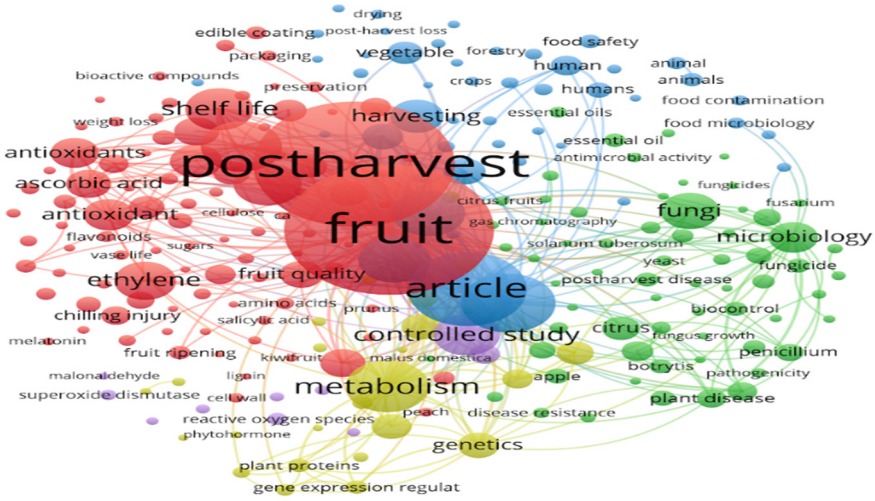


Figure 6. Co-occurrence network of keywords related to postharvest research based on Scopus-indexed publications generated using VOSviewer overlay visualization. Source: Data extracted from Scopus (Elsevier); analysis and preparation performed by the authors using VOSviewer software.

The largest cluster was centered on classical postharvest physiology and quality management, including terms such as *fruit*, *ethylene*, *shelf life*, and *antioxidant activity*, reflecting the historical foundation of the field based on physicochemical and physiological analyses [20,21]. A second cluster grouped studies related to microbiology and postharvest diseases, including *fungi*, *Botrytis*, *microbiology*, and *biocontrol*, highlighting the growing importance of sustainable disease management and food safety strategies [22,23]. Additional clusters were associated with food processing, essential oils, metabolism, gene expression, and plant proteins, demonstrating the progressive incorporation of biochemical and molecular approaches into postharvest research.

The overlay visualization also demonstrated a gradual thematic transition over time. More recent terms, represented by cooler colors in the network map, were associated with

advanced analytical technologies, molecular biology, predictive systems, and interdisciplinary approaches, indicating the increasing integration of biotechnology, food science, and digital technologies within postharvest research [1,24].

Geographical heat maps based on the 100 most-cited publications demonstrated a strong concentration of scientific impact in a limited number of countries and regions, particularly China and the United States, followed by contributions from India, Spain, and Israel (Figure 7). Although the absolute number of publications varied among countries and regions, the logarithmic scale allowed better visualization of intermediate publication ranges and scientific distribution patterns.

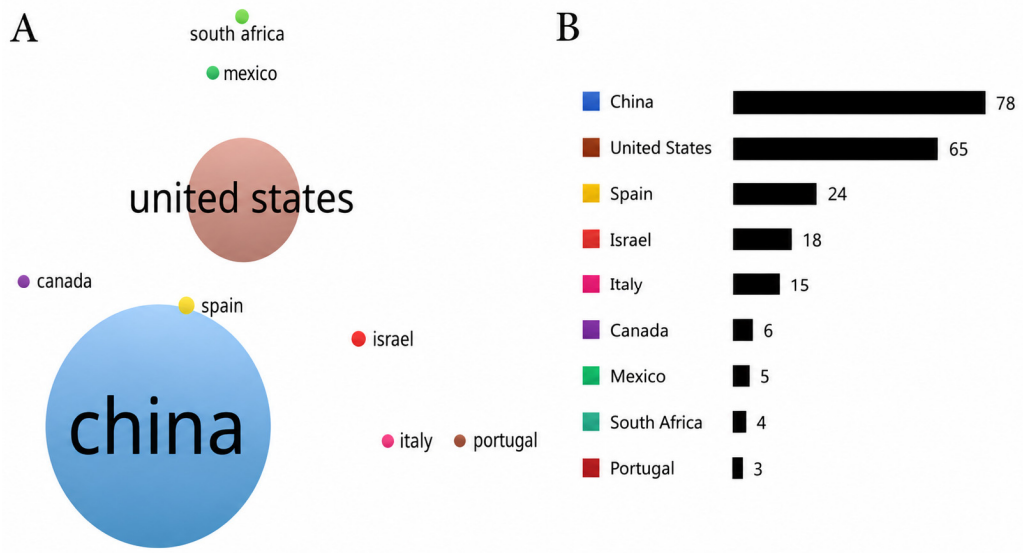


Figure 7. Global distribution of the 100 most-cited postharvest publications indexed in Scopus: (A) geographical heat map and (B) quantitative ranking of the leading countries and regions. Source: Prepared by the authors based on Scopus (Elsevier) data extracted in January 2026.

The temporal distribution of publications revealed that countries and regions such as the United States and Israel played pioneering roles in establishing the physiological and technological foundations of postharvest science, particularly regarding ethylene management, refrigerated storage, and controlled atmosphere technologies [13,14]. In contrast, China and India exhibited more recent and accelerated scientific growth, reflecting increased investments in agricultural innovation, food security, and reduction of postharvest losses [1,19].

Geographical analyses revealed a strong concentration of high-impact publications in China and the United States, followed by India, Spain, and Israel (Figure 7).

These findings indicate that the bibliometric analyses demonstrate that postharvest science has evolved into a globally interconnected and highly multidisciplinary research field. The identified thematic and geographical transitions reinforce the increasing importance of predictive technologies, sustainability-oriented approaches, food safety, and innovation-driven strategies aligned with global challenges related to food security and reduction of postharvest losses.

3.3. Technological Panorama and Innovation Trends in Postharvest Science: Patent Analysis

To complement the bibliometric analysis, a technological foresight assessment was conducted using the Lens.org patent database with the descriptors “postharvest” OR “pós-colheita”. The search included all available records until 2026. Results demonstrated a progressive increase in patent deposits after the 2000s, with a marked acceleration after 2010, following trends similar to those observed in scientific production (Figure 8). The rapid

increase in patent activity after 2015 coincides with the expansion of artificial intelligence, sensing technologies, and digital agriculture. This trend suggests a paradigm shift in postharvest science, moving from descriptive and preservation-oriented approaches toward predictive, intelligent, and integrated systems.

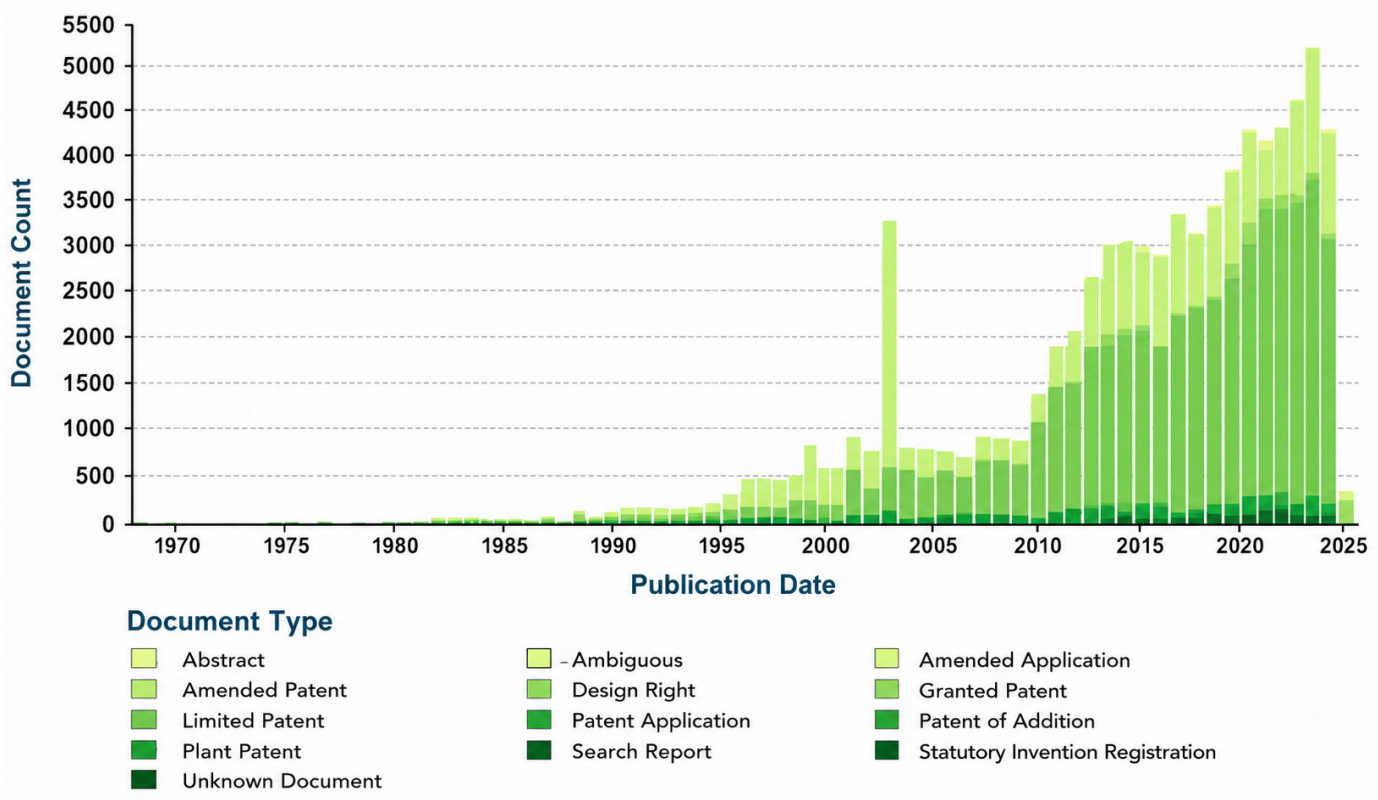


Figure 8. Temporal evolution of patent-related documents associated with postharvest technologies between 1970 and 2026 according to Lens.org data. Source: Prepared by the authors based on data extracted from the Lens.org platform (2026).

It is important to note that the apparent decline observed in 2025–2026 does not necessarily indicate a reduction in innovation activity. Patent data for these years are inherently incomplete due to the temporal boundary of the present analysis and the standard patent publication delay, which generally occurs up to 18 months after filing. Therefore, the most recent years should be interpreted with caution, and the long-term trend remains one of substantial and accelerated technological growth.

The comparison between Brazil and leading countries reveals an important asymmetry in the evolution of postharvest science. Although Brazil is among the countries with the highest scientific production in the field, its patent generation remains proportionally low. Conversely, countries such as China and the United States exhibit a more harmonious relationship between scientific output and technological innovation, indicating more mature innovation ecosystems and stronger technology transfer mechanisms.

This disparity suggests that scientific excellence alone is insufficient to guarantee technological leadership. The transformation of scientific knowledge into innovative products, processes, and digital solutions requires supportive public policies, investments in research and development, incentives for intellectual property protection, and stronger interactions among universities, research institutions, startups, and industry. In this context, Brazil represents a paradigmatic example of the challenges and opportunities faced by emerging economies seeking to accelerate the transition toward data-driven and AI-based agricultural systems.

This trend confirms the consolidation of postharvest science as a strategic innovation sector associated with shelf-life extension, reduction of food losses, and value addition within agricultural supply chains.

Geographical analysis revealed a strong concentration of technological innovation in countries and regions with high investments in applied research and industrial development. The United States led the number of patent records, followed by China, international WIPO publications, and European patents (Figure 9). This distribution highlights the centralization of technological innovation in consolidated scientific and industrial hubs characterized by strong interactions between universities, companies, and national innovation systems.

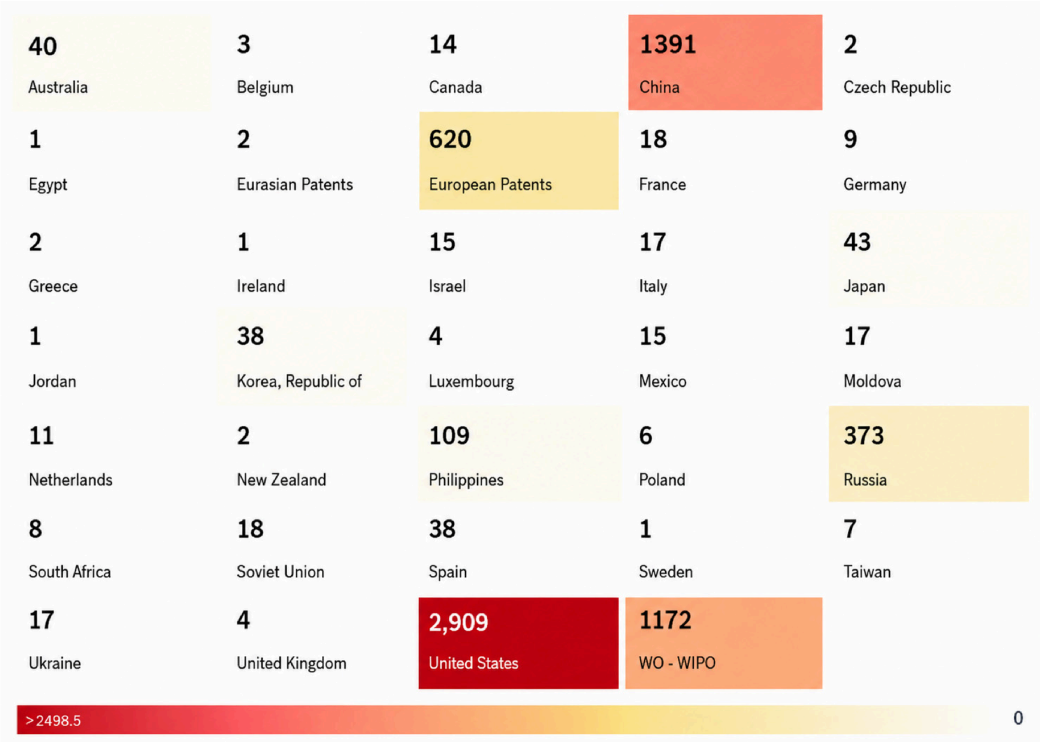


Figure 9. Heatmap showing the distribution and intensity of patent deposits related to postharvest technologies across countries or regions and patent offices. Higher color intensity indicates a greater number of patent deposits. Source: Prepared by the authors based on data extracted from the Lens.org platform (2026).

The United States presented the highest number of patent-related documents (2909 records), followed by China (1391), international WIPO publications (1172), and European patents (620), demonstrating the strong concentration of technological innovation in consolidated industrial and scientific hubs.

Despite Brazil's prominent scientific contribution to postharvest research, the country or region did not appear among the leading patent depositors, revealing a substantial asymmetry between scientific production and intellectual property protection. This discrepancy suggests structural limitations in technology transfer, innovation policies, and intellectual property culture within Brazilian research institutions.

To further investigate Brazilian technological participation, a specific search restricted to the Brazilian jurisdiction (*jurisdiction:BR*) was conducted using the descriptors "postharvest" OR "pós-colheita". Very few patent records were identified under these terms. Broader descriptors associated with fruit conservation increased the number of Brazilian records to 46 documents, although this value remained substantially lower than the global patent landscape.

These findings reinforce the existence of a technological gap between scientific knowledge generation and effective intellectual property protection in Brazil, despite the country's strong agricultural production and scientific relevance in tropical postharvest research. This structural bottleneck is not unique to Brazil; it reflects a broader technological gap prevalent in several emerging agricultural nations (such as India and other regions of the Global South). While these countries and regions possess robust public university networks addressing fundamental plant physiology, they remain dependent on external technological inputs for digital transition. Consequently, the indicators discussed here serve as a proxy to guide innovation policies, intellectual property culture, and public-private partnerships across developing global supply chains striving to adopt Agriculture 4.0 systems.

The analysis of leading patent applicants demonstrated the predominance of multinational private companies strongly associated with edible coatings, ethylene management, crop protection, and postharvest preservation technologies (Figure 10). Companies such as Nunhems BV, Apeel Sciences Inc., AgroFresh Inc., FMC Corporation, and Bayer occupied leading positions in patent deposits, indicating that technological innovation in postharvest science is highly market-oriented and industrially driven.



Figure 10. Main patent applicants related to postharvest technologies according to the number of registered documents. Source: Prepared by the authors based on data extracted from the Lens.org platform (2026).

Patent classification analysis demonstrated the predominance of CPC codes associated with food preservation, postharvest treatments, biocidal formulations, plant protection, and analytical methods (Figure 11). Codes related to food preservation technologies (A23B), bioactive formulations and growth regulators (A01N), and analytical characterization methods (G01N) were particularly frequent. The leading patent applicants were predom-

inantly multinational companies associated with edible coatings, ethylene management, crop protection, and postharvest preservation technologies, including Nunhems BV, Apeel Sciences Inc., AgroFresh Inc., FMC Corporation, and Bayer.

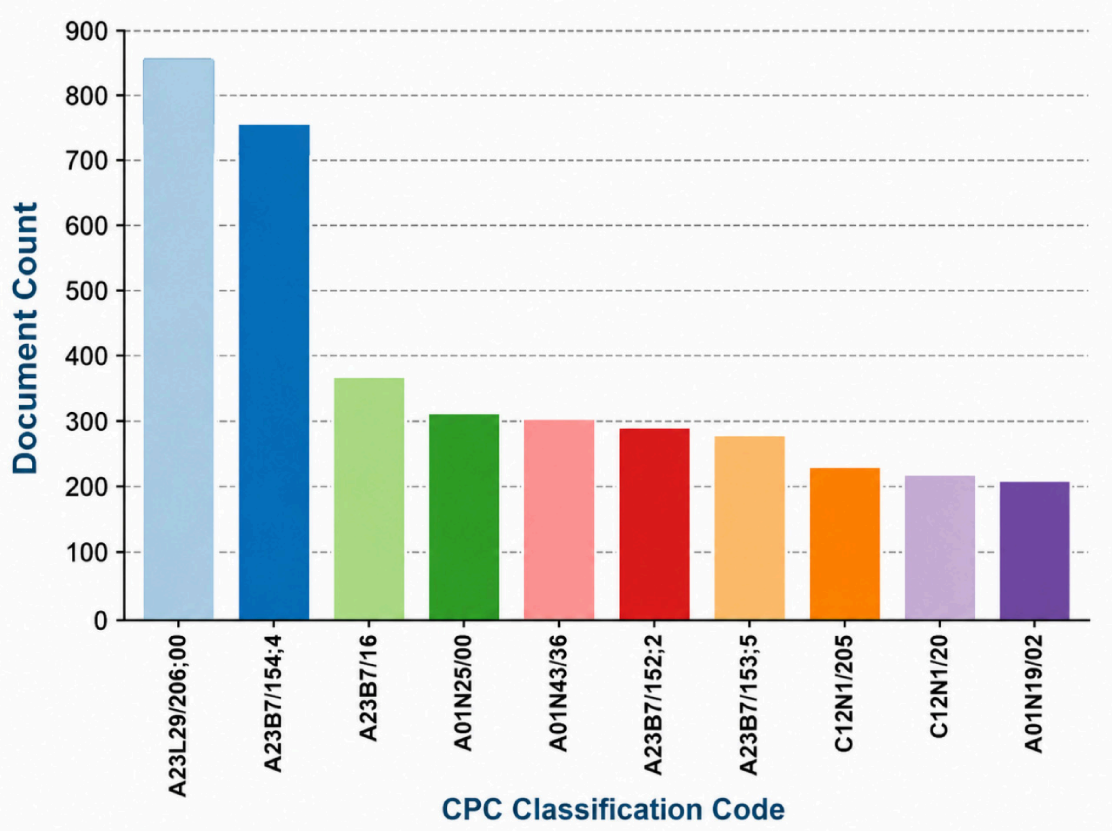


Figure 11. Main Cooperative Patent Classification (CPC) codes associated with postharvest technologies identified in the Lens.org database. Source: Prepared by the authors based on data extracted from the Lens.org platform (2026).

These results indicate that technological innovation in postharvest science has expanded far beyond traditional storage approaches, currently encompassing integrated systems involving crop improvement, biochemical preservation strategies, analytical monitoring, packaging technologies, and industrial processing solutions.

3.4. Integration Between Scientific Production and Technological Innovation

The integration of bibliometric and patent analyses revealed strong thematic convergence between academic research and industrial technological development. However, substantial asymmetries remain regarding intellectual property protection, particularly in developing countries and regions such as Brazil.

Technologies involving mathematical modeling, machine learning, and artificial intelligence applied to postharvest quality management still represent a relatively limited proportion of patent records, indicating important opportunities for future technological expansion. This scenario highlights the growing strategic relevance of integrating conventional physicochemical analyses with predictive systems and digital technologies in postharvest science.

3.5. Postharvest Science as a Strategic Component of Food Quality, Value Addition, and Competitiveness

Advances in postharvest technologies have played a central role in improving quality preservation, reducing losses, and increasing value addition within fruit and vegetable

supply chains. Technologies such as refrigeration, modified atmosphere systems, edible coatings, smart packaging, and non-destructive monitoring methods have become essential tools for maintaining product quality, extending shelf-life, and meeting international market requirements. In parallel, smart packaging systems, AI-assisted logistics, and sensor-based monitoring platforms are increasingly being incorporated into commercial postharvest chains to improve traceability, reduce losses, and optimize storage management in real time [25].

In Brazil, the strategic importance of postharvest technologies is particularly significant due to the country's or region strong tropical fruit production, long transportation distances, and export-oriented supply chains. The adoption of advanced postharvest systems has contributed directly to reducing losses, preserving nutritional and sensory quality, and improving competitiveness in international markets.

Overall, the results demonstrate that postharvest science has evolved into a highly interdisciplinary and innovation-oriented field integrating physiology, food science, engineering, biotechnology, digital technologies, and predictive systems. This transformation reinforces the strategic importance of postharvest research for sustainability, food security, technological innovation, and the reduction of global food losses.

3.6. Future Perspectives in Predictive Postharvest Systems

The rapid advancement of digital technologies is expected to further transform postharvest science into a highly integrated, automated, and predictive field over the coming decades. Emerging approaches involving artificial intelligence (AI), machine learning, automation, biosensors, and digital agriculture are progressively reshaping quality management systems, enabling more accurate monitoring, faster decision-making, and improved prediction of physiological and biochemical changes during storage and commercialization.

Among these technologies, AI-driven predictive systems have gained particular relevance due to their ability to process large datasets generated from non-destructive analyses, hyperspectral imaging, environmental sensors, and real-time monitoring platforms. Machine learning algorithms and artificial neural networks have demonstrated strong potential for predicting shelf life, detecting physiological disorders, estimating ripening stages, and optimizing storage conditions in fruits and vegetables [5,26]. Recent advances in explainable AI, federated learning, and multimodal deep learning architectures have further expanded the potential of predictive postharvest systems by enabling more transparent, scalable, and adaptive models for heterogeneous agricultural environments [7,19].

The integration of biosensors and Internet of Things (IoT)-based devices is also expected to expand significantly, allowing continuous real-time monitoring of temperature, humidity, ethylene concentration, gas composition, microbial activity, and quality attributes throughout the supply chain. Figure 12 illustrates the ongoing transformation of postharvest science into a digitally connected ecosystem in which sensors, artificial intelligence, and digital twins interact to support real-time decision-making throughout the supply chain. This transition represents not only a technological evolution but also a conceptual shift from reactive quality control to predictive and autonomous management systems.

In parallel, advances in omics technologies—including genomics, transcriptomics, metabolomics, and proteomics—are providing deeper insights into ripening regulation, stress responses, and quality preservation mechanisms. The integration of omics data with computational modeling and AI tools may enable the development of highly precise predictive systems capable of supporting breeding programs, physiological management strategies, and personalized postharvest protocols for different commodities.

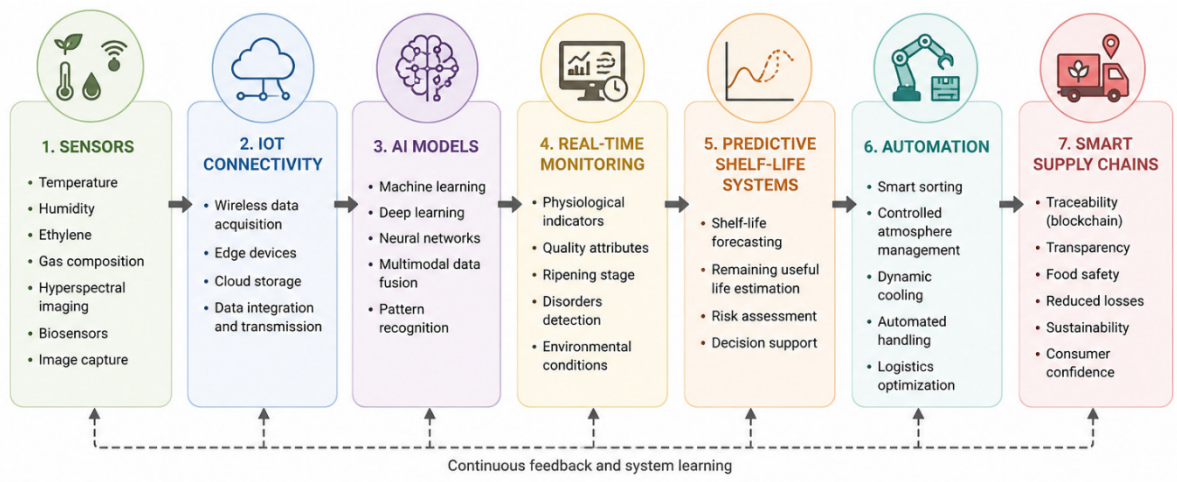


Figure 12. Framework of predictive postharvest systems integrating digital technologies, artificial intelligence, and real-time quality management. **Source:** Prepared by the authors with the aid of artificial intelligence (AI)-generated graphical resources based on current trends in digital agriculture, artificial intelligence, automation, and predictive postharvest systems.

Blockchain technology also represents an emerging perspective for postharvest systems, particularly regarding traceability, transparency, food safety, and supply chain management. By enabling secure and decentralized data recording, blockchain-based systems may improve product authentication, reduce information asymmetry, and increase consumer confidence in high-value horticultural products.

Despite these advances, important challenges remain for the implementation of predictive postharvest systems at commercial scale, including high technological costs, lack of methodological standardization, limited integration between research and industry, and restricted access to digital infrastructure in developing countries and regions. Furthermore, the effective adoption of AI-driven systems depends on the generation of robust and standardized datasets capable of supporting reliable predictive models.

Challenges for Industrial Implementation

Despite the remarkable advances in sensors, artificial intelligence, computer vision, and digital twins, their large-scale implementation in postharvest systems still faces important challenges. The high acquisition and maintenance costs of advanced sensors, the lack of standardized datasets for model training, difficulties in integrating heterogeneous data sources, and limited digital infrastructure in developing countries remain major barriers to adoption. In addition, predictive models often exhibit reduced robustness when transferred from controlled laboratory conditions to commercial environments, where variability in cultivars, climatic conditions, and management practices is considerably greater. Ethical issues related to data ownership and the need for explainable AI models are also emerging concerns. Therefore, future research should focus not only on improving prediction accuracy but also on enhancing model interpretability, scalability, affordability, and industrial applicability.

The results suggest that future postharvest systems are expected to become increasingly automated, data-driven, and interconnected, integrating digital agriculture, artificial intelligence, real-time monitoring, and advanced analytical technologies to improve quality preservation, sustainability, food safety, and reduction of global postharvest losses.

4. Conclusions

This study demonstrated, through historical, bibliometric, and technological analyses, that postharvest science has evolved from predominantly descriptive approaches based

on physicochemical evaluations into an integrated and multidisciplinary field combining physiology, biochemistry, microbiology, engineering, non-destructive technologies, digital sensing, and predictive systems. The bibliometric results revealed an exponential expansion of scientific production after the 2000s, accompanied by thematic diversification and increasing technological sophistication.

The global scientific landscape is currently dominated by countries and regions such as China and the United States, while Brazil has emerged as an important contributor, particularly in tropical and subtropical postharvest research. At the same time, the patent analysis demonstrated a strong concentration of technological innovation in consolidated industrial and scientific hubs, revealing substantial asymmetries between scientific production and intellectual property protection, especially in developing countries and regions.

The thematic evolution identified through co-occurrence networks and patent classifications confirmed the coexistence of classical postharvest topics—such as ethylene management, respiration, refrigerated storage, and modified atmospheres—with emerging areas involving edible coatings, bioactive compounds, hyperspectral imaging, artificial intelligence, machine learning, and predictive quality systems. These findings reinforce the transition of postharvest science toward data-driven and technology-oriented approaches aligned with current global demands for sustainability, food security, reduction of food losses, and innovation in agri-food systems.

Despite the substantial scientific advances observed over recent decades, important challenges remain, including the need for greater methodological standardization, stronger integration between scientific research and technological innovation, and faster transfer of laboratory-based solutions to industrial and commercial applications.

Emerging technologies such as digital twins, explainable AI, smart sensing platforms, and autonomous monitoring systems are expected to further accelerate the transition toward intelligent and highly interconnected postharvest systems.

Overall, the results demonstrate that postharvest science is undergoing a paradigmatic transformation toward integrated predictive systems supported by multidisciplinary and digital technologies, consolidating its strategic role in sustainable food systems and modern agricultural innovation. Future advances in postharvest science will likely depend on the successful integration of biological understanding, digital intelligence, and predictive technologies capable of supporting automated and sustainable food systems.

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