International Food Research Journal 32(2): 300 - 317 (April 2025)
Journal homepage: *http://www.ifrj.upm.edu.my*

Review

Advancements in carbon-based food packaging with antimicrobial properties: A bibliometric and content analysis

[1,2]*Indrawan, D. A., [1,4]Pranoto, B., [2]Efiyanti, L., [1]Firmansyah, I., [2]Pari, G., [3]Kusnandar, F. and [1]Karlinasari, L.

[1]*Natural Resources and Environmental Management Science (NREMS) Study Program, Graduate School, IPB University, 16144 Bogor, Indonesia*
[2]*Research Center for Biomass and Bioproduct, National Research and Innovation Agency, 16911 Bogor, Indonesia*
[3]*Department of Food Science and Technology, IPB University, 16680 Bogor, Indonesia*
[4]*Research Center for Limnology and Water Resources, National Research and Innovation Agency, 16911 Bogor, Indonesia*

Article history

Received:
13 August 2024
Received in revised form:
25 November 2024
Accepted:
29 November 2024

Keywords

food,
packaging,
antimicrobial,
carbon,
shelf life

Abstract

This review presents a comprehensive bibliometric analysis of advancements in antimicrobial food packaging involving carbon-based materials. By systematically examining research from January 1991 to December 2023, we highlight the evolution of studies focusing on the integration of antimicrobial agents to enhance food safety and extend product shelf life. The analysis utilises bibliometric indicators and thematic content analysis, covering key trends, publication outputs, and collaboration networks. Insights into the multidimensional research landscape reveal the pivotal role of carbon-based compounds in developing sustainable antimicrobial packaging solutions, aligning with global sustainability and public health objectives.

DOI
https://doi.org/10.47836/ifrj.32.2.01

Introduction

The study of food packaging integrated with antimicrobial properties has long been of interest due to its potential to improve food safety and prolong the shelf life of food products. Antimicrobial packaging works by reducing or inhibiting the growth of microorganisms that contaminate food, a concept explored in earlier research (LaCoste *et al*., 2005). This technology is consistent with efforts towards carbon neutrality, employing renewable or biodegradable biopolymer matrices combined with environmentally friendly antimicrobial agents (Zhao *et al*., 2023).

Early research has emphasised the potential of natural antimicrobial agents in reducing spoilage and pathogenic microorganisms (Irkin and Esmer, 2015). A study by Sulistyo *et al*. (2023) demonstrated that bacterial cellulose-based bioplastics fortified with fermented soymilk extract (FSME) containing *Lactobacillus acidophilus* metabolites effectively inhibited the growth of *E. coli*, *S. aureus*, and *S.* Typhimurium, while significantly increasing the shelf-life of strawberries as a model food system. Metal nanoparticles, particularly silver, have been studied for their antimicrobial effectiveness, although concerns regarding their toxicity have been noted (Ahmad *et al*., 2021). Additionally, biodegradable materials infused with phenolic acids and plant extracts have demonstrated promise as antimicrobial agents (Ordoñez *et al*., 2022). Another study by Tirdasari *et al*. (2021) emphasized the critical role of technical innovation and stakeholder collaboration—including government and industry—in the development of sustainable food packaging in Indonesia. The exploration of graphene oxide-

*Corresponding author.
Email: dianindrawan@apps.ipb.ac.id

reinforced bionanocomposite films has further expanded the potential for antibacterial applications in both food packaging and healthcare (Das *et al*., 2023). Carbon-based compounds continue to attract attention due to their inherent antimicrobial properties and their alignment with sustainable practices.

Recent reviews highlight advanced technologies' role in enhancing food safety, extending shelf life, and addressing environmental concerns. Nanotechnology innovations, such as carbon nanotubes and nano-biopolymers, improve food safety and release properties (Bhatt and Shilpa, 2020). Modified atmosphere packaging (MAP) helps prolong meat and fish shelf life by preventing microbial contamination and oxidation (Zouharová *et al*., 2023). Environmental concerns drive research into biodegradable films and coatings, with polysaccharide-based materials like cellulose, chitosan, and starch offering good barrier properties (Cazón *et al*., 2017). Efforts to improve these materials aim for functional, eco-friendly packaging solutions. Antimicrobial packaging technology aims to prevent microbial growth on food contact surfaces, expected to grow with new polymer materials and agents (Appendini and Hotchkiss, 2002). High-barrier film packaging, especially for fishery products, can significantly extend shelf life, but requires careful management to prevent foodborne illnesses (Reddy *et al*., 1991). Nanosilver-based materials offer high efficiency and safety without harmful by-products, enhancing food safety technologies (Bahcelioglu *et al*., 2021).

Scope of analysis

Our analysis encompasses scholarly publications from leading bibliographic databases, including Scopus and Web of Science. Articles published between 1 January 1991 and 31 December 2023 are included in the dataset, ensuring comprehensive coverage of research conducted in the past 32 years.

Key bibliometric indicators, such as publication output, citation metrics, international collaboration networks, and thematic content, are systematically analysed to provide a holistic overview of research activities in the field. Additionally, keyword co-occurrence analysis and network visualisation techniques are employed to elucidate the thematic clusters and emerging topics shaping the discourse on antimicrobial food packaging with carbon.

Antimicrobial carbon for food packaging

Recent studies have examined the antimicrobial properties of carbon-based materials like graphene, carbon nanotubes, and carbon nanoparticles in food packaging. Li *et al*. (2019) demonstrated the effectiveness of graphene-based materials against foodborne pathogens, enhancing food safety and shelf life. Wang *et al*. (2020) showed that carbon nanotube-based films inhibit spoilage and pathogenic microorganisms.

Carbon-based materials exhibit antimicrobial activity through mechanisms such as physical puncturing of microbial cell membranes, generating reactive oxygen species, and disrupting cellular functions (Liu *et al*., 2018). These mechanisms help mitigate microbial contamination in food packaging.

Additionally, carbon-based materials from renewable sources offer sustainable production and disposal, addressing environmental concerns. This research area holds promise for food safety, shelf-life extension, and waste reduction, positioning carbon-based materials as candidates for innovative, eco-friendly food packaging solutions.

Materials and methods

Research planning

We define the review's scope and formulate several research questions (RQs) to guide our exploration.

i. RQ1: What factors have contributed to the consistent annual growth rate in scholarly activity related to the antimicrobial properties of carbon in food packaging?
ii. RQ2: How have international collaborations influenced the research output and innovation in the field of antimicrobial carbon in food packaging?
iii. RQ3: What is the significance of the high citation per document ratio in antimicrobial food packaging with carbon studies?
iv. RQ4: How has the average document age impacted the focus and evolution of research topics in antimicrobial food packaging with carbon?

v. RQ5: What role do distinct author keywords play in defining the multidimensional nature of research endeavours related to antimicrobial food packaging with carbon?

Database selection

Scopus and Web of Science (WoS) databases are used for literature search. Approximately 95% of scientific papers worldwide are in these databases, largely acknowledged as trustworthy metadata sources (Macías-Quiroga *et al.*, 2022). As shown in Figure 1, this bibliometric analysis uses a multi-stage data collection procedure. The plan is modified to improved efficiency and clarity based on the methodology (Page *et al.*, 2021). The flow details a specific search and screening process used in bibliometric analysis for "Food Packaging Antimicrobial Carbon." The process starts by defining the scope and coverage, which includes searches in Scopus and Web of Science (WoS) databases using the fields Title, Abstract, and Keywords, ((food OR nourishment OR sustenance OR fare OR provisions OR edibles OR victuals OR eatables OR refreshments) AND (packaging OR wrapping OR packing OR encasement OR containerisation OR casing OR boxing OR enclosure OR covering) AND (antimicrobial OR antibacterial OR antiseptic OR germicidal OR disinfectant OR sanitising OR antifungal OR antiviral) AND (carbon OR graphite OR diamond OR charcoal OR carbonaceous OR "carbon compound" OR "carbon-based compound")) AND NOT TITLE-ABS-KEY (bibliometric OR scoping AND review OR systematic AND review OR review AND systematic AND literature AND review AND narrative AND review)) within a specified time frame from 1991 to 2024, up until 19 March 2024.

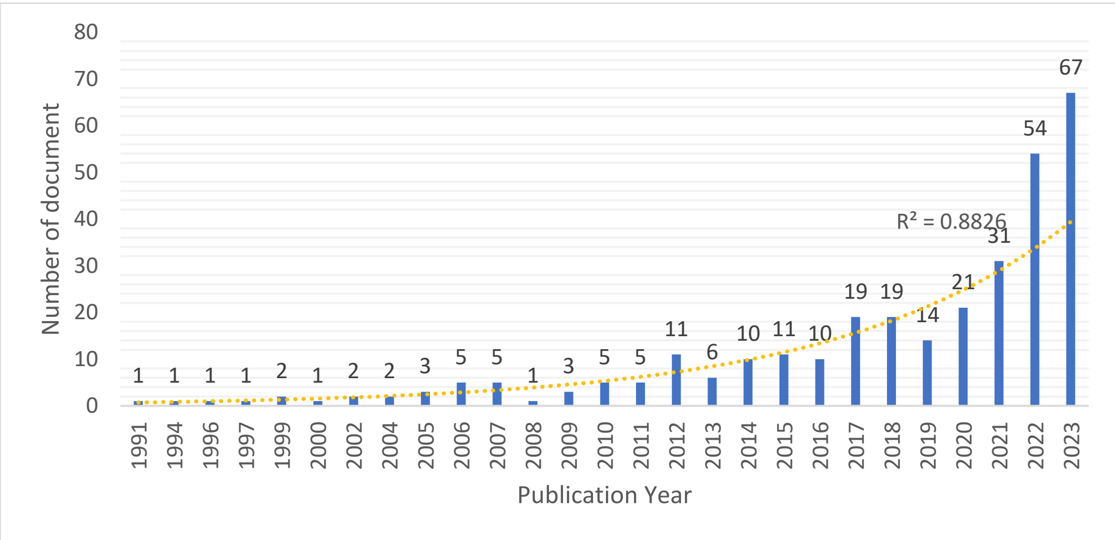

Figure 1. Annual scientific publications from 1991 to 2023.

Two separate search strategies are employed for Scopus and WoS, both utilising a complex string of keywords connected by Boolean operators to refine the search. These keywords encompass terms related to food packaging and antimicrobial carbon materials. Each database yields several documents: 472 from Scopus, and 467 from WoS. From there, the workflow involves filtering these results to include only journal articles written in English, which brings the counts down to 296 documents from Scopus, and 91 from WoS. After removing duplicate records from both databases, the number of unique articles stands at 343.

The final step in the diagram shows a data merge for bibliometric analysis, which seems to include a further refinement step—limiting the articles to those published on or before 31 December 2023. This results in a final count of 267 articles that will be used for the bibliometric analysis. It appears that articles from 2024 have been excluded from this analysis, likely to maintain a complete dataset for 2023. The diagram thus presents a structured approach to narrowing down a large volume of literature to a manageable dataset for in-depth bibliometric analysis.

The study begins with a Descriptive Analysis, where publication and citation trends are tracked over time to gauge the research's interest and impact. It then identifies key journals or venues in the Publication Outlet section, and pinpoints leading authors and countries to determine who have driven this research. The Bibliometric Analysis includes a Co-occurrence Analysis to uncover thematic clusters by examining how often certain terms are mentioned and a Co-authorship Country Analysis to explore international collaborations.

Bibliometric analysis is a quantitative method involving mathematical and statistical techniques to analyse publications within a specific field (Sedira *et al*., 2024). It focuses on examining and measuring various indicators in the published literature to identify patterns and trends (Chen *et al*., 2023). This analysis is crucial for understanding knowledge structure within a particular domain, such as the elaboration likelihood model (Srivastava and Saini, 2022). By conducting bibliometric analysis, researchers can visualise critical features of published articles, detect areas that need further development, and identify potential collaborators (Chiroma *et al*., 2020). Moreover, bibliometrics can help establish the profile of publications on a specific topic, determine qualitative and quantitative changes in scientific research, and identify trends within a discipline (Baier-Fuentes *et al*., 2018).

Bibliometric analysis is performed in the present review using the R Studio and application. Installing the package for the first time requires typing "install.packages('bibliometrix')" in the console tab. Then, to launch biblioshiny, type "library(bibliometrix)" and hit Enter or Run. Then, type "biblioshiny()" in the console tab and hit Run again. Lastly, the content analysis involves a full-text review, thoroughly examining the literature to understand the field's in-depth findings, methodologies, and discussions. This methodology provides a structured approach to understanding the evolution and current state of research on antibacterial carbon used in food packaging.

Bibliometric analysis offers a comprehensive approach to understanding scholarly literature within a specific field when combined with content analysis. While bibliometric analysis focuses on quantitative aspects such as publication patterns and citation analysis, content analysis delves into the qualitative aspects of research content (Tian *et al*., 2019). Content analysis involves systematically categorising and analysing the themes and subjects present in published literature, providing a deeper insight into the research content (Jain *et al*., 2021). By integrating both methods, researchers can better understand the development process, research status, and thematic content within a particular field (Zhang and Hur, 2022).

Results and discussion

The bibliometric analysis of research from 1991 to 2023 highlights several key findings. During this period, 128 sources and 267 documents were identified, reflecting consistent scholarly activity. The research shows an annual growth rate of 13.77%, indicating an increasing interest over time. The involvement of 1,234 authors emphasises the collaborative nature of this research, with single-authored documents accounting for only 1%. Notably, international co-authorship accounts for 25.84% of collaborations, showcasing global reach and established networks.

Each document, on average, has 5.59 co-authors, indicating a trend towards collaborative and interdisciplinary research on the antimicrobial properties of carbon in food packaging. The average document age is 5.95 years, pointing to a relatively recent focus. The presence of 805 distinct author keywords reflects the diverse range of issues and approaches, underscoring the multidimensional nature of this research. The average citation number per document is 44.85, indicating moderate impact and recognition within the scholarly community. This analysis highlights the dynamic and collaborative nature of research on carbon-based antimicrobial food packaging, as characterised by steady growth, international collaboration, and interdisciplinary engagement, with significant implications to the food industry, healthcare, and environmental sustainability.

General statistics

Figure 1 shows the growth of publications per year on antimicrobial carbon in food packaging, spanning from 1991 to 2023. The vertical bars represent the number of documents published each year. The number of publications appears low from the initial years, indicating limited research activity in this field. However, there is a clear upward trend towards more recent years, with a significant increase in publications. This surge reflects a growing interest and possibly advancements in the field. The chart includes a dotted line that represents a trend line fitted to the data points, and the accompanying R-squared (R^2) value is 0.8826. An R^2 value is a statistical measure that indicates the proportion of variance for a dependent variable explained by an independent variable or variables in a regression model.

In this context, the R^2 value suggests that approximately 88.26% of the variance in the yearly count of documents is explained by the year of publication, which is relatively high, and indicates a strong trend over time. This value could imply that factors over the years have consistently influenced the volume of research in this area, such as increased awareness of food safety and the importance of antimicrobial packaging materials. The most notable aspect is the sharp increase in the last few years, culminating with many publications in 2023. This peak may suggest interest, funding, and research output in the field, or it might be due to increased awareness and concern about food safety or technological advances that have made such research more feasible or necessary.

Most relevant sources

The journal with the most publications is the "International Journal of Biological Macromolecules" with 23 documents, followed by "Food Chemistry" with 14, and "Carbohydrate Polymers" with 13. Other significant sources include the "International Journal of Food Microbiology" with 11 documents, and the "Journal of Food Protection" and "Food Packaging and Shelf Life" with eight papers each. Journals such as the "Journal of Agricultural and Food Chemistry" the "Journal of Food Science" "Food Hydrocolloids" and "Food Microbiology" also contribute to the field, but with smaller numbers of publications, ranging from five to seven documents each. This distribution indicates a concentration of research activity within a subset of journals, with the "International Journal of Biological Macromolecules" being the most prominent publisher in this niche. The spread of journals across different focuses, from chemistry to microbiology, also suggests that the topic intersects various disciplines within food science.

Most relevant authors

The author with the most documents is RHIM J-W with 13 publications, followed by EZATI P with ten. Several authors, including WANG J, LIU Y, JIANG S, LIU L, MOLAEI R, SUN J, and ZHANG H, have each contributed five documents. The chart also includes GALOTTO MJ, who has authored four documents. This visualisation highlights the critical contributors to the research field, with the size of the bubble correlating to the number of documents by each author, indicating their relative influence and productivity within this area of study.

Most globally cited documents

i) DE FARIA AF, 2014, COLLOIDS SURF B BIO INTERFACES

This paper has the highest total citations (352) and a high normalised TC (3.6), indicating its significant impact in antibacterial food packaging. It has a moderate citation rate per year (32), suggesting a sustained interest. De Faria *et al.* (2014) presented findings on the antibacterial properties of graphene oxide-silver (GO-Ag) nanocomposites, effective against *Pseudomonas aeruginosa*, with a minimum inhibitory concentration of 2.5 - 5.0 μg/mL. The study highlighted the successful attachment of silver nanoparticles to GO sheets, enhancing antibacterial efficacy, suggesting practical applications in food packaging and medical devices.

ii) SERRANO M, 2005, INNOVATIVE FOOD SCI EMERG TECHNOL

Despite fewer total citations (300) and a lower normalised TC (1.78), it has a moderate citation rate per year. Serrano *et al.* (2005) reported the effects of essential oils on cherry quality; finding that eugenol, thymol, and menthol reduced microbial populations, and improved quality; while eucalyptol had detrimental effects. These findings suggest potential applications of MAP with essential oils for better cherry preservation.

iii) MATAN N, 2006, INT J FOOD MICROBIOL

With fewer total citations (298) and a lower normalised TC (1.74), its citation rate per year (15.68) is slightly higher. Matan *et al.* (2006) highlighted the inhibitory effects of cinnamon and clove oils on microbial growth, suggesting their use as natural antimicrobial agents in active packaging systems to enhance food preservation.

iv) CHEN H, 2013, SMALL

This paper has a moderate total citation count (223), but a high normalised TC (3). Chen *et al.* (2013) revealed that carbon nanotubes (CNTs) increased DNA and RNA release from bacteria, indicating their potential as effective antibacterial agents against drug-resistant bacteria, contributing to the understanding of CNTs in combating bacterial infections.

v) MARRA A, 2016, INT J BIOL MACROMOL

With fewer total citations (198), but a high normalised TC (4.87), Marra *et al.* (2016) discussed PLA biocomposite films with zinc oxide (ZnO) for food packaging. The study demonstrated improved mechanical properties and antimicrobial activity against *Escherichia coli*, suggesting significant implications for enhancing food packaging safety.

vi) ATTAR, 2023

This paper has a moderate total citation count (175), but a high normalised TC (14.15). Attar *et al.* (2023) explored the combined effects of MAP and chitosan coating on pistachio preservation, demonstrating significant improvements in quality and shelf life, offering practical applications for commercial use in enhancing food quality.

vii) VALVERDE JM, 2005, J AGRIC FOOD CHEM

With a lower total citation count (161) and a low normalised TC (0.96), Valverde *et al.* (2005) presented results on active packaging for table grapes, showing improvements in quality and reduction in microbial spoilage with MAP and natural antimicrobial compounds, suggesting practical implications for the food industry.

viii) ARFAT YA, 2018, INT J BIOL MACROMOL

With a moderate total citation count (143) and a normalised TC (2.86), Arfat *et al.* (2018) discussed PLA composite films with clove leaf oil and graphene oxide for food packaging, highlighting enhanced mechanical properties and antimicrobial activity, showcasing potential applications in food preservation.

ix) DAS M, 2009, NANOTOXICOLOGY

With a lower total citation count (131) and a moderate normalised TC (1.73), Das *et al.* (2009) highlighted nanotechnology's role in food safety through pathogen detection nanosensors, while stressing the need for comprehensive toxicological assessments of nanoparticles to ensure consumer protection.

x) ROJAS, 2023

This paper has the lowest total citation count (117), but an exceptionally high normalised TC (26), indicating extraordinary impact, given its recent publication. Its citation rate per year (117) is also extremely high, suggesting immediate and widespread recognition. Rojas *et al.* (2023) introduced innovative antimicrobial food packaging materials by impregnating EU-PHE co-crystals into foams, showing prolonged antimicrobial activity. The study demonstrated that PLAF-EU-PHE reduced *Salmonella* by approximately 80%, and inhibited *Listeria monocytogenes* and *Salmonella* Enteritidis attachment. These findings have significant practical implications, potentially mitigating salmonellosis and listeriosis on an industrial scale, and improving food safety standards. The development also addresses limitations in pharmaceutical co-crystallisation, showing versatility across sectors (Rojas *et al*., 2023).

Countries' production over time

The USA steadily increased in articles, starting with four documents in 1991, and reaching 127 by 2023, indicating a growing research interest. Recent US research has focused on developing antimicrobial carbon-based materials for food packaging (Xu *et al*., 2023).

South Korea began to generate output in 2007, and showed a significant jump from 28 documents in 2021, to 96 in 2023, indicating a recent surge. Wagh *et al*. (2023) introduced cellulose nanofibre-based films with *Brassica oleracea*-derived carbon dots and anthocyanins, showing UV-blocking and antibacterial properties.

India's publications were low until 2009, but rapidly grew to 92 documents in 2023. The research focuses on enhancing the shelf life and safety of perishables using carbon-based additives. Studies include cellulose nanofibres with carbon dots, reinforcing polymers with nanoparticles, and biodegradable composites with improved barrier properties (Wagh *et al*., 2023).

China's publications rose exponentially to 426 documents in 2023. The research includes integrating carbon quantum dots and nitrogen-doped carbon dots into chitosan films, and developing edible films with essential oils and nanofibre films with zinc oxide nanoparticles (Yuan *et al*., 2023).

Italy's output began in 2012, growing to 96 documents in 2023. Lacivita *et al.* (2023) used carbon quantum dots from sour whey in cheese packaging, doubling shelf life.

These data highlight a global effort in developing antimicrobial carbon for food packaging, with China, the USA, and India leading in recent publications.

Most frequent words

The term "food packaging" leads the count significantly, with 267 occurrences, underlining the central theme of the research. "Carbon dioxide" and "*Escherichia coli*", respectively, with 138 and 137 mentions, highlight the focus on MAP and foodborne pathogen studies.

The word "chitosan", a biopolymer known for its antimicrobial properties, has 89 occurrences, indicating its importance in this field. Words like "food preservation" and "anti-infective agent" correspond to extending shelf life, and preventing bacterial contamination.

Further down the list, "*Staphylococcus aureus*", another pathogen of interest, and "carbon", which relates to the carbon-based materials used in packaging, have reasonable mentions as well. The occurrences of the words "chemistry" and "tensile strength," which refer to the materials science aspect, suggest studies on packaging materials' physical properties and chemical interactions.

"Oxygen" and "cellulose" are likely to relate to packaging materials' permeability and biodegradable options. The term "antibacterial agents" indicates the focus on antimicrobial activity within the packaging context. "Controlled study" suggests a methodological research approach. "Graphite" and "nanocomposites" imply advanced materials for improved packaging functions.

"Shelf life", "packaging materials", and "packaging" reaffirm the concentration on the longevity and quality of food storage methods. The list collectively indicates a robust interdisciplinary research area intersecting food science, microbiology, materials science, and environmental concerns, focusing on innovation in food packaging.

Trending topics

Figure 2 shows a bubble timeline chart displaying the trends of specific terms over the years within the context of food packaging and preservation research. The bubbles' size represents the terms' frequency or importance in a given year.

Terms such as "carbon", "antibacterial", and "*Escherichia coli*" are prominent, with a consistent presence over several years, indicating ongoing relevance in the field. The increased size of bubbles for these terms in recent years, particularly for "carbon", suggests a growing emphasis on research or possibly a recent breakthrough or innovation related to carbon materials in food packaging.

The term "nanoparticles" shows a visible increase in prominence from the mid-2000s onwards, peaking around 2015. This subject could reflect the rise of nanotechnology in food packaging. Similarly, "active packaging" and "food storage" are consistent topics, focusing on improving packaged foods' shelf life and quality.

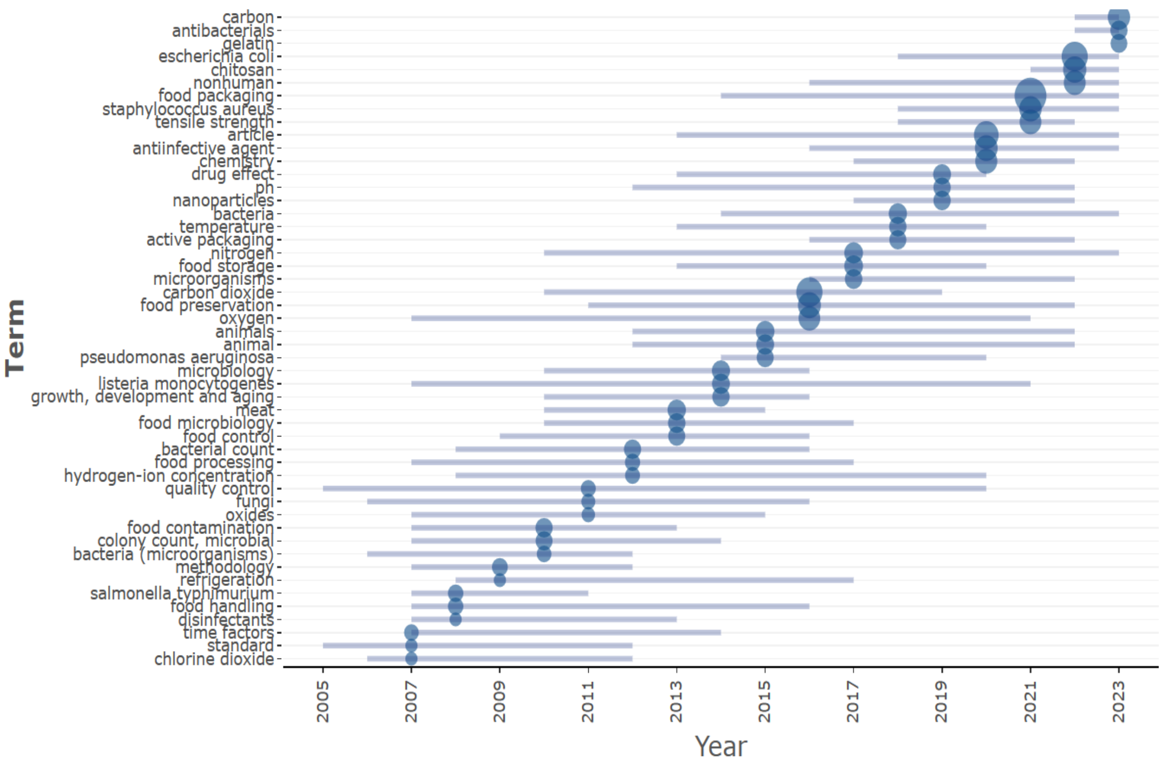

Figure 2. Trending topics.

Terms like "oxygen", "antimicrobials", and "food preservation" maintain a steady interest over time, underscoring their foundational role in food science.

Emerging terms with larger bubbles in recent years, such as "nanocomposites", may indicate new directions in food packaging research, emphasising incorporating advanced materials.

In summary, Figure 2 showcases the dynamic nature of food packaging research, highlighting foundational topics and emerging trends. The size and spread of the bubbles over time provide a visual representation of how the focus of research shifts, potentially influenced by technological advancements, regulatory changes, consumer preferences, or global health concerns.

Collaboration networks

Figure 3 shows a network graph of author collaborations. Each node represents an author, and their connections (edges) indicate collaborations. The node size corresponds to the author's prominence in the network, which could be influenced by their number of publications, collaborations, or centrality measures like those in the previous table.

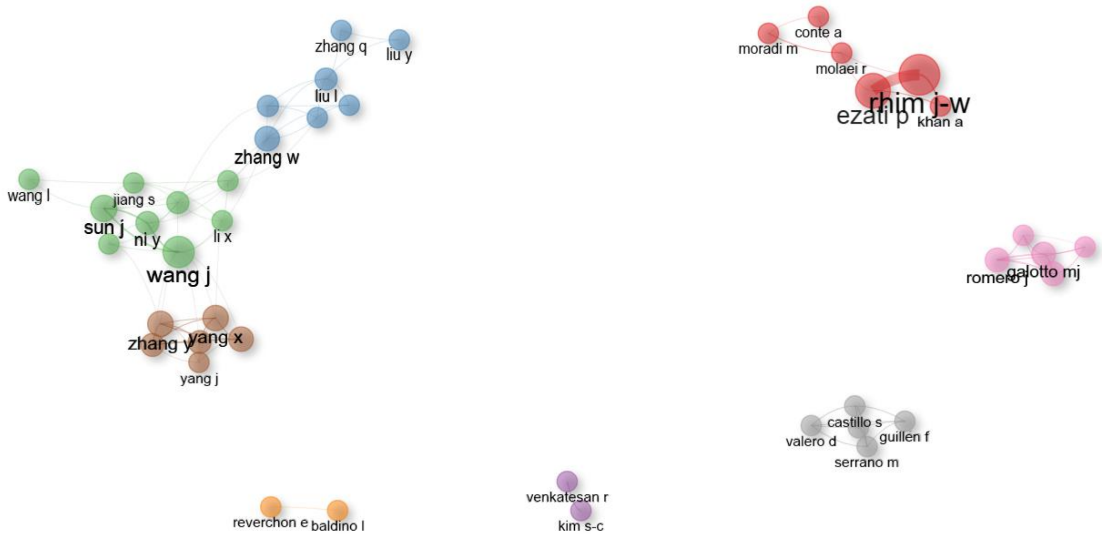

Figure 3. Collaboration networks.

Authors in the network

RHIM J-W and EZATI P are prominent, correlating with their high PageRank and betweenness centrality from the table. Their larger node size and central placement imply that they are key figures in the network, likely having numerous collaborations and significant influence.

WANG J appears to be a central node in another cluster, confirming the table's data showing high centrality. This condition suggests that WANG J is also an important connector in the research community.

The network comprises several clusters, each potentially representing different research groups or topics within the broader field. For instance, RHIM J-W's and EZATI P's clusters might focus on one aspect of the field, while WANG J's cluster could specialise in another.

The clusters with VENKATESAN R and KIM S-C, and the ones with REVERSION E and BALDINO L, appear isolated from the main network, which might indicate that these authors work in a specialised niche, or have not co-authored with researchers in other clusters.

The layout suggests a few highly connected individuals and several researchers with fewer connections, which is typical in academic networks. There may be leading figures whose work bridges various subfields or research groups.

In summary, Figure 3 visually reinforces the information from the table, showcasing the structure and dynamics of collaborations among researchers in this field. It shows how knowledge and research might flow within the community, highlighting potential influencers and key collaborators.

Thematic topics

Figure 4 indicates a thematic map clustered into two labels, with terms related to "food packaging" and "*Escherichia coli*".

i. Cluster 1 - Food Packaging: This cluster includes terms highly associated with food packaging. Terms like "carbon dioxide", "food preservation", "shelf life", and "food storage" suggest a focus on extending the shelf life of food products, and maintaining food quality. "Oxygen" and "nitrogen" point toward controlled packaging atmospheres to preserve food. "Non-human" and "animals" indicate that the studies may involve food products of animal origin or research conducted in non-human systems. This cluster represents a broad spectrum of research focused on preserving food quality and safety.

ii. Cluster 2 - *Escherichia coli*: The second cluster revolves around "*Escherichia coli*", a common foodborne pathogen. This cluster contains terms like "chitosan", "anti-infective agent", "*Staphylococcus aureus*", and "carbon". These terms indicate research focused on antimicrobial agents and materials, such as chitosan and carbon-based substances that are relevant in combating or controlling the presence of pathogens like *Escherichia coli* and *Staphylococcus aureus* in food products. The presence of "chemistry" and "tensile strength" suggests that this cluster may also involve studies on the properties of packaging materials that contribute to preventing bacterial contamination. "Nanocomposites", "graphite", and "packaging materials" indicate that advanced materials and nanotechnologies are prominent themes in this cluster.

In summary, Figure 4 reflects that the primary research focus in these clusters is on developing and applying food packaging strategies to ensure food safety, and combat microbial contamination. The prominence of terms related to antimicrobial materials and controlled packaging atmosphere indicates a strong interest in innovative packaging technologies that can extend shelf life, and improve food safety.

Here is the summary of the top-cited papers in cluster 1 related to "food packaging" with some connected keywords:

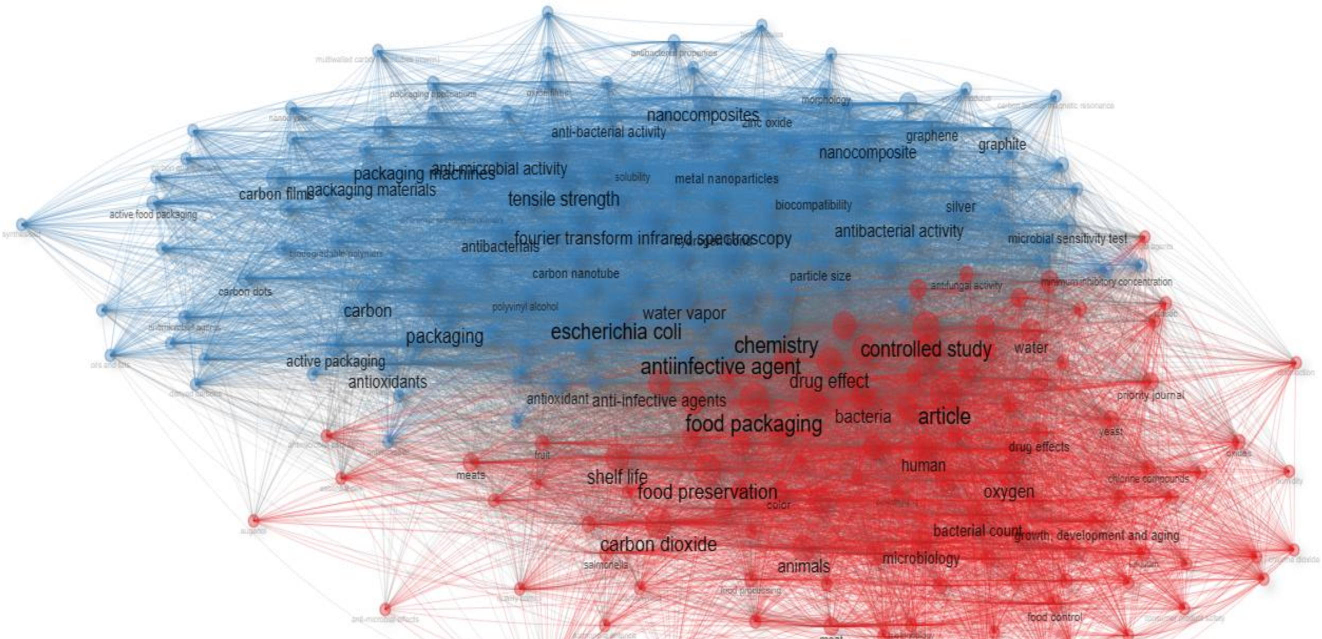

Figure 4. Thematic map.

i. Matan *et al*. (2006) (cited 298 times) examined the antimicrobial effects of cinnamon and clove oils in MAP. They found that 1:1 mixtures of these oils inhibited microorganisms, particularly under specific oxygen and carbon dioxide conditions, showing broad-spectrum activity against moulds, yeasts, and bacteria.
ii. Gómez-López *et al*. (2007) (cited 101 times) explored chlorine dioxide (ClO_2) gas to extend the shelf life of minimally processed carrots. ClO_2 extended shelf life by one day without affecting respiration or sensory attributes, and equilibrium-modified atmosphere packaging (EMAP) helped maintain optimal O_2 and CO_2 levels, although yeast ultimately limited the extension.
iii. Guillén *et al*. (2007) (cited 86 times) developed packaging with essential oils like eugenol, thymol, and carvacrol for table grapes. This reduced microbial counts and decay, enhancing the sensory quality and reducing weight loss, colour changes, and softening during cold storage at 1°C.
iv. Lee and Baek (2008) (cited 84 times) studied the effects of sodium hypochlorite and chlorine dioxide with different packages on *E. coli* in spinach. MAP with these sanitisers reduced *E. coli* O157:H7 during refrigerated storage, with storage conditions and packaging significantly impacting pathogen control.
v. Bai *et al*. (2017) (cited 64 times) investigated shelf-life extension of semi-dried buckwheat noodles using aqueous ozone treatment with MAP. This combination reduced initial microbial loads by 1.8 $\log_{10}$ CFU/g, and maintained noodle quality during storage by altering O_2 and CO_2 levels in the packages, inhibiting aerobic microorganism growth.

These studies highlighted the effectiveness of various antimicrobial treatments and packaging methods in extending shelf life, and maintaining food quality.

Here is a condensed summary of top-cited papers in cluster 2 related to "*Escherichia coli*":

i. Arfat *et al*. (2018) (cited 143 times) developed PLA composite films with clove oil and graphene oxide, enhancing thermo-mechanical and barrier properties. They showed significant antimicrobial potential against Gram-negative bacteria, suggesting use in active food packaging, although further research on clove oil release kinetics is needed.
ii. Pal *et al*. (2017) (cited 102 times) synthesised cellulose nanocrystals, and reduced graphene oxide, improving PLA matrix tensile strength, thermal stability, antibacterial response, and biocompatibility. This was achieved through ultrasonic treatment and a modified Hummer's method.
iii. Fan *et al*. (2018) (cited 91 times) created Ag-graphene nano-agents with strong antibacterial properties using a mussel-inspired adhesion approach and dopamine-conjugated polysaccharide sulphate, showing effectiveness in disinfection and antimicrobial applications.
iv. Dong *et al*. (2021) (cited 44 times) enhanced PLA nano-fibrous films with TiO_2 nanoparticles and graphene oxide, improving tensile strength, water barrier properties, and antibacterial effects, extending the preservation of green peppers.
v. Zhao *et al*. (2020) (cited 36 times) synthesised a g-C_3N_4/ZnO/ cellulose composite with superior antibacterial properties and improved charge transfer, showing enhanced photogenerated electron-hole pair separation and electron transfer for effective antimicrobial applications.

These studies highlighted the advancements in nanocomposite films for antimicrobial food packaging, focusing on improving mechanical properties, barrier functions, and antimicrobial efficacy to enhance food safety and preservation.

Thematic evolution

Figure 5 presents a thematic evolution map, showing how topics within the field of food packaging have developed and transitioned over time from 1991 to 2024.

From 1991 to 2000, "food packaging" and "*Listeria monocytogenes*" were highlighted themes. This suggests that during this period, the focus was on general packaging methods, and the control of this specific foodborne pathogen.

Moving from 2002 to 2010, we see a diversification of themes. "Carbon dioxide" emerged, likely indicating a growing interest in its use in MAP to extend the shelf life of food products. This theme was supported by the appearance of related terms such as "modified atmosphere packaging", "antimicrobial activity", "food quality", and "shelf life". The term "eugenol" also appeared, suggesting an interest in natural antimicrobial compounds for packaging applications.

In the 2011 - 2020 window, "food packaging" remained a strong theme, continuing from the previous period, but "carbon dioxide" became more prominent, reinforcing its established role in MAP. During this time, there was a notable focus on the technical aspects of packaging, as indicated by the specific mention of "modified atmosphere packaging."

The most recent period, 2021 - 2024, shows that "food packaging" and "carbon dioxide" remain dominant topics, maintaining their importance in the field. The term "carbon" also appears, which might signify a new focus on carbon-based materials, possibly related to advancements in packaging technologies, such as developing biodegradable or more sustainable packaging solutions.

This thematic map suggests that while some aspects of food packaging research, like the focus on "food packaging" and "carbon dioxide", have remained consistently critical, there have been shifts towards more specialised themes, such as the use of specific technologies (*e.g.*, MAP) and materials (*e.g.*, carbon-based). The evolution reflects the field's responses to technological advances, environmental concerns, and food safety regulations.

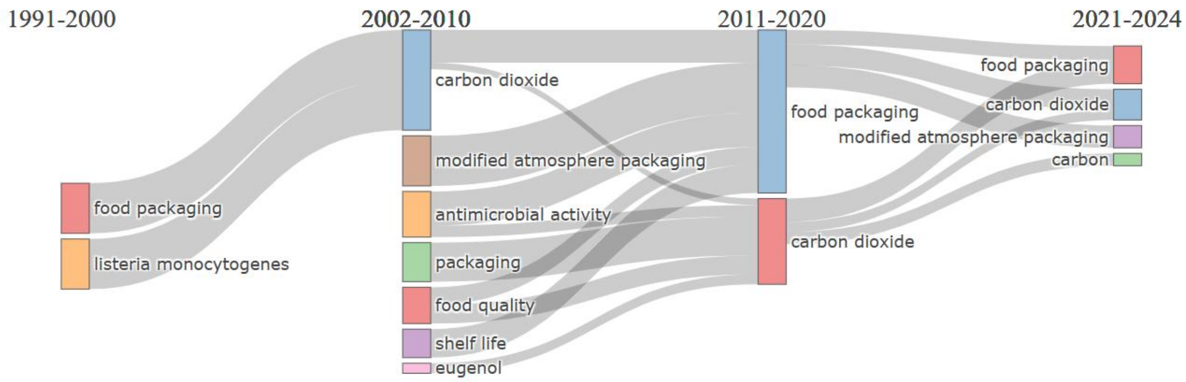

Figure 5. Thematic evolution.

Impacts of carbon-based antimicrobial agents

Carbon-based antimicrobial agents have gained traction in food preservation due to their effectiveness against microbial contamination. However, their applications are not without negative impacts, which necessitates the exploration of relevant countermeasures.

One of the primary concerns regarding carbon-based antimicrobial agents is the potential for toxicity and environmental impacts. For instance, while carbon nanotubes exhibit strong antibacterial properties, their interaction with bacterial cells can lead to cellular damage and toxicity, raising concerns about their safety in food applications (Liu *et al*., 2010). Furthermore, the excessive use of antimicrobial agents, including carbon-based ones, can contribute to the development of antimicrobial resistance, posing a significant public health risk (Roskam *et al*., 2023). The emergence of resistant strains due to the overuse of these agents in food systems can lead to challenges in treating infections in humans and animals, as highlighted by studies indicating a correlation between antimicrobial use in livestock and increased resistance in foodborne pathogens (Törneke *et al*., 2015).

In addition to toxicity and resistance, the use of carbon-based antimicrobial agents can also affect food quality. For example, while these agents can effectively inhibit microbial growth, their interaction with food matrices may alter the sensory properties of the food, such as taste and texture. This is particularly relevant in the context of consumer preferences for natural and minimally processed foods, where the presence of synthetic antimicrobial agents, including carbon-based ones, may be viewed unfavourably (Saeed *et al*., 2019).

To mitigate these negative impacts, several countermeasures can be implemented. One approach is the development of nanotechnology-based delivery systems that enhance the efficacy of carbon-based antimicrobial agents while minimising their concentration in food products. For instance, the use of amine-coated carbon dots has shown promise in enhancing antimicrobial activity against Gram-negative bacteria while potentially reducing toxicity (Devkota *et al*., 2021). Additionally, the incorporation of carbon-based agents into biodegradable packaging materials can help to limit direct contact with food, thereby reducing the risk of altering food quality while still providing antimicrobial protection (Emam-Djomeh *et al*., 2015).

Moreover, there is a growing emphasis on the use of natural antimicrobial agents as alternatives to synthetic ones, including carbon-based agents. Natural compounds, such as essential oils and plant extracts, have demonstrated effective antimicrobial properties without the associated risks of synthetic preservatives (Romeiro *et al*., 2024). This shift towards natural preservatives aligns with consumer demand for healthier food options and can help to reduce the reliance on carbon-based antimicrobial agents.

While carbon-based antimicrobial agents offer significant benefits for food preservation, their negative impacts, including toxicity, potential for resistance, and effects on food quality necessitate careful consideration. Employing strategies such as nanotechnology for targeted delivery, exploring natural alternatives, and adhering to regulatory guidelines can help mitigate these risks while maintaining the efficacy of food preservation methods.

Cultural impacts

The impacts of different food cultures on the use of carbon-based antimicrobials in food preservation are multifaceted, reflecting variations in traditional practices, consumer preferences, and regulatory frameworks across regions. Carbon-based antimicrobials, including nanoparticles and carbon-derived compounds, have been increasingly integrated into food preservation strategies, but their acceptance and applications can vary significantly based on cultural contexts.

In many cultures, traditional food preservation methods often prioritise natural ingredients and processes. For instance, the use of lactic acid bacteria (LAB) in fermented foods is prevalent in various cultures, where these microorganisms are valued for their ability to enhance food safety and shelf life through natural fermentation processes. LAB produce antimicrobial compounds that can inhibit spoilage organisms and pathogens, thus serving as a natural alternative to synthetic preservatives, including carbon-based antimicrobials (Khalil *et al*., 2021; Monika *et al*., 2021; Obioha *et al*., 2023). In regions where fermented dairy products are staples, such as in parts of Africa and Eastern Europe, the reliance on LAB reflects a cultural preference for traditional methods over modern chemical preservatives (Ołdak *et al*., 2017).

Conversely, in food cultures that are more open to technological advancements, such as in North America and parts of Asia, there is a growing acceptance of carbon-based antimicrobials due to their effectiveness and the convenience they offer in food preservation. For example, the incorporation of carbon nanoparticles into food packaging has been shown to enhance antimicrobial properties while maintaining food quality (Ruiz-Rico *et al*., 2018; Zhao *et al*., 2023). This technological integration aligns with consumer trends favouring longer shelf life and safety in processed foods, indicating a shift towards more modern preservation techniques (Maurya *et al*., 2021).

However, the acceptance of carbon-based antimicrobials is not without challenges. Concerns about potential toxicity and environmental impacts associated with synthetic antimicrobials can lead to resistance among consumers, particularly in cultures that prioritise organic and natural food products (Barbosa *et al*., 2016; Romeiro *et al*., 2024). For example, in Mediterranean and South Asian cultures, there is a strong emphasis on using natural preservatives, such as essential oils from herbs and spices, which are traditionally recognised for their antimicrobial properties (Weerakkody *et al*., 2010;

Hintz *et al*., 2015). This cultural inclination can hinder the adoption of carbon-based alternatives, as consumers may perceive them as artificial or harmful.

Moreover, the regulatory landscape surrounding food safety and preservatives varies widely across countries, influencing how carbon-based antimicrobials are utilised. In the European Union, stringent regulations on food additives and preservatives can limit the use of certain carbon-based antimicrobials, whereas in other regions, such as the United States, there may be more leniency, allowing for broader applications in food products (Rai *et al*., 2016; Alhammadi *et al*., 2023). This regulatory disparity can create challenges for food manufacturers aiming to market their products internationally, as they must navigate different cultural expectations and legal requirements regarding food safety and preservation methods.

The impact of different food cultures on the use of carbon-based antimicrobials in food preservation is shaped by a complex interplay of traditional practices, consumer preferences, and regulatory frameworks. While some cultures embrace modern technological solutions for food safety, others remain committed to traditional methods that prioritise natural ingredients. Understanding these cultural nuances is essential for the effective implementation of carbon-based antimicrobials in global food systems.

Future research

Several key themes and potential future research directions emerge:

i) Exploration of novel materials and combinations

Future research should emphasise on exploring different materials and their combinations to enhance antibacterial properties and packaging functionality. This includes investigating new coatings, polymers, nanoparticles, and bioactive compounds to develop effective and sustainable antibacterial food packaging solutions (Wagh *et al*., 2023; Yuan *et al*., 2023).

ii) Enhancement of antimicrobial properties

Many researchers have highlighted the importance of improving the antimicrobial efficacy of existing materials or developing new materials with stronger antibacterial properties. This involves exploring different concentrations, combinations, and application methods of antimicrobial agents such as essential oils, nanoparticles, carbon dots, and bioactive compounds (Wagh *et al*., 2023; Wen *et al*., 2023).

iii) Investigation into long-term stability and durability

Several researchers have stressed the need to study the long-term stability, scalability, and durability of antibacterial packaging materials. Understanding how these materials perform over time and under various conditions is crucial for their practical applications in food packaging (Adamopoulou *et al*., 2023; Huang *et al*., 2023).

iv) Diverse applications and industry integration

Few researchers have been exploring broader applications of antibacterial packaging materials beyond food preservation, including pharmaceutical, cosmetic, and industrial uses. This points towards the potential versatility and market expansion of these technologies (Wagh *et al*., 2023; Yuan *et al*., 2023).

v) Environmental impacts and sustainability

Studying the environmental impacts and sustainability aspects of antibacterial packaging is essential. This includes exploring biodegradable materials, assessing recyclability, and understanding the fate of these materials in the environment (Natalia *et al*., 2023; Wagh *et al*., 2023).

Addressing these themes will contribute significantly to developing safer and more sustainable food packaging options in the coming years.

Answers to research questions

RQ1 - Factors contributing to growth rate

Considering the 13.77% annual growth rate in research, the data highlight the importance of antimicrobial properties in food packaging materials, driven by the need to ensure food safety, and extend shelf life. Factors contributing to the growth rate of research in this area may include advancements in materials science, particularly in developing carbon-based materials with antimicrobial properties. Additionally, increased consumer awareness and demand for sustainable packaging solutions could drive research interest. Regulatory pressures and industry efforts to reduce food waste, and prevent contamination may also drive the growth rate.

RQ2 - Impact of international collaborations

The data mention that 25.84% of research collaborations are international, indicating a substantial level of global cooperation in this field. International collaborations likely enhance research output and innovation by enabling the exchange of knowledge, expertise, and resources across different countries and regions. Collaborating with researchers from diverse backgrounds can lead to a broader perspective on antimicrobial food packaging with carbon, facilitating the development of more robust and applicable solutions that address a variety of cultural, regulatory, and market-specific factors.

RQ3 - Significance of citation per document ratio

The high citation per document ratio (44.85 citations per document) suggests that research on antimicrobial food packaging with carbon is highly influential within the academic community. This may be attributed to the importance of food safety and sustainability issues this research addresses. Furthermore, the field's interdisciplinary nature, which combines aspects of materials science, microbiology, food science, and packaging technology, may contribute to its broad appeal and impact across multiple disciplines.

RQ4 - Impact of document age on research focus

The average document age of 5.95 years indicates that research in this field is relatively recent, suggesting ongoing exploration and innovation. The age of documents may influence research focus by highlighting emerging trends and technologies, such as the development of novel carbon-based materials or innovative packaging designs. Additionally, the relatively short document age may indicate a dynamic research landscape, with rapid advancements and evolving priorities shaping the direction of current and future research endeavours.

RQ5 - Role of distinct author keywords

The documents mention 805 distinct author keywords, reflecting the multidimensional nature of research in this field. These keywords likely encompass various aspects related to antimicrobial food packaging with carbon, including material properties, antimicrobial mechanisms, packaging technologies, food safety regulations, consumer preferences, and environmental sustainability. Analysing these keywords can provide insights into the breadth and depth of research topics and perspectives within the field, guiding future research directions and collaborations.

Conclusion

The exploration of carbon-based compounds in food packaging with antimicrobial properties has emerged as a crucial area of research with significant implications on food safety, sustainability, and waste reduction. Our bibliometric analysis presents a robust trajectory of scholarly activity, marked by a growing body of international collaborations and innovative technological applications. The findings emphasise carbon-based materials' antimicrobial efficacy and environmental benefits, positioning them as viable solutions for future food packaging technologies. The present review sheds light on current research dynamics, and sets the stage for future explorations to enhance the functional properties and environmental impacts of food packaging materials. Future research should continue to explore the potential of novel carbon-based materials and their composites to meet the increasing demands for food safety and eco-friendly packaging solutions.

References

Adamopoulou, V., Salvanou, A., Bekatorou, A., Petsi, T., Dima, A., Giannakas, A. E. and Kanellaki, M. 2023. Production and *in situ* modification of bacterial cellulose gels in raisin side-stream extracts using nanostructures carrying thyme oil: Their physicochemical/textural characterization and use as antimicrobial cheese packaging. Gels 9(11): 859.

Ahmad, S. S., Yousuf, O., Islam, R. U. and Younis, K. 2021. Silver nanoparticles as an active packaging ingredient and its toxicity. Packaging Technology and Science 34(11-12): 653-663.

Alhammadi, Y., Tang, D. Y. Y., Chew, K. W., Amornraksa, S. and Show, P. L. 2023. Climate-conscious food preserving technologies for food waste prevention. E3s Web of Conferences 428: 02004.

Appendini, P. and Hotchkiss, J. H. 2002. Review of antimicrobial food packaging. Innovative Food Science and Emerging Technologies 3(2): 113-126.

Arfat, Y. A., Ahmed, J., Ejaz, M. and Mullah, M. 2018. Polylactide/graphene oxide nanosheets/clove essential oil composite films for potential food packaging applications. International Journal of Biological Macromolecules 107(PartA): 194-203.

Bahcelioglu, E., Unalan, H. E. and Erguder, T. H. 2021. Silver-based nanomaterials: A critical review on factors affecting water disinfection performance and silver release. Critical Reviews in Environmental Science and Technology 51(20): 2389-2423.

Bai, Y. P., Guo, X. N., Zhu, K. X. and Zhou, H. M. 2017. Shelf-life extension of semi-dried buckwheat noodles by the combination of aqueous ozone treatment and modified atmosphere packaging. Food Chemistry 237: 553-560.

Baier-Fuentes, H., Merigó, J. M., Amorós, J. E. and Gaviria-Marín, M. 2018. International entrepreneurship: A bibliometric overview. International Entrepreneurship and Management Journal 15(2): 385-429.

Barbosa, M. S., Todorov, S. D., Ivanova, I. V., Belguesmia, Y., Choiset, Y., Rabesona, H., … and Franco, B. D. G. M. 2016. Characterization of a two-peptide plantaricin produced by *Lactobacillus plantarum* MBSa4 isolated from Brazilian salami. Food Control 60: 103-112.

Bhatt, S. and Shilpa, M. 2020. A critical review on nano-food packaging and its applications. Journal of Commercial Biotechnology 25(3): 3-17.

Cazón, P., Velazquez, G., Ramírez, J. A. and Vázquez, M. 2017. Polysaccharide-based films and coatings for food packaging: A review. Food Hydrocolloids 68: 136-148.

Chen, H., Tsang, Y. P. and Wu, C. H. 2023. When text mining meets science mapping in the bibliometric analysis: A review and future opportunities. International Journal of Engineering Business Management 2023: 15.

Chen, H., Wang, B., Gao, D., Guan, M., Zheng, L., Ouyang, H., … and Feng, W. 2013. Broad-spectrum antibacterial activity of carbon nanotubes to human gut bacteria. Small 9(16): 2735-2746.

Chiroma, H., Ezugwu, A. E., Jauro, F., Al-Garadi, M. A., Abdullahi, I. N. and Shuib, L. 2020. Early survey with bibliometric analysis on machine learning approaches in controlling COVID-19 outbreaks. PeerJ Computer Science 6: e313.

Das, M. Saxena, N. and Dwivedi, P. D. 2009. Emerging trends of nanoparticles application in food technology: Safety paradigms. Nanotoxicology 3(1): 10-18.

Das, M., Panda, R., Ray, L., Sethy, C., Kundu, C. N. and Tripathy, J. 2023. Fabrication of graphene oxide reinforced bio-nanocomposite films with antibacterial potential. Macromolecular Symposia 407(1): 2100416.

De Faria, A. F., Martinez, D. S. T., Meira, S. M. M., de Moraes, A. C. M., Brandelli, A., Filho, A. G. S. and Alves, O. L. 2014. Anti-adhesion and antibacterial activity of silver nanoparticles supported on graphene oxide sheets. Colloids and Surfaces B - Biointerfaces 113: 115-124.

Devkota, A., Pandey, A., Yadegari, Z., Dumenyo, K. and Taheri, A. 2021. Amine-coated carbon dots (NH2-FCDs) as novel antimicrobial agent for Gram-negative bacteria. Frontiers in Nanotechnology 3: 768487.

Dong, X., Liang, X., Zhou, Y., Bao, K., Sameen, D. E., Ahmed, S., … and Liu, Y. 2021. Preparation of polylactic acid/TiO_2/GO nano-fibrous films and their preservation effect on green peppers. International Journal of Biological Macromolecules 177: 135-148.

Emam-Djomeh, Z., Moghaddam, A. and Ardakani, S. A. Y. 2015. Antimicrobial activity of pomegranate (*Punica granatum* L.) peel extract, physical, mechanical, barrier and antimicrobial properties of pomegranate peel extract-incorporated sodium caseinate film and application in packaging for ground beef. Packaging Technology and Science 28(10): 869-881.

Fan, X., Yang, F., Nie, C., Yang, Y., Ji, H., He, C., … and Zhao, C. 2018. Mussel-inspired synthesis of NIR-responsive and biocompatible Ag-graphene 2D nanoagents for versatile bacterial disinfections. ACS Applied Materials and Interfaces 10(1): 296-307.

Gómez-López, V. M., Devlieghere, F., Ragaert, P. and Debevere, J. 2007. Shelf-life extension of minimally processed carrots by gaseous chlorine dioxide. International Journal of Food Microbiology 116(2): 221-227.

Guillén, F., Zapata, P. J., Martínez-Romero, D., Castillo, S., Serrano, M. and Valero, D. 2007. Improvement of the overall quality of table grapes stored under modified atmosphere packaging in combination with natural antimicrobial compounds. Journal of Food Science 72(3): S185-S190.

Hintz, T., Matthews, K. K. and Di, R. 2015. The use of plant antimicrobial compounds for food preservation. Biomed Research International 2015: 1-12.

Huang, L., Lin, H., Bu, N., Pang, J. and Mu, R. 2023. Robust microfluidic construction of polyvinyl pyrrolidone microfibers incorporated with W/O emulsions stabilized by amphiphilic konjac glucomannan. International Journal of Biological Macromolecules 241: 124563.

Irkin, R. and Esmer, O. K. 2015. Novel food packaging systems with natural antimicrobial agents. Journal of Food Science and Technology 52(10): 6095-6111.

Jain, D., Dash, M. K. and Thakur, K. 2021. Development of research agenda on demonetization based on bibliometric visualization. International Journal of Emerging Markets 17(10): 2584-2604.

Khalil, N., Dabour, N., El-Ziney, M. G. and Kheadr, E. 2021. Food bio-preservation: An overview with particular attention to *Lactobacillus plantarum*. Alexandria Journal of Food Science and Technology 18(1): 33-50.

Lacivita, V., Tarantino, F., Molaei, R., Moradi, M., Conte, A. and Alessandro Del Nobile, M. 2023. Carbon dots from sour whey to develop a novel antimicrobial packaging for fiordilatte cheese. Food Research International 172: 113159.

LaCoste, A., Schaich, K. M., Zumbrunnen, D. and Yam, K. L. 2005. Advancing controlled release packaging through smart blending. Packaging Technology and Science 18(2): 77-87.

Lee, S. Y. and Baek, S. Y. 2008. Effect of chemical sanitizer combined with modified atmosphere packaging on inhibiting *Escherichia coli* O157:H7 in commercial spinach. Food Microbiology 25(4): 582-587.

Li, F., Yu, H. Y., Wang, Y. Y., Zhou, Y., Zhang, H., Yao, J. M., … and Tam, K. C. 2019. Natural biodegradable poly(3-hydroxybutyrate- co-3-hydroxyvalerate) nanocomposites with multifunctional cellulose nanocrystals/graphene oxide hybrids for high-performance food packaging. Journal of Agricultural and Food Chemistry 67(39): 10954-10967.

Liu, S., Ng, A. K., Xu, R., Wei, J., Tan, C. M., Yang, Y. and Chen, Y. 2010. Antibacterial action of dispersed single-walled carbon nanotubes on *Escherichia coli* and *Bacillus subtilis* investigated by atomic force microscopy. Nanoscale 2(12): 2744.

Liu, Y., Vincent Edwards, J., Prevost, N., Huang, Y. and Chen, J. Y. 2018. Physico- and bio-activities of nanoscale regenerated cellulose nonwoven immobilized with lysozyme. Materials Science and Engineering C 91: 389-394.

Macías-Quiroga, I. F., Rengifo-Herrera, J. A., Arredondo-López, S. M., Marín-Flórez, A. and Sanabria-González, N. R. 2022. Research trends on pillared interlayered clays (PILCs) used as catalysts in environmental and chemical processes: Bibliometric analysis. The Scientific World Journal 2022: 5728678.

Marra, A., Silvestre, C., Duraccio, D. and Cimmino, S. 2016. Polylactic acid/zinc oxide biocomposite films for food packaging application. International Journal of Biological Macromolecules 88: 254-262.

Matan, N., Rimkeeree, H., Mawson, A. J., Chompreeda, P., Haruthaithanasan, V. and Parker, M. 2006. Antimicrobial activity of cinnamon and clove oils under modified atmosphere conditions. International Journal of Food Microbiology 107(2): 180-185.

Maurya, A., Prasad, J. P., Das, S. and Dwivedy, A. K. 2021. Essential oils and their application in food safety. Frontiers in Sustainable Food Systems 5: 653420.

Monika, K., Malik, T., Gehlot, R., Rekha, K. S., Kumari, A., Sindhu, R. and Rohilla, P. 2021. Antimicrobial property of probiotics. Environment Conservation Journal 22: 33-48.

Natalia, W., Nadia, K., Marta, N.-L., Abdelkrim, E. K., Lisowska, K., Wrońska, N., … and Lisowska, K. 2023. Biodegradable chitosan-based films as an alternative to plastic packaging. Foods 12(18): 3519.

Obioha, P. I., Anyogu, A., Awamaria, B., Ghoddusi, H. B. and Ouoba, L. I. I. 202). Antimicrobial resistance of lactic acid bacteria from *Nono*, a naturally fermented milk product. Antibiotics 12(5): 843.

Ołdak, A., Zielińska, D., Rzepkowska, A. and Kołożyn-Krajewska, D. 2017. Comparison of antibacterial activity of *Lactobacillus plantarum* strains isolated from two different kinds of regional cheeses from Poland: Oscypek and Korycinski cheese. Biomed Research International 2017: 1-10.

Ordoñez, R., Atarés, L. and Chiralt, A. 2022. Biodegradable active materials containing phenolic acids for food packaging applications. Comprehensive Reviews in Food Science and Food Safety 21(5): 3910-3930.

Page, M. J., Mckenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … and Moher, D. 2021. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ 2021: 372.

Pal, N., Dubey, P., Gopinath, P. and Pal, K. 2017. Combined effect of cellulose nanocrystal and reduced graphene oxide into poly-lactic acid matrix nanocomposite as a scaffold and its anti-bacterial activity. International Journal of Biological Macromolecules 95: 94-105.

Rai, M., Pandit, R., Gaikwad, S. and Kövics, G. J. 2016. Antimicrobial peptides as natural bio-preservative to enhance the shelf-life of food. Journal of Food Science and Technology 53(9): 3381-3394.

Reddy, N. R., Armstrong, D. J., Rhodehamel, E. J. and Kautter, D. A. 1991. Shelf-life extension and safety concerns about fresh fishery products packaged under modified atmospheres: A review. Journal of Food Safety 12(2): 87-118.

Rojas, A., Misic, D., Zizovic, I., Dicastillo, C. L., Velásquez, E., Rajewska, A., … and Galotto, M. J. 2023. Supercritical fluid and cocrystallization technologies for designing antimicrobial food packaging PLA nanocomposite foams loaded with eugenol cocrystals with prolonged release. Chemical Engineering Journal 481: 148407.

Romeiro, P. F. R., Coelho, A. S., Almeida, J. M., Alonso, V. P. P., Prata, A. S., Crippa, B. L. and Silva, N. C. C. 2024. Unraveling the antimicrobial activity of nutmeg and turmeric essential oils against *Staphylococcus aureus*, *Listeria monocytogenes*, *Escherichia coli*, and *Salmonella* Spp. Food Science and Technology 44: e00206.

Roskam, J. L., Oude Lansink, A. G. J. M. and Saatkamp, H. W. 2023. The economic value of antimicrobial use in livestock production. Antibiotics 12(10): 1537.

Ruiz-Rico, M., Pérez-Esteve, É., Treddyorre, C., Jiménez-Belenguer, A., Quiles, A., Marcos, M. D., … and Baviera, J. M. B. 2018. Improving the antimicrobial power of low-effective antimicrobial molecules through nanotechnology. Journal of Food Science 83(8): 2140-2147.

Saeed, F., Afzaal, M., Tufail, T. and Ahmad, A. 2019. Use of natural antimicrobial agents: A safe preservation approach. In Var, I. and Uzunlu, S. (eds). Active Antimicrobial Food Packaging, p. 1-18. United Kingdom: IntechOpen.

Sedira, N., Pinto, J., Bentes, I. and Pereira, S. 2024. Bibliometric analysis of global research trends on biomimetics, biomimicry, bionics, and bio-inspired concepts in civil engineering using the Scopus database. Bioinspiration and Biomimetics 19(4): 41001.

Serrano, M., Martínez-Romero, D., Castillo, S., Guillén, F. and Valero, D. 2005. The use of natural antifungal compounds improves the beneficial effect of MAP in sweet cherry storage. Innovative Food Science and Emerging Technologies 6(1): 115-123.

Srivastava, M. and Saini, G. K. 2022. A bibliometric analysis of the elaboration likelihood model (ELM). Journal of Consumer Marketing 39(7): 726-743.

Sulistyo, J., Winarno, P. S., Pratiwi, I. Y., Ridfan, L. P., Pranata, K. M. and Chik, R. M. R. 2023. Preparation of active food packaging and coating material based on bacterial cellulose to increase food safety. Jurnal Teknologi dan Industri Pangan 34(1): 48-61.

Tian, Y., Liu, P., Yi-Ning, X., Zhou, Y., Chang, H. and Chen, J. 2019. Bibliometric and visualized analysis of the research on Nüshu in China. In The Proceedings of the 4th Annual International Conference on Social Science and Contemporary Humanity Development (SSCHD 2018), p. 230-236. Wuhan, China.

Tirdasari, N. L., Oktariani, A., Indrawan, D. and Hasanah, N. 2021. Critical factors in developing sustainable food packaging. Jurnal Manajemen and Agribisnis 18(1): 45-52.

Törneke, K., Torren-Edo, J., Grave, K. and Mackay, D. K. J. 2015. The management of risk arising from the use of antimicrobial agents in veterinary medicine in EU/EEA countries - A review. Journal of Veterinary Pharmacology and Therapeutics 38(6): 519-528.

Valverde, J. M., Guillén, F., Martínez-Romero, D., Castillo, S., Serrano, M. and Valero, D. 2005. Improvement of table grapes quality and safety by the combination of modified atmosphere packaging (MAP) and eugenol, menthol, or thymol. Journal of Agricultural and Food Chemistry 53(19): 7458-7464.

Wagh, R. V., Khan, A., Priyadarshi, R., Ezati, P. and Rhim, J. W. 2023. Cellulose nanofiber-based multifunctional films integrated with carbon dots and anthocyanins from *Brassica oleracea* for active and intelligent food packaging applications. International Journal of Biological Macromolecules 233: 123567.

Wang, L., Lin, L. and Pang, J. 2020. A novel glucomannan incorporated functionalized carbon nanotube films: Synthesis, characterization and antimicrobial activity. Carbohydrate Polymers 245: 116619.

Weerakkody, N. S., Caffin, N., Lambert, L. K., Turner, M. S. and Dykes, G. A. 2010. Synergistic antimicrobial activity of galangal (*Alpinia galanga*), rosemary (*Rosmarinus officinalis*) and lemon iron bark (*Eucalyptus staigerana*) extracts. Journal of the Science of Food and Agriculture 91(3): 461-468.

Wen, F., Li, P., Yan, H. and Su, W. 2023. Turmeric carbon quantum dots enhanced chitosan nanocomposite films based on photodynamic inactivation technology for antibacterial food packaging. Carbohydrate Polymers 311: 120784.

Xu, H., Chen, L., McClements, D. J., Cheng, H., Long, J. and Jin, Z. 2023. Development and characterization of active starch-based films incorporating graphene/polydopamine/Cu^{2+} nanocomposite fillers. Carbohydrate Polymers 305: 120498.

Yuan, Y., Tian, H., Huang, R., Liu, H., Wu, H., Guo, G. and Xiao, J. 2023. Fabrication and characterization of natural polyphenol and ZnO nanoparticles loaded protein-based biopolymer multifunction electrospun nanofiber films, and application in fruit preservation. Food Chemistry 418: 135851.

Zhang, R. and Hur, J. 2022. Sustainable development trend of Chinese advertising design from 1992 to 2020: A bibliometric and content analysis. Sage Open 12(4): 215824402211340.

Zhao, S. W., Zheng, M., Sun, H. L., Li, S. J., Pan, Q. J. and Guo, Y. R. 2020. Construction of heterostructured g-C_3N_4/ZnO/cellulose and its antibacterial activity: Experimental and theoretical investigations. Dalton Transactions 49(12): 3723-3734.

Zhao, Y., Li, B., Zhang, W., Zhang, L., Zhao, H., Wang, S. and Huang, C. 2023. Recent advances in sustainable antimicrobial food packaging: Insights into release mechanisms, design strategies, and applications in the food industry. Journal of Agricultural and Food Chemistry 71(31): 11806-11833.

Zouharová, A., Bartáková, K., Bursová, Š., Necidová, L., Haruštiaková, D., Klimešová, M. and Vorlová, L. 2023. Meat and fish packaging and its impact on the shelf life - A review. Acta Veterinaria Brno 92(1): 95-108.