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Integration of edible coatings with postharvest storage technologies for fruits and vegetables: A systematic review and network analysis

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Abstract

Integrating edible coating applications with optimized storage technologies represents a promising strategy to enhance the physicochemical stability, microbial safety, and shelf life of fruits and vegetables. This systematic review and network analysis examines global research trends in integrating edible coatings with storage technologies such as refrigeration, modified atmosphere packaging (MAP), controlled atmosphere storage (CA), and cold-chain systems. Following PRISMA guidelines, a comprehensive literature search was conducted in Scopus, yielding 425 initial records. After screening and eligibility assessment, 47 key studies were included in the final analysis. The results show a consistent growth in publications since the mid-2000s with a sharp increase after 2014, peaking in 2024. Spain emerged as a central hub of international collaboration, while key journals served as main dissemination channels. The most frequently combined components were chitosan, alginate, and pectin as biopolymers; essential oils and plant extracts as active compounds; and refrigeration and MAP as storage technologies. Network analysis revealed that biopolymers functioned as central connectors that repeatedly link with the other components. The integrated coating-storage systems improved several postharvest quality attributes of fruits and vegetables to varying degrees, including shelf-life extension ranging from 2 to more than 60 days, preservation of nutritional quality, significant reduction in microbial loads, and maintenance or improvement of sensory attributes. Future research is predicted to focus on active phenolic coatings with controlled release in MAP, smart packaging with real-time monitoring, integration of scavengers and moisture absorbers with coatings, and development of bio-based sensors for detecting temperature abuse in the cold chain. These findings provide a comprehensive knowledge map and research agenda for advancing sustainable postharvest quality management of fresh produce.

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1. Introduction

Global needs for food security, reduction of postharvest losses, and sustainable production have increased interest in integrating edible coating technology with postharvest storage technologies with storage technologies during the distribution and storage of fruits and vegetables. Biopolymer-based edible coatings are often enriched with bioactive compounds, such as essential oils, plant extracts, or antimicrobials, which act as selective barriers to water vapor and gases, as well as functional components that suppress respiration, oxidation, and microbial growth when combined with refrigeration, modified atmosphere packaging (MAP), or controlled atmosphere (CA). These treatments may have additive or complementary effects in maintaining sensory and nutritional quality, as well as extending shelf life. The analyzed Scopus corpus shows a rapid increase in publications in 2024–2025, indicating accelerated innovation in formulations (e.g., starch/protein–polysaccharide composites) and combinations of plant essential oils, cross-linked chitosan, and structured lipid carriers, along with a shift in focus from single commodities to cross-technology integration in realistic cold chain situations (1–5). Strategically, this theme aligns with the Sustainable Development Goals, particularly SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-Being), and SDG 12 (Responsible Consumption and Production). Although the global demand for fresh agricultural products continues to rise, significant postharvest losses still occur due to inadequate handling, storage, and distribution systems, especially along extended supply chains. These losses not only reduce food availability and nutritional quality, but also increase resource inefficiency and food system losses. Therefore, strengthening postharvest preservation strategies that minimize quality degradation and food waste is crucial for supporting sustainable food supply chains and contributing to the broader SDG agenda. Thus, a systematic review and network analysis on this topic are important to map global trends, identify dominant combinations of biopolymers–active compounds–storage technologies and their interrelations, and assess their contributions to postharvest quality attributes (shelf life, nutritional value, microbial safety, and sensory properties) within the framework of sustainable food policy and circular economy (1–5).

The complexity of developing and implementing the synergy of coatings can be addressed with storage technology throughout the cold chain, which is rooted in the heterogeneity of commodities, variability in coating formulations and application methods, and non-uniform evaluation standards across studies. However, coatings must create selective barriers for water vapor and gases while maintaining exchange to prevent anaerobiosis and condensation, while storage conditions (refrigeration, MAP, CA) and the dynamics of cold chain logistics introduce fluctuations that affect respiration, microbiota, and the rate of quality degradation. Diverse experimental designs, limited sample sizes, inconsistent replication, and differing performance indicators (shelf life, microbial load, mass loss, sensory and nutritional attributes) complicate quantitative evidence synthesis and the generalization of findings across commodities and scales (from laboratory to industry) (1,2). However, significant opportunities arise from advancements in biopolymers and co-polymers derived from renewable resources, nanocarriers for the controlled release of antimicrobials/antioxidant active compounds, and the design of composite coatings compatible with modern MAP/CA protocols (3,4). Additionally, the integration of IoT sensors (time indicators, temperature, and gas sensors) and data analytics enables real-time monitoring and adaptive control to maintain quality at critical points in the cold chain. Overall, these methodological and operational challenges simultaneously open avenues for innovation in formulation, process integration, and precise quality management along the cold chain. The working principles of edible coating and storage technology are shown in Figure 1.

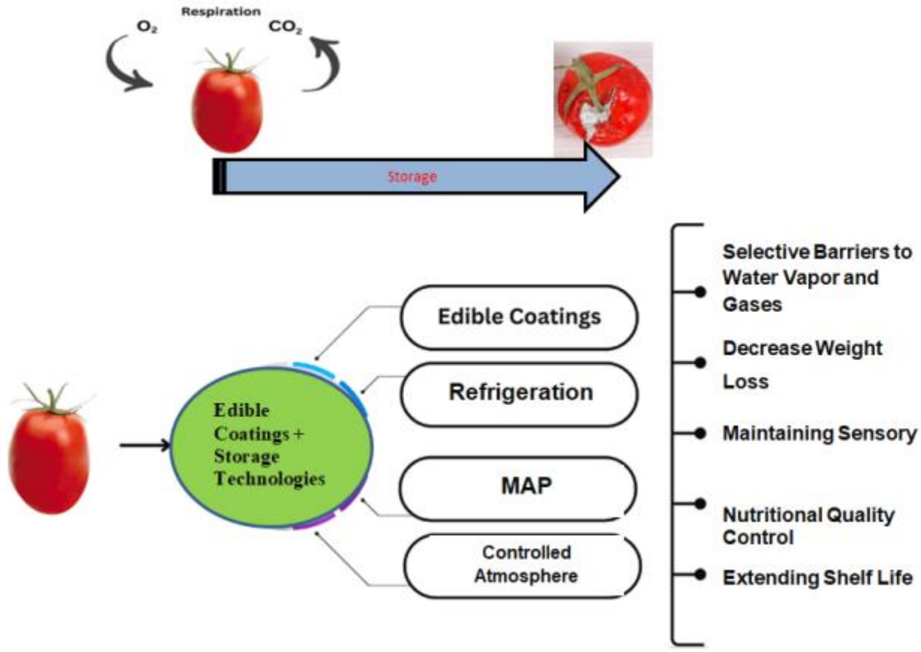


Figure 1. Conceptual mechanisms of edible coating and storage technology.

Recent literature indicates that research on edible coatings for horticultural commodities has shifted from merely comparing single formulations to testing combinations with low-temperature storage technologies, particularly refrigeration and modified/controlled atmosphere (MAP/CA) with consistent findings on extended shelf life, microbial load control, and the preservation of nutritional and sensory attributes (1,2,4). Studies on starch-based coatings enriched with essential oils for bananas, cactus extract on fresh-cut mangoes, and protein–polysaccharide composites for blueberries illustrate a growing focus on synergistic processes (1,2,4). On the other hand, exploration of active systems and nano-delivery platforms (for example, nanostructured lipid carriers loaded with cinnamaldehyde), as well as innovative polymer matrices (for example, cellulose derivatives with active ingredients), demonstrate the potential for programmed control of respiration and microbial contamination (3,6). However, previous reviews have generally focused only on individual coating formulations or storage technologies. This study systematically combines a PRISMA-based systematic review with bibliometric and network analyses to build a comprehensive knowledge map of how biopolymers, active compounds, and storage technologies (refrigeration, MAP, and CA) are interconnected in postharvest research on fruits and vegetables. By revealing the structural relationships, dominant combinations, and central linking materials within the research network, this review provides a descriptive overview and offers evidence-based insights into how technological synergy is conceptualized and operationalized across various studies. Furthermore, this study identifies methodological fragmentation, underexplored integration scenarios, and emerging research directions, thereby offering a forward-looking research agenda to guide future experimental design, pilot-scale validation, and sustainable cold chain innovation. In summary, this review asks how global trends in the integration of edible coatings with storage technologies have developed, which combinations are most frequently used, how these components are interrelated, and to what extent the integrated systems improve postharvest quality. These questions address a gap that has not been comprehensively examined in previous publications (1–6).

Based on the description above, this review aims to: map the dynamics and direction of publication trends on the synergy between edible coatings and storage technologies for fruits and vegetables; illustrate the contributions and collaborative networks between countries/affiliations; identify the most influential authors and articles along with the structure of their influence within the citation map; project the evolution of topics through bibliometric analyses (co-occurrence, co-authorship, and thematic evolution); synthesize global trends in the integration of coatings with cold chain technologies, including refrigeration, modified atmosphere packaging (MAP), and controlled atmosphere (CA); map the combinations of biopolymers, active compounds, and storage technologies, as well as the interrelations among these elements based on network analysis; and assess the extent to which such synergy enhances postharvest quality attributes, shelf life, nutritional value, microbial safety, and sensory properties. Thus, this review provides a coherent framework for science and technology policy, bridging gaps in the literature and positioning this field on a research trajectory that is actionable and measurable in its impact.

2. Materials and Methods

This study combined bibliometric network analysis with a systematic literature review.

2.1. Network Analysis

Network analysis in bibliometric studies refers to a methodological approach that constructs and examines relationships among scientific entities**,** such as authors, publications, keywords, and institutions, by representing them as interconnected nodes within a network structure. Bibliometric analysis serves as a robust approach for identifying influential scholars and institutions, thereby facilitating collaboration and advancing scholarly knowledge exchange. It further enables the mapping of publications by country and source, offering insights into the geographical distribution and publication landscape. Additionally, it supports the identification of the most productive articles, institutions, and journals within a specific research domain (7,8). This bibliometric method relies on the Scopus database as an extensive data source, thereby providing a solid foundation for conducting rigorous bibliometric analyses (9). The search strategy was designed to identify publications related to edible coatings and storage technologies for fruits and vegetables. The search keywords used were: (“edible coating*” OR “active packaging” OR “edible film*”) AND (fruit* OR vegetable*) AND (“cold chain” OR refrigeration OR “controlled atmosphere” OR “modified atmosphere packaging” OR MAP OR CA). Publications issued before 2003 were excluded to ensure comprehensive historical coverage. The initial search yielded 425 records. The dataset included articles, reviews, books, book chapters, and conference papers published in English, thus obtaining a total of 390 records that passed screening and became a representative working corpus. Subsequently, this set of 390 documents was used as the basis for network analysis to map trends, key contributors, and conceptual relationships between edible coatings and storage technologies in the context of the cold chain for fruits and vegetables, while also preparing the eligibility (full-text) stage so that the resulting evidence synthesis remains transparent, focused, and in line with the PRISMA guidelines (Figure 2). Scopus data collection was conducted on September 6, 2025. A total of 390 documents obtained from Scopus for network analysis were processed using OpenRefine (version 3.9.5) to clean the data with the aim of minimizing data bias caused by inconsistent spelling and word repetition. The results of the cleaned data were then exported to the visualization application VOSviewer (version 1.6.20), which was used to map relationships among authors, journals, and keywords through network visualization. Additional statistical analysis and visualization were conducted using Tableau (version 2025.2) and RStudio (version 2025.05.1), while data management and export were facilitated by Microsoft Office. Through this approach, network analysis provides a comprehensive overview of the knowledge structure, focusing on centers of influence and potential directions for further research in the field of cold chain synergy with edible coatings for fruits and vegetables.

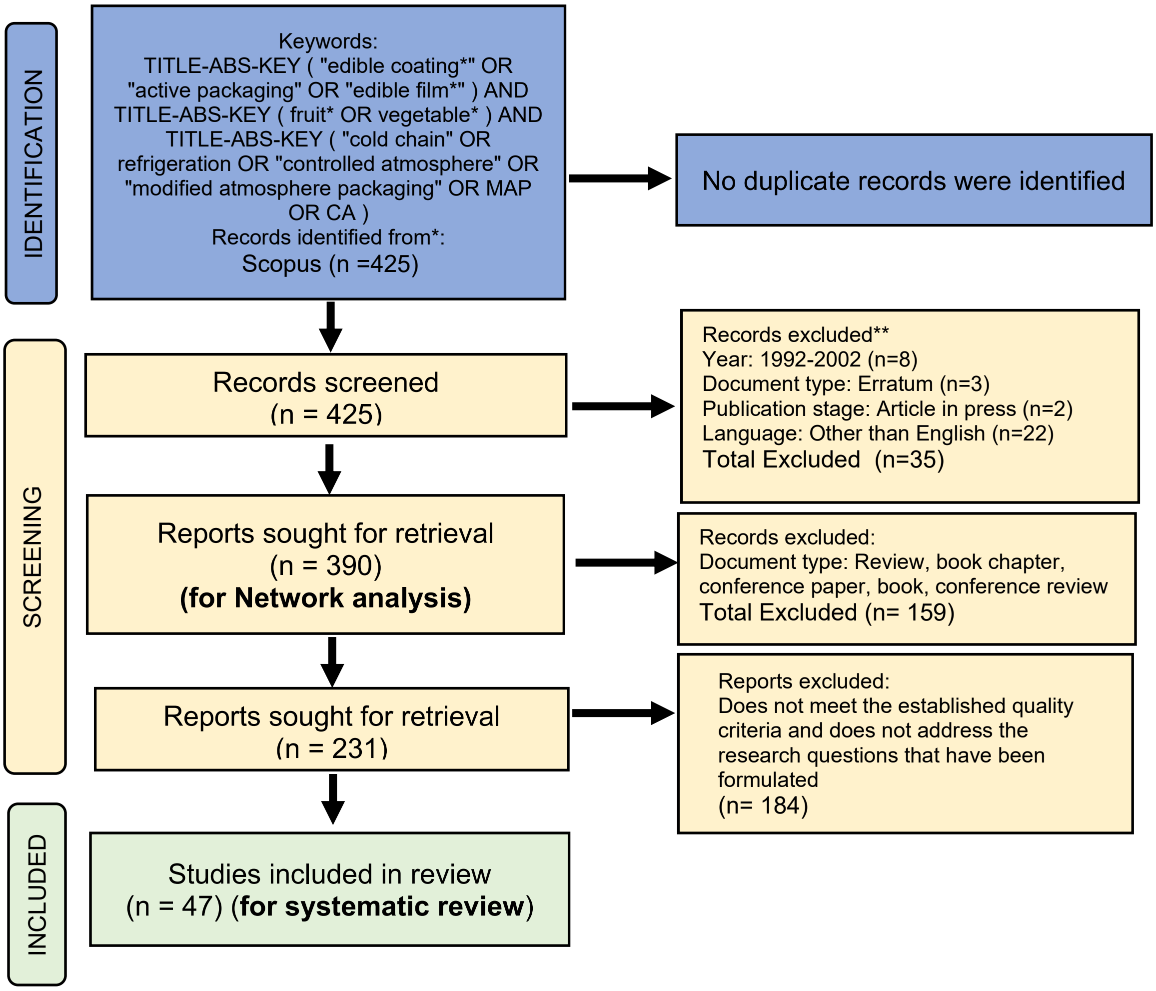


Figure 2. PRISMA flow diagram for bibliometric network analysis and systematic literature review.

2.2. Systematic Literature Review

The PRISMA approach improves transparency and reduces bias in systematic reviews, thereby enhancing the credibility of evidence synthesis and supporting evidence-based decision-making in policy-relevant research areas (10). In this study, PRISMA (Figure 2) was used as a systematic approach to examine the application of edible coatings and storage technologies in fruits and vegetables. Relevant keywords were carefully defined, and articles were rigorously selected to ensure a focused and comprehensive literature review.

2.2.1 Identification

At the identification stage, a systematic literature search was conducted using the Scopus database because of its broad coverage of peer-reviewed literature in food science, food packaging, and postharvest technology. The search was performed using the advanced search function and the predefined combination of terms related to edible coatings, fruits and vegetables, and postharvest storage technologies. The search was conducted on September 6, 2025, and initially identified 425 records. After the application of the predefined database-level restrictions concerning language, publication stage, and eligible bibliographic records, 35 records were excluded, leaving 390 documents. These 390 documents constituted the dataset used for bibliometric and network analyses. Their metadata were exported in CSV and BibTeX formats for data cleaning, bibliometric mapping, and subsequent study-selection procedures for the systematic review.

2.2.2. Screening

The screening stage began with the 390 documents retained for bibliometric and network analyses. For the systematic review component, the dataset was first restricted to primary research articles. Review articles, books, book chapters, conference papers, conference reviews, editorials, errata, and other non-research publications were excluded. The titles and abstracts of the remaining research articles were then screened to assess their relevance to the combined application of edible coatings and postharvest storage technologies for fruits and vegetables. Studies were considered potentially eligible when they met the following criteria: (1) the study investigated an edible coating applied in combination with at least one postharvest storage technology or controlled storage condition, such as refrigeration, modified atmosphere packaging, or controlled atmosphere storage; (2) the study focused on whole or minimally processed fruits and vegetables; (3) the publication was a primary research article; (4) the article had reached the final publication stage; and (5) the article was written in English.

Studies were excluded when the title or abstract indicated that: (1) the study evaluated only the formulation or physicochemical characterization of an edible film or coating without application to fruits or vegetables; (2) the study examined only a storage or packaging technology without an edible coating treatment; (3) the study did not evaluate the combined application of an edible coating and a storage condition or technology; (4) the investigated commodity was outside the scope of fruits and vegetables; or (5) the article did not provide sufficient information to determine its relevance to the review questions. Following the document-type restriction and title-and-abstract screening, 231 research articles were retained for full-text eligibility assessment. These articles were subsequently evaluated in greater detail with respect to their alignment with the review scope, methodological adequacy, completeness of outcome reporting, and relevance to the predefined research questions. This procedure allowed the broader dataset of 390 documents to be used for bibliometric and network analyses, while ensuring that the systematic review was based specifically on relevant primary experimental studies.

2.2.3. Eligibility

At this full-text assessment stage, 231 articles that passed the previous screening were systematically reviewed to ensure that the substance was aligned with the focus on the cold chain synergy of edible coatings combined with storage technologies for fruits and vegetables. The evaluation was based on the following five eligibility criteria: (i) whether the research objectives were clearly stated; (ii) whether the cold chain synergy between edible coatings and storage technologies was described specifically and explicitly (not merely a single component discussion); (iii) whether the research findings were clearly presented and supported by adequate data (test design, performance metrics, and/or relevant statistical analysis); (iv) whether the full version of the publication could be accessed through relevant institutional/association subscriptions; and (v) whether the study did not deviate from the predetermined research question. Manuscripts that failed to meet any of these criteria were eliminated at this stage to maintain the consistency of scope, traceability of methods, and strength of inference. As a result, 47 articles met all eligibility criteria and were deemed included in the final qualitative synthesis. This arrangement ensures that the final corpus represents the most relevant and transparent evidence for an in-depth review within the framework of a systematic review, focusing on understanding the real synergy between edible coatings and storage technologies throughout the cold chain of fresh fruits and vegetables.

2.2.4. Included

Of the 231 articles evaluated in the previous stage, 47 (20.35%) were included in the final review, while 184 (79.65%) were excluded. The final selection was based on the articles' ability to address the main research questions: mapping global research trends on the integration of edible coatings with storage technologies (cold chain, refrigeration, MAP, CA); identifying the most frequently combined biopolymers, active compounds, and technologies and analyzing their interconnections through network analysis; and assessing the extent to which these combinations improve postharvest quality (shelf life, nutritional value, microbial safety, sensory properties) and meet the criteria for inclusion and methodological quality (clarity of design, adequacy of sample size/replication, analytical validation, and relevance to food packaging context). Articles were primarily excluded because they were not directly relevant to the research questions or had significant methodological limitations

1. Global research trends: Mapping the development of edible coating integration with storage technologies (cold chain, refrigeration, MAP, and CA) to extend the shelf life of fruits and vegetables.
2. Combinations and interconnections: Identifying the most frequently combined biopolymers, active compounds, and storage technologies and examining the structure of their relationships through network analysis.
3. Postharvest quality impact: Evaluating the extent to which these combinations improve the shelf life, nutritional value, microbial safety, and sensory properties of fruits and vegetables.

Strict selection enhances the credibility of the findings and enables the identification of patterns and gaps, such as the predominance of laboratory studies and limited evidence available at the industrial scale, highlighting the need for multi-lot and multi-location trials, industrial pilot validation, and standardization of performance metrics across commodities in future research.

3. Results and Discussion

3.1. Publication Trends and Number of Documents

Research on edible coatings combined with storage technologies has shown consistent growth since the mid 2000s and surged sharply after 2014, reaching its peak output in 2024 (61 documents); a spike in citations peaking around 2020 (1,569 citations) indicates that this theme has entered the mainstream and has begun to be widely used as a methodological reference in the postharvest field (Figure 3). This trend aligns with recent findings that the combination of edible coatings with Modified Atmosphere Packaging (MAP) and cold storage does indeed produce a synergistic effect edible coatings reduce respiration and water loss, while MAP/cold storage stabilizes gas composition and temperature, thereby better preserving sensory quality. However, research that truly optimizes their “combination” remains limited and is a research agenda being promoted by the international scientific community (11). Thematically, the graph also shows an acceleration of publications after 2018; this aligns with the literature emphasizing the need for an integrated approach (edible coatings + MAP/cold storage) to extend the shelf life of fresh and fresh-cut fruits/vegetables while minimizing single-use plastics and chemical inputs (12). During this period, numerous studies and review articles on edible coatings, active packaging, and storage technologies, such as refrigeration and modified atmosphere packaging, were published in high-impact journals, making them primary references for subsequent research. Additionally, the increasing global focus on food system resilience and supply chain efficiency during the COVID-19 pandemic has further accelerated the development and citation of research related to storage technologies and food loss reduction.

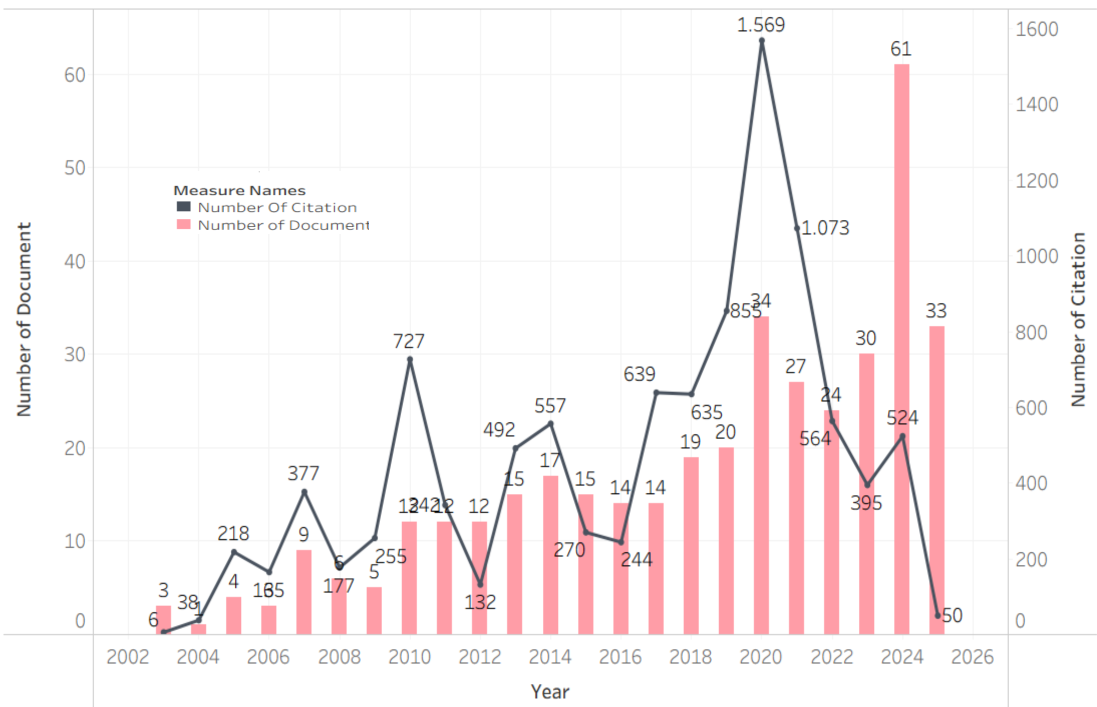


Figure 3. Annual trends in publications and citations on edible coatings combined with storage technologies for fruits and vegetables.

3.2. Country Contribution Analysis

Based on the co-authorship map obtained from VOSviewer (Figure 4), the international collaboration network on edible coatings and storage technologies revealed four major clusters with strong hubs in Spain, the United States, China, and India. The Spanish node emerged as the most dominant (e.g., 49 documents; 2,189 citations; highest TLS), also bridging citation flows between Europe and Latin America (Portugal–Brazil–Mexico) and Europe–North America (Spain–US–Canada). These findings are consistent with recent bibliometric reviews indicating that the field of edible coatings is spread across 151 sources/journals and is driven by hundreds of institutions across countries. This study also confirms the presence of intense international collaboration among productive countries (13). The United States shows a higher research contribution despite having fewer publications because the bibliometric impact is influenced not only by publication quantity, but also by citation influence and journal visibility. Many studies from the United States have been published in high-impact journals and involve international collaborations, which tend to attract broader academic attention and higher citation rates. Consequently, a smaller number of highly influential publications can generate a greater overall scientific impact.

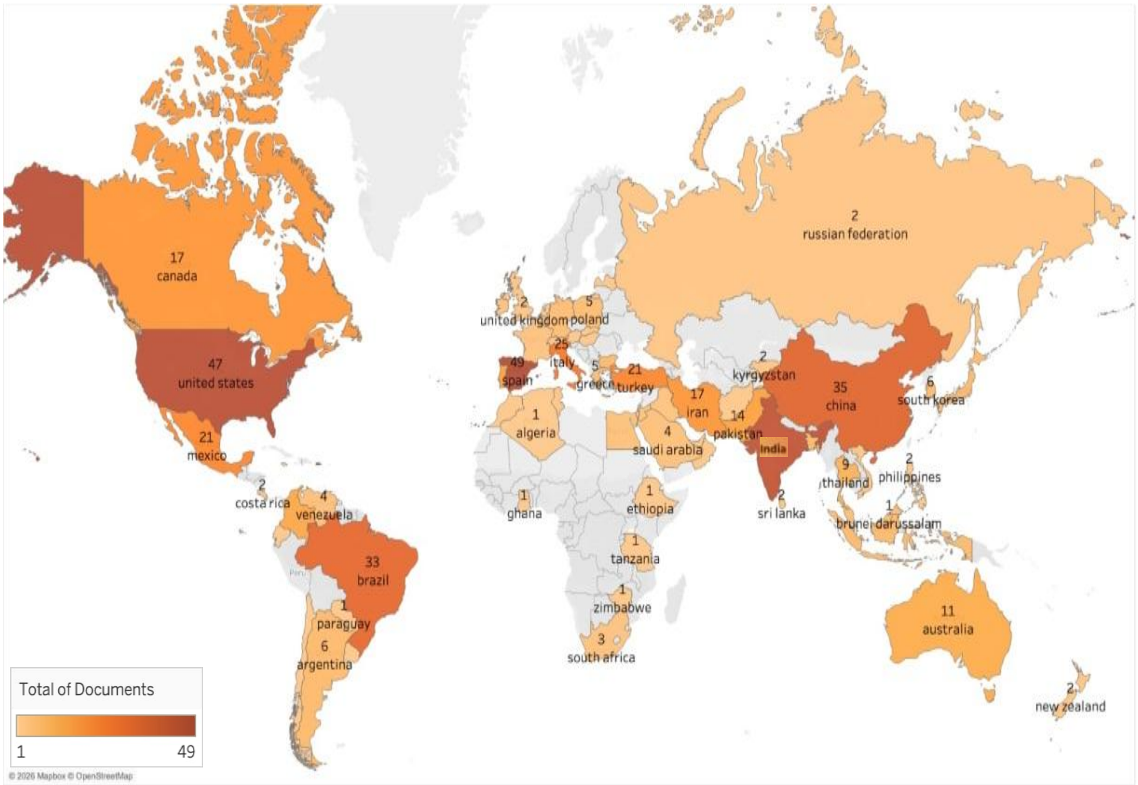


Figure 4. Country and number of publications on edible coatings combined with storage technologies for fruits and vegetables.

The dominance of China, as shown in the map of author/country productivity on this topic, can be explained by two main factors: (i) leadership in publications in the field of edible coatings/films for horticultural commodities; recent bibliometric mapping shows that Brazil and China are the most productive countries; and (ii) the significant domestic need to reduce postharvest losses along the cold chain, thereby driving R&D investments and interinstitutional collaborations on the “coatings + cold chain” theme (both points are clearly documented in the abstract and results section of the bibliometric study) (13). Thus, the pattern of increasing documents in the figure is not just about “quantity,” but reflects a scientific practical impetus to synergize surface technology (coatings) with atmospheric and temperature management areas that are now at the forefront of research and are increasingly cited in postharvest literature (11).

In terms of journal and institutional contributions, postharvest research on fruits and vegetables is widely disseminated through top-tier journals such as the International Journal of Biological Macromolecules, LWT, Journal of Food Processing and Preservation, and Postharvest Biology and Technology, which serve as central hubs for citations and primary channels for dissemination, a reflection of the active involvement of the research community and interconnected academic affiliations (12). Spain’s dominance (e.g., University Miguel Hernández/UMH) on the map highlights its pioneering role in the application of *Aloe vera* as a commercial coating for cold stored fruits; their seminal work with UMH affiliation was the first to demonstrate that *Aloe vera* coating effectively maintains the quality and microbiological integrity of table grapes during cold storage and shelf life (14). A strong postharvest tradition (especially regarding citrus, grapes, and Mediterranean products), the central role of European journals as citation hubs, and the intercontinental collaborative networks observed on the map all help explain why Spain appears so dominant in this topic (13,15,16).

Figure 5 shows a map of country contributions highlighting the United States, Brazil, Mexico, Canada, India, China, as well as several Asia-Pacific countries, such as Vietnam and Australia. The pattern of scientific production on the topic of edible coating synergy and storage technology is clustered in countries with strong postharvest research capacity and large horticultural ecosystems. This finding is consistent with global bibliometric studies showing Brazil and China as the top producers of publications, while Spain, Brazil, China, India, and the United States serve as “central nodes” in international collaboration networks; countries such as Australia, Spain, and Canada display high ratios of cross-country collaboration. In terms of publication channels, journal network analyses place the International Journal of Biological Macromolecules, Postharvest Biology and Technology, and LWT as the most productive and closely inter-referencing sources, thus functioning as “hubs” for dissemination and methodological standardization in this field. The roles of institutions can also be visualized on the country map; node size represents the number of articles by authors/institutions in each country, indicating output concentration at major universities and food research centers (13). The consistency of publication channel patterns is further supported by systematic bibliometric reviews on specific commodities (e.g., bananas), which identified contributions from 45 different journals and mapped indicators of contributors, academic affiliations, and collaboration networks (Shinga, Silue, and Fawole 2025; Silué and Fawole 2024). The relevance of cross-country and cross-journal collaboration is becoming increasingly strategic, as the scientific substance connects to “Edible Coatings Combined with Storage Technologies” practices. Experimental literature shows that combining edible coatings with modified atmosphere packaging (MAP) outperforms single treatments in suppressing respiration, browning, and microbial loads in fresh-cut fruits (15). This aligns with mechanistic reviews indicating that coating layers form semi-permeable barriers that create a modified atmosphere around the fruit. Overall, the research mapping aligns with the latest bibliometric evidence: the contributions of core journals, output concentration at leading institutions in countries with strong research capabilities, and international partnership networks together drive the acceleration of research on the synergy of coatings with refrigeration/MAP/CA along the cold chain. (13,15–17).

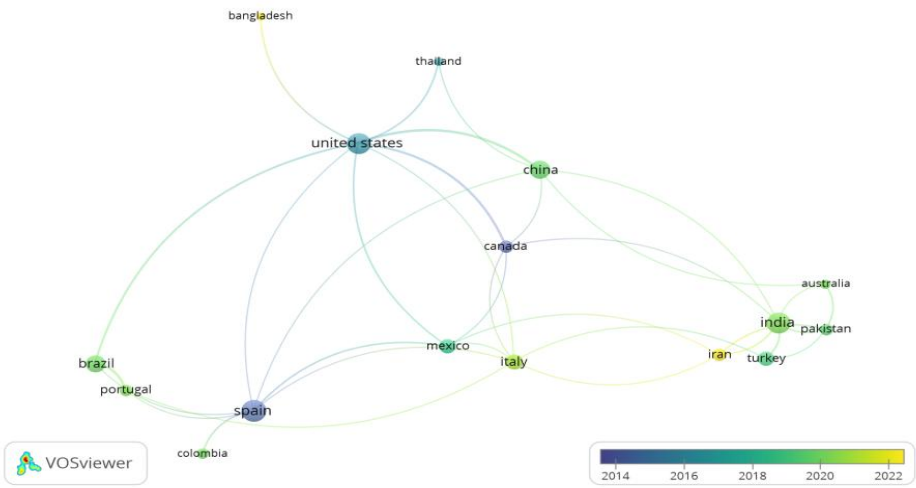
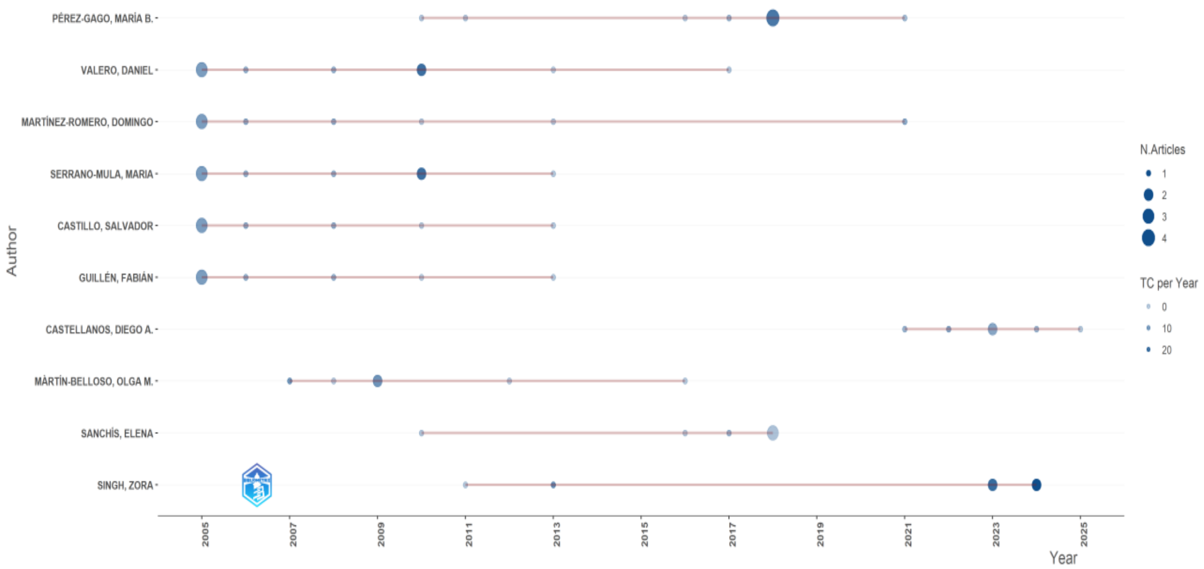


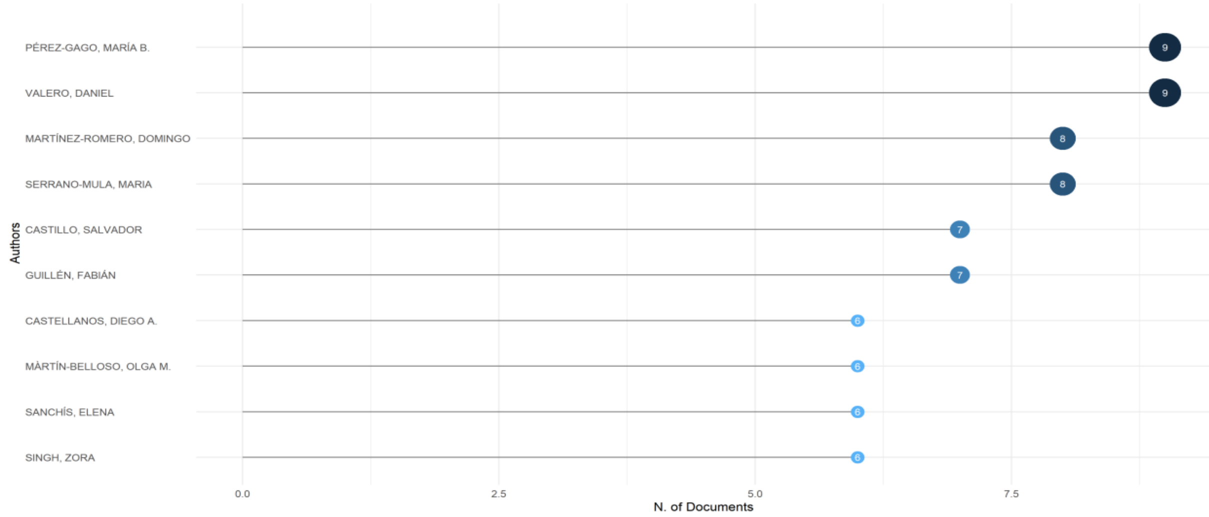
Figure 5. Collaboration network between countries on edible coatings combined with storage technologies for fruits and vegetables.

3.3. Author's Production Over Time and The Most Relevant Author

Authors' production over time and most relevant author on the topic edible coatings combined with storage technologies for fruits and vegetables (Figure 6) shows that the most influential writers are dominated by the Spanish cluster, especially María B. Pérez Gago, Daniel Valero, Domingo Martínez Romero, María Serrano Mula, Salvador Castillo, and Fabián Guillén, who have shown a consistent publication record from the mid-2000s to the late 2010s; the large TC/Year bubbles in the 2018–2019 range indicate a high citation impact. Another strong contributor based in Spain is Olga M. Martín-Belloso (Universitat de Lleida), while the latest expansion phase can be seen with Diego A. Castellanos (2021–2025) and Zora Singh (Australia), reflecting recent global interconnectedness.



(a)



(**b**)

Figure 6. Authors' production over time and the most productive authors (a) and the most relevant authors (b) on the topic edible coatings combined with storage technologies for fruits and vegetables

The analysis of the most relevant authors (Figure 6) indicates that Pérez is the most productive contributor within the dataset, reflecting a strong and sustained research presence in the field of edible coatings and postharvest storage technologies. The high productivity of Pérez is accompanied by a substantial citation impact, suggesting that the author's publications have gained significant recognition and influence within the scientific community. María B. Pérez-Gago, affiliated with the Instituto Valenciano de Investigaciones Agrarias (IVIA), Valencia, Spain, has extensively contributed to studies on biopolymer-based edible coatings, antimicrobial formulations, and integrated postharvest preservation strategies for fresh produce. Overall, the prominence of Pérez in this analysis highlights the role of leading scholars in shaping intellectual structure and scientific research on edible coating technologies and postharvest storage systems. This pattern is consistent with the international bibliometric analysis that positions Spain as a central node in the collaboration network, with a high ratio of international collaborations, and ranks it among the most productive countries, along with Brazil, China, India, Italy, and the US; Spain's collaboration metrics and central position are noted (18). In addition to these networks, Spain's dominance in our dataset is also reasonable considering the large number of postharvest Mediterranean horticulture "research schools" (e.g., UMH and Univ. de Lleida) that have historically been active in edible coatings for fruit. In terms of the most influential articles, contributions that integrate coatings with storage technologies tend to achieve citation impact: recent reviews confirm that the synergistic effect of coating + MAP is still underexplored and requires further research, so works that bridge these two domains receive greater attention (11). Applied evidence about the combination of composite coatings with MAP that extends shelf life (e.g., for tropical fruits) affirms the cross-technology relevance seen in the author production patterns (12). The publication channels most frequently at the core of these key studies, namely the International Journal of Biological Macromolecules, Postharvest Biology and Technology, and LWT, have also been identified as sources that inter-cite one another within the network of journals in this field (18).

The most influential articles (Table 1) show that the work by Daniel *et al.* (2010) ranks at the top with 320 citations (20 per year), followed by Tapia *et al.* (2007) (218 citations) and a surge in contributions from the "new generation" with a high citation rate per year, such as Mostafidi *et al.* (2020) (35.33 per year) and Gaikwad (2020) (31.67 per year). Meanwhile, the work by Zhang *et al.* (2021) has also shown an upward trend (36.20 per year), marking a shift in influence toward articles that link coatings with cold chain/MAP/CA and postharvest quality attributes.

Table 1. The most influential articles on edible coatings combine storage technologies for fruit and vegetables.

Rank	Authors	Title	Year	Total Citation	TC per Year
1	(19)	Postharvest Biology and Technology for Preserving Fruit Quality	2010	320	20.00
2	(20)	Alginate- and Gellan-Based Edible Films for Probiotic Coatings on fresh-cut Fruits	2007	218	11.47
3	(21)	A review of recent trends in the development of the microbial safety of fruits and vegetables	2020	212	35.33
4	(22)	Ethylene scavengers for active packaging of fresh food produce	2020	190	31.67
5	(23)	Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables	2019	189	27.00
6	(24)	The use of packaging techniques to maintain freshness in fresh-cut fruits and vegetables: a review	2009	187	11.00
7	(25)	Advances in biochemical mechanisms and control technologies to treat chilling injury in postharvest fruits and vegetables	2021	181	36.20
8	(26)	Mango; Postharvest Biology and Biotechnology	2013	177	13.62
9	(27)	Improvement of Table Grapes Quality and Safety by the Combination of Modified Atmosphere Packaging (MAP) and Eugenol, Menthol, or Thymol	2005	174	8.29
10	(28)	Sweet cherry (*Prunus avium*): Critical factors affecting the composition and shelf life	2014	172	14.33

* Total citations per year (TC/year)

3.4. Trend of topic development of edible coatings combined with storage technologies for fruit and vegetables

The research landscape of edible coatings combined with storage technologies for fruits and vegetables shows a thematic axis increasingly focused on integrating edible coatings with active/smart packaging and gas management (O_2/CO_2/ethylene) (Figure 7). The highest frequency topics edible coating (n=137), active packaging (n=98), modified atmosphere packaging/MAP (n=95), food preservation (n=111), essential oils (n=63), cellulose (n=40), and crosslinking (n=23) appear early and continue through 2024–2025, while new terms such as smart packaging in the third quarter of 2025 and specific phenolic compounds, such as caffeic acid, by mid-2025 indicate a shift toward enhanced functional and sensory bio-based coatings in cold chain systems. In line with this pattern, recent reviews confirm that single treatments (coating or MAP alone) have limitations, and their optimization requires a synergistic approach of sequential application of edible coating followed by modified atmosphere packaging and further research to assess the appropriate gas conditions for layered products (29).

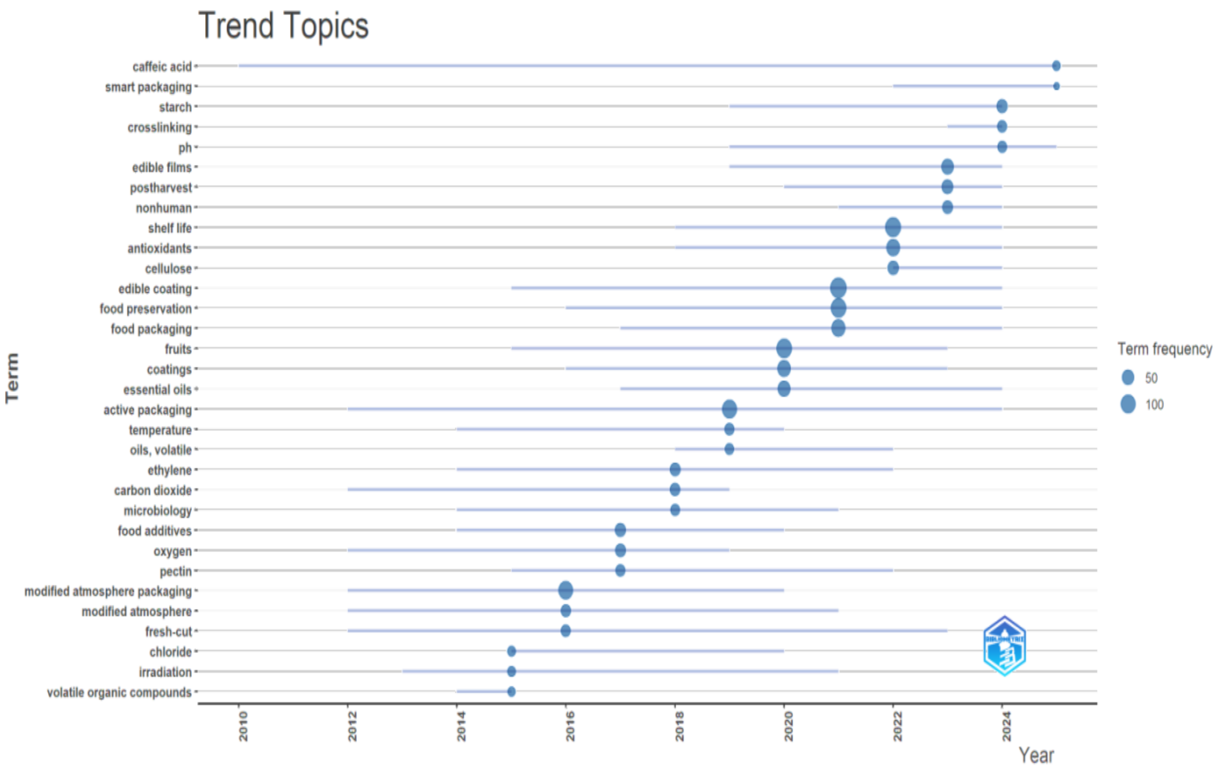


Figure 7. Trend-topic map of edible coatings combined with storage technologies for fruits and vegetables.

The research of (29) predicts for the next 2–3 years: (i) phenolic/EO-based active coatings with controlled release within MAP, following recommendations to expand research on active vapour producing pad/film in controlled packaging (ii) Smart packaging that monitors temperature/humidity/gas in real-time via sensor/IoT will become mainstream in the fruit vegetable cold chain (iii) The integration of scavengers (oxygen/ethylene) and moisture absorbers along with coatings is seen as the "next leap" in MAP, with editorial evidence highlighting the combination gap and the synergistic effect of both (iv) Development of bio-based biosensors (anthocyanin/curcumin, etc.) (30).

Based on the table of articles and influential authors (Table 1), the writing landscape on the topic of cold chain synergy of edible coatings combined with storage technologies for fruits and vegetables shows that the work of Daniel *et al.* (2010) ranks first with 320 citations (20/year), followed by Tapia *et al.* (2007) (218 citations) and a surge of "new generation" contributions with high annual citation rates, such as Mostafidi *et al.* (2020) (35.33/year) and Gaikwad (2020) (31.67/year). Meanwhile, according to Zhang *et al.*, there is also an upward trend (36.20/year), marking a shift of influence towards articles linking coatings with cold chain/MAP/CA and postharvest quality attributes (31).

These bibliometric findings are consistent with empirical evidence and recent reviews over the last five years: a study (15) on fresh-cut pineapple showed that EC + MAP outperforms single EC or MAP treatments in suppressing respiration, reducing PPO/POD, delaying browning, and extending storage quality (30). In persimmon fresh-cut fruit, (32) reported that EC+MAP provides the highest sensory scores and best microbial control; even the reduction in respiration rate by coating is significant only when samples are within active MAP. Synthetically, the review (29) emphasizes that single treatments (EC or MAP) are limited and calls for the optimization of EC + MAP synergy. Therefore, the most influential authors and articles are not only historically highly cited but also those that promote the combined paradigm (EC with refrigeration/MAP/CA) which is now proven to have the greatest impact on the quality, microbiological safety, and shelf life of fruits and vegetables throughout the cold chain

3.5. Global Research Trends in The Integration of Edible Coatings With Storage Technologies For Fruit and Vegetables

Edible coatings combined with controlled storage conditions were generally associated with extended shelf life and improved quality retention in fruits and vegetables. Formulations based on essential oils, chitosan, pectin, alginate, starch, and related biopolymers reduced weight loss, maintained firmness and colour, and suppressed microbial growth when used together with refrigeration or modified atmosphere packaging. For example, one report on a buckwheat starch-based composite noted negligible weight loss versus 35.3% in uncoated produce, and another on acid-enhanced coatings reduced browning from 82% to 7% compared to controls. Research data related to countries that widely apply edible coatings combined with storage technology on several fruit and vegetable commodities are presented in Tables 2 and 3.

Table 2. Characteristics of included studies on edible coatings combined with storage technologies for fruit and vegetables.

Study Focus	Coating Type	Storage Technology	Target Produce	Study
Alginate-based coating with essential oils for shelf life and quality	Sodium alginate + thyme/oregano essential oils	Refrigeration (4 °C, 12 days), modified atmosphere packaging (polypropylene trays)	Fresh-cut papaya cubes	(33)
Buckwheat starch-xanthan gum-lemongrass oil composite for plum preservation	Buckwheat starch, xanthan gum, lemongrass oil	Refrigeration (4 °C, 20 days)	Plums ('Santa Rosa')	(34)
Tamarind starch/gelatin + apricot oil for grape shelf life	Tamarind starch, gelatin, apricot oil	Refrigeration (4 °C, 20 days); ambient	Grapes	(35)
Multiple coatings (alginate, starch, chitosan, pectin) for prickly pear	Alginate, starch, chitosan, pectin	Refrigeration (5 ± 2 °C, 6 weeks)	Prickly pear (orange, red)	(36)
Galbanum gum + cumin oil for cherry quality	Galbanum gum, cumin oil, calcium chloride	Refrigeration (2 ± 1 °C, 30 days, 90-95% relative humidity)	Sweet cherry (cultivar Bing)	(37)

Study Focus	Coating Type	Storage Technology	Target Produce	Study
Carrageenan + green tea extract for antiviral berry coatings	Kappa-, iota-, lambda-carrageenan, green tea extract	Refrigeration (10 °C, 4 days, 54% relative humidity)	Blueberries, raspberries	(38)
Guar gum + essential oils for mango shelf life	Guar gum, essential oils, glycerol	Refrigeration (10 °C, 80-85% relative humidity, 24 days), modified atmosphere packaging (zip-lock bags)	Unripe green mangoes	(39)
Guar gum coating + modified atmosphere packaging for blackberry preservation	Guar gum, sorbitol, glycerol, canola oil, Tween 80	Refrigeration (5 °C, 13 days), modified atmosphere packaging (PET/PLA clamshells)	Blackberries (cultivar Castilla)	(40)
Edible coatings + modified atmosphere packaging for persimmon quality	Whey protein isolate, soy protein isolate, hydroxypropyl methylcellulose, pectin, beeswax, glycerol, antibrowning agents	Refrigeration (5 °C, 9 days), modified atmosphere packaging (5 kPa O_2/N_2)	Fresh-cut persimmon ('*Rojo Brillante*')	(41)
Chitosan + Thymus oil for strawberry shelf life	Chitosan, Thymus capitatus oil	Refrigeration (5 ± 0.5 °C, 15 days, 70% relative humidity)	Strawberries (*Fragaria x ananassa*)	(42)
Gelatin + propolis extract for antifungal raspberry coatings	Gelatin, propolis extract, glycerol	Refrigeration (5 °C, 14 days)	Raspberries	(43)
Carboxymethyl cellulose/alginate + acids for apple browning and shelf life	Carboxymethyl cellulose, sodium alginate, citric/oxalic acid	Refrigeration (4 °C, 12 days, 95% relative humidity)	Fresh-cut apple ('*Annurca Rossa del Sud*')	(44)
Pectin + bacteriocin for blackberry storage	Celery pectin, bacteriocin, glycerol monostearate	Refrigeration (4 °C, 16 days, 75% relative humidity)	Blackberries (*Rubus fruticosus*)	(45)
Solid lipid nanoparticle-xanthan gum for guava shelf life	Xanthan gum, polyethylene glycol, Candeuba wax (solid lipid nanoparticle)	Refrigeration (10 °C, 85% relative humidity, 30 days)	Guava ('Media China')	(46)
Gelatin/konjac + hiba oil for ethylene inhibition in peach	Gelatin, konjac glucomannan, hiba oil, glycerol	Refrigeration (10 °C, 22 days; 0 °C, 28 days, 90% relative humidity)	Peaches ('Hikawa Hakuho')	(47)
Chitosan-citric acid for guava rot control	Chitosan, citric acid	Refrigeration (4 ± 2 °C, 14 days); room temperature (24 ± 2 °C, 7 days)	Fresh-cut guava	(48)
Carboxymethyl cellulose + gamma irradiation for pear storage	Carboxymethyl cellulose	Refrigeration (3 ± 1 °C, 45/60 days, 80% relative humidity); ambient	Pear (William)	(49)

Study Focus	Coating Type	Storage Technology	Target Produce	Study
Hydroxypropyl methylcellulose + beeswax for early guava shelf life	Hydroxypropyl methylcellulose, beeswax, stearic acid, glycerol	Cold chamber (22 ± 0.3 °C, 8 days, 65 ± 8% relative humidity)	Guava ('Pedro Sato')	(50)
Chitosan for fresh-cut mango shelf life	Chitosan	Refrigeration (4 °C, 6 months, 70-85% relative humidity); ambient	Mango ('Langra')	(51)
Pectin + plant extracts for pear preservation	Pectin, strawberry tree/apple pomace extract	Dynamic controlled atmosphere (-0.5 °C, 0.5% O_2, 0.4% CO_2, 4 months); normal atmosphere (2°C)	Pear ('Rocha')	(52)
Agar + pomegranate oil for guava conservation	Agar, pomegranate seed oil	Refrigeration (10 °C, 10 days, 40% relative humidity)	Guava ('Paluma')	(53)
Alginate + cinnamaldehyde nanostructured lipid carrier for date shelf life	Sodium alginate, cinnamaldehyde, nanostructured lipid carrier	Refrigeration (4 °C, 180 days); ambient (25 °C)	Date (Mazafati)	(54)
Gum Arabic + plant extracts for guava storage	Gum Arabic, cactus/moringa/henna extracts	Refrigeration (7 ± 1 °C, 24 days, 90 ± 5% relative humidity)	Guava ('Maamoura')	(55)
Guar gum + Pycnocycla bashagardiana essential oil for pistachio shelf life	Guar gum, *Pycnocycla bashagardiana* oil	Refrigeration (2 ± 1 °C, 60 days, 85 ± 5% relative humidity)	Pistachios ('Ahmad-Aghaei')	(56)
Cellulose-based multifunctional coating for fruit preservation	Cellulose microgel, montmorillonite, cationic cellulose, ascorbic acid	Ambient (15–26 °C, 35% relative humidity)	Strawberries, Shine Muscat grapes	(57)
Essential oil-based coatings + irradiation/modified atmosphere packaging for food safety	Essential oils (various)	Modified atmosphere packaging, irradiation, refrigeration (4 °C, 28+ days)	Carrots (ready-to-eat)	(58)
storage technologies for date palm	Chitosan, wheat gluten, waxes	Refrigeration, modified atmosphere packaging, ozone, irradiation	Date palm ('Khalas', 'Kabkab')	(59)
Essential oils + modified atmosphere packaging for fruit quality	Essential oils (various)	Modified atmosphere packaging, cold storage	Sweet cherry, table grapes, strawberry	(60)
Cellulose acetate + Cucumis extract for antioxidant packaging	Cellulose acetate, Cucumis metuliferus extract	Standard (30 °C, 92 hours)	Cucumis metuliferus, fresh-cut apples	(61)
Gaseous citral for grape spoilage control	Citral vapor	Standard (12 °C, 80-85% relative humidity, 5-15 days)	Table grapes (cultivar Italia)	(62)

Study Focus	Coating Type	Storage Technology	Target Produce	Study
Modified atmosphere packaging + antioxidant dip for apple shelf life	Ascorbic/citric acid dip	Modified atmosphere packaging (various gases), refrigeration (4 °C, 11 days)	Apples ('Golden Delicious')	(63)
Metabolomic/transcriptomic analysis of mulberry ripening	Flavonoids (potential coatings)	Standard	Mulberry (Da10)	(64)

Table 3. Global research distribution on the topic of edible coatings combines with storage technologies for fruit and vegetables.

Geographic Region	Research Volume	Dominant Technologies	Emerging Trends	Study
South Asia	High	Alginate + essential oil, refrigeration	Essential oils, modified atmosphere packaging	(65)
South Asia	High	Starch/gum/essential oil, refrigeration	Composite coatings	(66)
South Asia	Moderate	Starch/gelatin/essential oil, refrigeration	Antimicrobial oils	(35)
Europe/South America	Moderate	Multiple coatings, refrigeration	Chitosan/starch/pectin	(67)
Middle East	Moderate	Gum/essential oil, refrigeration	Bioactive coatings	(37)
Europe	Moderate	Carrageenan, refrigeration	Antiviral coatings	(68)
South Asia	Moderate	Guar gum/essential oil, refrigeration/modified atmosphere packaging	Essential oils	(39)
South America	Moderate	Guar gum + modified atmosphere packaging, refrigeration	Biodegradable films	(40)
Europe	Moderate	Protein/polysaccharide, modified atmosphere packaging	Antibrowning agents	(41)
Europe	Moderate	Chitosan + essential oil, refrigeration	Scanning electron microscopy analysis	(69)
South America	Moderate	Gelatin + propolis, refrigeration	Encapsulation	(43)
Europe	Moderate	Carboxymethyl cellulose/alginate + acids, refrigeration	Layer-by-layer coatings	(44)
Europe	Moderate	Pectin + bacteriocin, refrigeration	Bacteriocins	(70)
Latin America	Moderate	Solid lipid nanoparticle-xanthan, refrigeration	Nanoparticles	(46)
East Asia	Moderate	Gelatin/konjac + essential oil, refrigeration	Ethylene inhibition	(47)
South America	Moderate	Chitosan-citric acid, refrigeration	Fungal control	(48)
South Asia	Moderate	Carboxymethyl cellulose + irradiation, refrigeration	Gamma irradiation	(49)
South America	Moderate	Hydroxypropyl methylcellulose + beeswax, cold chamber	Early harvest	(50)

Geographic Region	Research Volume	Dominant Technologies	Emerging Trends	Study
South Asia	Moderate	Chitosan, refrigeration	Long-term storage	(51)
Europe	Moderate	Pectin + extract, dynamic controlled atmosphere	Metabolomics	(52)
South America	Moderate	Agar + oil, refrigeration	Nutraceuticals	(53)
Middle East	Moderate	Alginate + nanostructured lipid carrier, refrigeration	Nanostructured carriers	(71)
North Africa	Moderate	Gum Arabic + extracts, refrigeration	Plant extracts	(72) 2022
Middle East	Moderate	Guar gum + Pycnocycla bashagardiana essential oil, refrigeration	Aflatoxin control	(56)
East Asia	Moderate	Cellulose-based, ambient	Multifunctional coatings	(73)
North America/Europe	Moderate	Essential oil + modified atmosphere packaging + irradiation	Food safety	(58)
North Africa	Review	Chitosan/wax, refrigeration/modified atmosphere packaging	Ozone, electron beam	(74)
Europe	Review	Essential oil + modified atmosphere packaging, cold storage	Active packaging	(75)
South America	Moderate	Cellulose acetate + extract, standard	Antioxidant packaging	(61)
Europe	Moderate	Citral vapor, standard	Gaseous antimicrobials	(62)
Europe	Moderate	Modified atmosphere packaging + antioxidant, refrigeration	Alternative gases	(76)
East Asia	Moderate	Flavonoids (potential), standard	Omics-guided coatings	(77)

3.6. Biopolymers, Active Compounds and Storage Technologies Most Commonly Combined in Edible Coating Applications

The most frequently combined components in edible coating applications are chitosan, alginate, and pectin as biopolymers; essential oils and plant extracts as active compounds; and refrigeration and modified atmosphere packaging as storage technologies, with network analysis showing that biopolymers function as central hubs that repeatedly connect with the other components (Table 4). Edible coating studies have shown that polysaccharide-based biopolymers dominate, with chitosan, alginate, and pectin appearing most frequently (Table 5). In these studies, essential oils (for example, lemongrass, thyme, and oregano) and plant extracts (such as pomegranate peel and propolis) are the active compounds most often combined with these biopolymers. Refrigeration and Modified Atmosphere Packaging (MAP) are the preferred storage technologies; refrigeration appears in 30 studies and MAP in 14, sometimes in combination. Network analysis showed that chitosan, alginate and pectin serve as central hubs that repeatedly co-occur with essential oils or plant extracts and with specific storage methods. For instance, systems comprising a biopolymer, essential oil, and refrigeration are reported in seven studies, while those combining a biopolymer, plant extract, and MAP are described in 4 studies. Documentation across studies links these combination shelf-life extension, antimicrobial and antioxidant preservation of quality attributes such as moisture retention and color stability.

Table 4. Frequency analysis of component combinations on the topic edible coatings combined with storage technologies for fruit and vegetables.

Component Combination	Freq. Count	Primary Applications	Performance Outcomes
Biopolymer-Active Compound Pair			
Chitosan + Essential Oil (various)	5	Strawberry, mango, prickly pear, beef, berries	Antimicrobial, antioxidant, shelf life extension
Alginate + Essential Oil	3	Papaya, date, prickly pear	Antimicrobial, moisture retention, shelf life extension
Pectin + Plant Extract	3	Pear, blackberry, apple	Antioxidant, color/texture preservation
Guar Gum + Essential Oil	2	Mango, pistachio	Antimicrobial, shelf life extension
Cellulose Derivative + Plant Extract	2	Apple, general fruit	Antioxidant, oxygen barrier, shelf life extension
Gelatin + Plant Extract	2	Raspberry, goat meat	Antimicrobial, antioxidant, shelf life extension
Biopolymer-Storage Technology Pair			
Chitosan + Refrigeration	5	Mango, strawberry, prickly pear, beef, berries	Shelf life extension, quality maintenance
Alginate + Modified Atmosphere Packaging (MAP)	3	Papaya, date, prickly pear	Moisture retention, reduced respiration
Pectin + Refrigeration	3	Pear, blackberry, apple	Color/texture preservation, shelf life extension
Guar Gum + Modified Atmosphere Packaging (MAP)	2	Mango, blackberry	Shelf life extension, reduced weight loss
Cellulose Derivative + Refrigeration	2	Apple, general fruit	Oxygen barrier, shelf life extension
Biopolymer-Essential Oil-Refrigeration			
Combination Type	Freq. Count	Primary Applications	Performance Outcomes
Biopolymer + Essential Oil + Refrigeration	7	Mango, papaya, strawberry, prickly pear, pistachio, beef, berries	Antimicrobial, antioxidant, shelf life extension
Biopolymer + Plant Extract + Modified Atmosphere Packaging (MAP)	4	Pear, apple, blackberry, table grapes	Antioxidant, color/texture preservation, shelf life extension
Biopolymer + Essential Oil + Modified Atmosphere Packaging (MAP)	3	Papaya, date, pistachio	Antimicrobial, shelf life extension
Biopolymer + Plant Extract + Refrigeration	3	Guava, goat meat, raspberry	Antimicrobial, antioxidant, shelf life extension

Table 5. **The central hub component of edible coatings combines with storage technologies for fruits and vegetables.**

Network Parameter	Value/Description	Key Nodes	Structural Implications
Most Central Biopolymers	Chitosan, alginate, pectin	Chitosan, alginate, pectin	Serve as hubs connecting to multiple actives and storage technologies
Most Central Active Compounds	Essential oils, plant extracts	Lemongrass, thyme, oregano, propolis, pomegranate peel	Frequently co-occur with central biopolymers
Most Central Storage Technologies	Refrigeration, Modified Atmosphere Packaging (MAP)	Refrigeration, Modified Atmosphere Packaging (MAP)	Ubiquitous across applications, often combined with coatings

4. Conclusions

This article reviews global research trends in integrating edible coatings with storage technologies such as cold chain, refrigeration, modified atmosphere packaging (MAP), and controlled atmosphere (CA) to extend the shelf life of fruits and vegetables. A systematic literature review based on PRISMA guidelines and network analysis of bibliometric data from Scopus identified 47 key studies out of the initial 425 records. The analysis shows a consistent growth in publications since the mid-2000s, with a sharp increase after 2014, peaking in 2024. Spain emerged as a central hub of international collaboration, while key journals such as the International Journal of Biological Macromolecules, LWT, Journal of Food Processing and Preservation, and Postharvest Biology and Technology served as the main dissemination channels. The most frequently combined components were chitosan, alginate, and pectin as biopolymers; essential oils and plant extracts as active compounds; and refrigeration and MAP as storage technologies. Network analysis revealed that the biopolymers function as central connectors that repeatedly link with the other components. The integrated coating-storage systems were found to improve several postharvest quality attributes of fruits and vegetables to varying degrees, including shelf life extension by 2 to over 60 days, preservation of nutritional quality, significant reduction in microbial loads, and maintenance or improvement of sensory attributes like appearance, texture, and flavor. Future research should focus on active phenolic coatings with controlled release in MAP, smart packaging with real-time monitoring of storage conditions, integration of scavengers and moisture absorbers with coatings, and the development of bio-based sensors for detecting temperature abuse in the cold chain.

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Author Contributions

Conceptualization, M, S.H.H., and A.D.; methodology, M. and S.H.H.; software, S.H.H. and A.D.; validation, G.S. and F.A.; formal analysis, M., S.H.H., and A.D.; investigation, S.H.H.; resources, M. and S.M.; data curation, S.M. and R.; writing original draft preparation, M.; writing, review, and editing, M., S.H.H., S.M., G.S., F.A., R., and A.D. ; visualization, M. and

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Conflicts of Interest

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