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Advancing Modified Atmosphere Packaging for Horticultural Products: A Systematic Review and Bibliometric Analysis

Sri Handayani Nofiyanti[1]*, Usman Ahmad[2], Yuvita Lira Vesti Arista[3], Michael Alexander Hutabarat[3] and Muhammad Rizqi[4]

[1]Department of Agricultural and Biosystems Engineering, Udayana University, Badung, Indonesia
[2]Department of Agricultural and Biosystem Engineering, IPB University, Bogor, Indonesia
[3]Department of Food Technology, Institut Teknologi Kalimantan, Balikpapan, Indonesia
[4]Rintama Foundation, Mataram, Indonesia

**Corresponding author*

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A B S T R A C T

The present study aimed to perform a bibliometric analysis regarding Modified Atmosphere Packaging (MAP) for horticultural products and its effectiveness in postharvest management. A literature search was conducted using the Scopus database with the keyword "Modified Atmosphere Packaging". The retrieved articles were imported into Mendeley software version 1.19.8 for attribute verification. A total of 117 articles met the inclusion criteria. The bibliometric database was analyzed using the Bibliometrix package on R version 4.2.2 and VOSviewer version 1.6.18. The analysis revealed that the most frequently occurring keywords included shelf life, food preservation, biodegradable packaging, gas composition, and smart monitoring systems. The most widely cited articles addressed gas composition optimization, postharvest quality maintenance, and sustainable packaging solutions. The USA, China, and India emerged as the leading contributors to MAP research. Despite its benefits, high costs, lack of standardization, and limited real-world applications pose challenges, particularly in regions with inadequate infrastructure. The study highlights emerging preservation techniques, such as high-pressure processing and ozone treatment, which enhance MAP's effectiveness. Future research should focus on large-scale field trials, cost-effective innovations, and sustainability assessments to optimize MAP applications in postharvest management.

Introduction

The global significance of horticultural products in food security and the economy cannot be overstated. Horticulture encompasses the cultivation of fruits, vegetables, nuts, seeds, herbs, sprouts, mushrooms, algae, flowers, seaweeds, and non-food crops, which collectively play a pivotal role in enhancing nutrition and providing livelihoods worldwide. As the global population is projected to reach approximately 9.7 billion

by 2050, the demand for food, particularly nutrient-rich horticultural products, is expected to surge significantly (Ngcobo and Bertling, 2023). These products are not only vital for dietary diversity and health but also contribute substantially to the economic development of many countries, especially in rural areas where horticulture serves as a primary source of income for smallholder farmers (Workineh, 2020; Etefa *et al.,* 2022).

However, despite their importance, horticultural products face significant postharvest challenges that threaten their availability and quality. Postharvest losses in fruits and vegetables can range from 15% to as high as 70% in some regions, primarily due to perishability, quality loss, and inadequate storage and handling practices (Etefa *et al.,* 2022; Onyegbula *et al.,* 2023). The perishability of horticultural products is a critical concern; they are often highly susceptible to spoilage and decay, which can occur rapidly after harvest due to factors such as temperature fluctuations, humidity, and microbial infections (Workineh, 2020; Etefa *et al.,* 2022). For instance, tropical conditions can exacerbate these issues, leading to increased losses during market storage and transportation (Underhill *et al.,* 2019).

Quality loss is another significant challenge, as horticultural products undergo physiological changes postharvest that can diminish their nutritional value and market appeal. Ethylene production, a natural ripening hormone, plays a crucial role in this process, leading to accelerated senescence and deterioration of quality attributes such as texture, flavor, and appearance. Consequently, the economic viability of horticultural products is compromised, affecting both producers and consumers (Porat *et al.,* 2018).

To mitigate these postharvest challenges, Modified Atmosphere Packaging (MAP) has emerged as a promising solution. MAP involves altering the composition of the internal atmosphere of packaging to slow down the respiration rate of fresh produce, thereby extending shelf life and maintaining quality (Corpas, 2023).

By reducing oxygen levels and increasing carbon dioxide concentrations, MAP can effectively delay ripening and senescence processes, minimizing spoilage and preserving the nutritional quality of horticultural products (Corpas, 2023). This technology not only helps in reducing postharvest losses but also enhances the marketability of fruits and vegetables, ultimately contributing to improved food security and economic stability in the horticultural sector (Corpas, 2023).

Despite the recognized benefits of MAP, there is a limited comprehensive analysis of its effectiveness across diverse horticultural products. Existing literature often presents fragmented findings, making it challenging for stakeholders to draw conclusive insights regarding the optimal application of MAP (Bulgari *et al.,* 2021). An integrated understanding of MAP's effectiveness is essential for developing best practices that can be widely adopted in the horticultural industry. This systematic review aims to fill this gap by synthesizing existing research and providing a clearer picture of MAP's role in postharvest preservation.

In addition to synthesizing the existing findings on MAP's effectiveness, this study incorporates a bibliometric analysis to evaluate the research trends, collaboration networks, and influential contributions in this domain. Bibliometric analysis offers a systematic and quantitative approach to map the scientific landscape, identify knowledge gaps, and uncover emerging themes in MAP-related research. By integrating a systematic review with bibliometric analysis, this study provides a comprehensive evaluation of MAP's role in postharvest preservation.

The objectives of this study are twofold: (1) to systematically review the literature on the effectiveness of MAP in preserving the quality of horticultural products, including its impact on shelf life, sensory qualities, and nutritional attributes, and (2) to conduct a bibliometric analysis to identify research trends, influential publications, and collaboration networks. This integrated approach aims to offer evidence-based recommendations for optimizing MAP practices, guiding future research, and improving postharvest management in the horticultural sector.

Materials and Methods

This study combines a Systematic Literature Review (SLR) and Bibliometric Analysis (BA), collectively referred to as Systematic Literature Network Analysis (SLNA) in certain publications. SLNA has been widely adopted in academic research to identify trends and patterns by integrating the structured framework of SLR (Donthu *et al.,* 2021) with the quantitative insights provided by bibliometric analysis (Zupic & Ater, 2015).

Systematic Literature Review (SLR)

The SLR component follows the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure methodological rigor, transparency, and reproducibility. As depicted in Figure 2, the SLR process begins with the identification of relevant articles from the Scopus database, selected for its comprehensive coverage of peer-reviewed scientific journals and rigorous indexing standards. Predefined keywords relevant to the study, such as "Modified Atmosphere Packaging," "horticultural products," and "quality preservation," were used to retrieve a robust dataset of articles.

After identification, the screening process involved removing duplicate records and excluding studies deemed irrelevant based on their titles and abstracts. Articles that passed this stage were subjected to a full-text review to assess their alignment with the study's objectives and eligibility criteria.

Studies that met the inclusion requirements were incorporated into the analysis. These criteria were designed to ensure that only high-quality and directly relevant research was included, enhancing the reliability of the results.

Bibliometric Analysis (BA)

Bibliometric analysis was employed to systematically organize, categorize, and statistically evaluate bibliographic data. This method enables the examination of extensive datasets to uncover historical trends, the evolution of knowledge in a given field, and future research directions (Merigó *et al.,* 2015; Albort-Morant & Ribeiro-Soriano, 2016).

The analysis aimed to categorize information based on key criteria, such as publication years, journals, countries, and author affiliations. It also focused on identifying research trends, uncovering dominant themes, and highlighting emerging research hotspots geographically and contextually (Yan & Zhiping, 2023). Visualization techniques, including co-authorship networks, keyword co-occurrence maps, and citation analysis, were used to uncover patterns and relationships across the studies.

Benefits of SLNA

The integration of SLR and bibliometric analysis provides a comprehensive framework for understanding a field's intellectual structure. SLNA facilitates the identification of influential publications, key authors, and prominent institutions while simultaneously revealing the evolution of research topics and themes. Furthermore, it enables the prediction of future research priorities and the identification of gaps in the existing literature. This holistic approach ensures a robust and multidimensional evaluation of the domain.

Process Overview

The overall methodology for SLR and bibliometric analysis is depicted in Figure 2, which illustrates the stages of identification, screening, and inclusion of relevant studies based on PRISMA guidelines (Donthu *et al.,* 2021). By following this structured process, the study ensures a rigorous evaluation of the literature, yielding reliable and actionable insights into the effectiveness of Modified Atmosphere Packaging in preserving the quality of horticultural products.

The Scopus database, accessed on 7 January 2024, served as the primary source for data collection in this study. Scopus was selected due to its extensive indexing of peer-reviewed journal articles and its reputation as a reliable academic database widely recognized for its comprehensive coverage of high-impact international journals. This ensured that the selected studies met rigorous academic and methodological standards, providing a credible foundation for the analysis.

To identify relevant studies, a search query was designed using keywords and Boolean operators: ("Modified Atmosphere Packaging") AND ("crops") OR ("horticultural") AND NOT ("meet"). These terms were chosen to align with the research objectives and focus on studies that explore the role of MAP in maintaining the quality and extending the shelf life of horticultural products.

The search was refined using inclusion and exclusion criteria to ensure a focused and high-quality analysis (see Table 1). The selection process involved an initial identification of 186 articles based on the search query. Titles and abstracts were screened to exclude irrelevant studies, and a full-text review was conducted for 117 articles that passed the initial screening. Ultimately, 117 articles were selected for systematic review and bibliometric analysis due to their close alignment with the research objectives.

Several tools were employed to organize, analyze, and visualize the data collected from Scopus. Microsoft Excel was used to edit, filter, and arrange the data for further processing. Bibliometric visualization was conducted using VOSviewer (version 1.6.20), which generated co-authorship networks, co-citation maps, and keyword co-occurrence analyses. VOSviewer was specifically chosen for its ability to produce large and easily interpretable bibliometric maps, as highlighted by van Eck and Waltman (2010). Additionally, R Studio, with its powerful data visualization packages such as ggplot2 and bibliometrix, was utilized to create high-quality graphs, visualizing trends in publication, citation distributions, and keyword occurrences. R Studio enabled the customization of graphics for clarity and precision, ensuring they effectively conveyed the research findings.

The bibliometric analysis revealed important trends in MAP research, including key themes, influential journals, prominent authors, and collaborative networks. Keyword co-occurrence analysis highlighted recurring themes and focus areas within the field, while citation and co-citation analysis mapped the most cited papers and their interrelationships. Collaborative networks among authors and institutions were visualized to identify the leading contributors to MAP research globally. From the final set of 50 articles, the top 10 studies were selected for in-depth analysis based on their relevance to MAP and horticultural product preservation, methodological rigor, and influence determined by citation counts and journal impact factors.

Results and Discussion

Development of MAP Research in Horticultural Product Preservation

Research on the effectiveness of Modified Atmosphere Packaging (MAP) in preserving the quality of horticultural products has been ongoing since 2014. Based on a search in the Scopus database, 138 articles were identified, with an annual growth rate of approximately 7.18 (Table 2).

Although studies on MAP began in 1987, the volume of research on this topic remained relatively low in the early years, with fewer than 10 studies published annually until 2017. The number of publications began to rise significantly in 2018, with more than 20 articles per year, and by 2021 through 2024, the volume of research reached over 30 articles annually. This increase correlates with the growing recognition of the importance of MAP technology in reducing spoilage and extending the shelf life of horticultural products.

The most frequently cited articles on MAP primarily focus on its application for extending the shelf life of vegetables, fruits, and flowers (Table 3). Journals that have published the most on this topic include *Postharvest Biology and Technology*, *Acta Horticulturae*, and *Food Control*.

The most cited articles relate to the use of MAP in reducing respiration rates, slowing ripening, controlling microbial growth, and preserving the quality and nutritional content of horticultural products.

Analysis of the Most Contributive Countries in Modified Atmosphere Packaging (MAP) Research

The thematic trend developing in the top 10 countries contributing to the research on Modified Atmosphere Packaging (MAP) for horticultural products is analyzed and presented in detail in Figure 4 (countries). Based on the map in Figure 4, the countries contributing to Modified Atmosphere Packaging (MAP) research are visually represented, showcasing the global distribution of authors in this field. Researchers from the United States are the most prominent contributors, as indicated by the dark green color on the map.

With 9 total publications, the USA has become a leading force in MAP studies. Other significant contributors include India and China, both marked in lighter green, with 9 and 8 publications, respectively, reflecting a growing interest in MAP technologies in these regions.

This data emphasizes the growing global interest and contributions to the field of MAP, with diverse countries leading in different aspects of the research, from innovative packaging solutions to food preservation methods. Further analysis could explore the factors contributing to these countries' successes in MAP research and the collaboration between institutions worldwide.

This map highlights the international collaboration in MAP research, underscoring the growing interest across the world in enhancing food preservation and extending

the shelf life of horticultural products. As this global network of research expands, we can expect greater advancements in sustainable packaging solutions.

Keyword Analysis

Several keywords that frequently appear in the research on Modified Atmosphere Packaging (MAP) for horticultural product preservation include Modified Atmosphere Packaging, food storage, food packaging, packaging, shelf life, crops, fruits, etc (Table 4). The development of the MAP research topic over the years is illustrated in Figure 5. In the last three years (2021-2024), the most frequently studied aspects of MAP research have focused on food preservation. These emerging trends highlight the growing relevance of MAP in addressing critical issues in food preservation and supply chain management**.**

The factorial analysis, represented in the conceptual structure map for the Modified Atmosphere Packaging (MAP) research, is shown in Figure 6. This map reveals the structure of MAP-related keywords and their relationships, which are grouped into four distinct clusters, each color-coded to highlight different thematic areas. Cluster 1 (highlighted purple), the largest cluster, is centered around core terms that represent the main applications and benefits of MAP. The purple cluster represents the core applications and benefits of MAP, with prominent keywords such as food quality, storage, modified atmosphere, shelf life, oxygen, and temperature. These terms illustrate the primary function of MAP in maintaining the quality and freshness of horticultural products, especially fruits and vegetables. MAP works by adjusting the internal atmosphere of packaging, specifically controlling levels of oxygen and carbon dioxide to slow down respiration and reduce spoilage. By extending the shelf life of fresh produce, MAP plays a crucial role in food preservation, helping to reduce food waste and improve food security. The focus on cold storage and packaging materials in this cluster indicates the importance of using the right materials to maintain the optimal conditions for preservation during storage and transport.

Therefore, Cluster 2 (represented in green) emphasizes the environmental and biological aspects of MAP. Prominent keywords like food preservation, temperature, carbon dioxide, and fungi highlight MAP's role in controlling environmental conditions during storage. By adjusting the gas composition inside the packaging, MAP reduces the activity of microorganisms and enzymatic processes that lead to food degradation. The regulation of temperature and oxygen levels within packaging creates optimal conditions to maintain the freshness of products, reducing reliance on chemical preservatives and extending the shelf life of perishable items. This cluster also includes quality control and fungi, indicating MAP's importance in microbial management, especially in preventing the growth of harmful microorganisms that contribute to spoilage. Additionally, ascorbic acid and phenol derivatives underscore the role of MAP in preserving the nutritional quality of fruits and vegetables. The ability of MAP to slow down growth development and aging ensures that fresh produce retains its appearance, taste, and nutritional content for a longer period. This cluster is particularly important for maintaining both quality and microbial safety in perishable goods.

As a result, cluster 3 (red cluster) is more specialized, the red cluster is centered around the role of food packaging, with keywords such as atmosphere, food packaging, and crop. This cluster emphasizes the importance of packaging technologies in the MAP process, especially in controlling the atmosphere around the produce. Modified atmosphere packaging is essential for creating an environment that slows down the ripening and degradation of fruits and vegetables by altering the composition of gases within the packaging. The inclusion of terms like article and human suggests a broader interest in research articles and the human factors involved in packaging design and technology. This cluster points to the technological innovations in packaging materials that optimize the performance of MAP. Cluster 4 (colored blue) focuses on the application of MAP to specific products, particularly fruits and vegetables, with keywords like moisture, dehydration, and postharvest period. This cluster underscores the importance of moisture regulation in preserving the quality and freshness of perishable products. MAP works by adjusting the internal atmosphere to maintain the optimal moisture level within the packaging, preventing dehydration and wilting.

This is crucial for maintaining the textural quality of fresh produce and ensuring that fruits and vegetables retain their visual appeal and nutritional value during storage and transport. By reducing moisture loss, MAP also helps in extending the shelf life of products, making it a vital technology for the horticultural industry.

The relationships between these clusters are further explored in the network visualization presented in Figure 7. In this network, "Modified Atmosphere Packaging" appears as the central theme, interlinked with all related keywords. The visualization shows how MAP acts as a nexus between various fields of research, including food quality, environmental control, microbial growth, and product-specific preservation methods. By observing the positioning of these terms in the network, we can infer that MAP is influenced by a combination of technological innovations (e.g., packaging materials) and environmental factors (e.g., oxygen levels, temperature). At the same time, MAP impacts the quality and shelf life of products, making it a key factor in the modern food supply chain.

In-depth analysis of these clusters and keywords reveals that MAP is a multifaceted concept. It is not only a technology for extending shelf life but also an enabler of sustainable food preservation. As MAP interacts with various internal and external factors, it influences the preservation and quality of horticultural products in a complex way. This interconnection underscores the importance of MAP in achieving both economic and environmental benefits, such as reducing food waste and improving the efficiency of food distribution networks.

Relevance, Challenges, and Future Trends of MAP in Horticultural Product Preservation

Modified Atmosphere Packaging (MAP) has emerged significant relevance in the global food preservation landscape, especially in the horticultural sector. The bibliometric analysis shows a clear increase in publications on MAP, with a steady rise in research interest since 2018. This growing body of work highlights MAP's ability to extend the shelf life of fruits, vegetables, and flowers, thereby reducing postharvest losses (Rao and Shivashankara, 2018; Yeboah, 2023). As the demand for fresh produce continues to rise globally, MAP provides an effective solution for preserving the nutritional quality, texture, and appearance of horticultural products (Rao and Shivashankara, 2018; Eum *et al.,* 2021; Sun *et al.,* 2022; Yeboah, 2023; Liu, 2024). Additionally, MAP plays a crucial role in improving food security and reducing food waste, both of which are increasingly important as the global population grows and agricultural systems are stressed. The ability to maintain the freshness of products without extensive refrigeration or chemical preservatives also aligns MAP with the growing focus on sustainability in food production and packaging (Falagán and Terry, 2018; Qian, 2022; Moradinezhad and Ranjbar, 2024).

The bibliometric analysis of MAP research reveals several important trends and gaps that highlight the challenges of implementing MAP in real-world agricultural practices. Despite the significant volume of research on MAP, particularly in high-income countries such as the United States, India, and China, the research on practical challenges such as cost, accessibility, and infrastructure remains limited. As shown in the bibliometric analysis, there has been a growing interest in shelf-life extension and quality preservation, but there is a noticeable lack of studies that address economic barriers and implementation strategies for smallholder farmers or producers in developing regions. The growing publication trend since 2018 (with an annual growth rate of 7.18%) reflects increasing recognition of MAP's potential to reduce postharvest losses, but challenges such as the high cost of specialized packaging materials and storage conditions still limit its widespread use. The bibliometric analysis reveals that research hotspots on MAP are concentrated in regions with more advanced agricultural systems and better infrastructure, but there is little representation from areas with limited resources. For instance, the countries with the highest number of MAP-related publications (e.g., the U.S., India, and China) often have more access to the technology and better infrastructure to implement it on a large scale.

The economic challenge of MAP implementation is also reflected in the literature, as research often focuses on its effectiveness in reducing spoilage but not on the cost-effectiveness for small-scale farmers. The bibliometric analysis shows that there is a notable absence of studies on the financial barriers to adoption, which suggests that there is a gap in understanding how MAP can be scaled to benefit smaller agricultural operations (Noor, 2024). Furthermore, the logistical challenges of MAP, such as the need for precise control of temperature, humidity, and gas composition during storage and transportation, have not been sufficiently addressed in recent studies (Fernández *et al.,* 2019).

To overcome these challenges, future research should focus on cost-reduction strategies, such as developing more affordable packaging materials or finding ways to optimize packaging for diverse horticultural products.

Table.1 Inclusion – Exclusion Criteria

Inclusion Criteria	Exclusion Criteria
Articles focused on Modified Atmosphere Packaging (MAP) and its application in horticultural products	Not the main theme of the article
Journal article in English	Proceedings paper, book review, book chapter, editorial
Studies discussing the preservation of quality attributes (e.g., texture, color, freshness, shelf life)	Studies not related to the preservation of quality in horticultural products

Table.2 General Information on the Database Regarding MAP Research

Description	Result
Timespan	1987-2024
Number of Documents	117
Annual Growth Rate (%)	7.18
Citation per Year	10.7
Citations per Document	14.88
Number of Authors	412
Authors per Document	21
Number of Keywords	648

Table.3 Most Cited Articles on MAP Research in Horticultural Product Preservation

Reference and Publisher	Cites	Title	Key Concepts	Scholarly Highlights	Future Research
(Luna *et al.*, 2012) in Acta Horticulturae	67	Long-term deficit and excess of irrigation influences quality and browning related enzymes of lettuce	Modified Atmosphere Packaging (MAP), lettuce quality, irrigation, phenolic metabolism	MAP is crucial for maintaining lettuce quality during storage by preventing browning and quality degradation. This study highlights the significant role of MAP in preserving freshness under varying irrigation conditions.	Future research could focus on MAP optimization in conjunction with irrigation techniques to preserve a wider range of leafy vegetables.
(Nishijima *et al.*, 2004) in Plant Disease	33	Association of *Enterobacter cloacae* with rhizome rot of edible ginger in Hawaii	Rhizome rot, *Enterobacter cloacae*, bacterial spoilage, ginger	The study highlights how MAP could be a potential solution for managing microbial spoilage, like *Enterobacter cloacae*, in ginger.	Future research could explore MAP's effectiveness in controlling microbial growth in other root crops and spices.
(Kou *et al.*, 2013) in LWT - Food Science and Technology	124	Postharvest biology, quality, and shelf life of buckwheat microgreens	Buckwheat microgreens, MAP, shelf life, temperature effects	Investigated MAP's role in extending the shelf life of microgreens, ensuring higher quality retention	Further studies should assess MAP effectiveness for other highly perishable crops, such as leafy greens.

				during storage.	
(Bai *et al.*, 2017) **in Food Chemistry**	82	Shelf-life extension of semi-dried buckwheat noodles by aqueous ozone and MAP	Shelf-life extension, buckwheat noodles, MAP, aqueous ozone treatment	Combined MAP with aqueous ozone treatment to extend shelf life and improve quality retention of buckwheat noodles.	Future research could explore non-chemical MAP combinations for other food products to maintain quality and nutritional value.
(Sousa-Gallagher, Mahajan and Mezdad, 2013) **in Journal of Food Engineering**	71	Engineering packaging design accounting for transpiration rate: Model development and validation with strawberries	MAP, transpiration rate, strawberries, packaging design	MAP was optimized using a model that accounted for transpiration in strawberry packaging, ensuring longer shelf life.	More research is needed to refine MAP materials for other fruits with similar perishability.
(Kim, Luo and Gross, 2004) **in Postharvest Biology and Technology**	101	Effect of package film on the quality of fresh-cut salad savoy	Fresh-cut savoy, MAP, packaging film, shelf life, quality attributes	Explored the effectiveness of different MAP packaging films in maintaining quality of fresh-cut savoy.	Future studies could include other leafy greens and assess optimal MAP configurations for different produce.
(Guillaume *et al.*, 2010) **in Innovative Food Science and Emerging Technologies**	56	Biobased packaging for improving preservation of fresh common mushrooms	Biobased packaging, mushrooms, MAP, water vapour permeability, environmental impact	Studied the use of biobased MAP materials to preserve mushrooms, showing the environmental benefits of using sustainable packaging.	Further research could explore biodegradable MAP alternatives for a wider range of fresh produce.
(Alegbeleye *et al.*, 2022) **In Applied Food Research**	89	Microbial spoilage of vegetables, fruits, and cereals	Microbial spoilage, MAP, food safety, fruits, vegetables	The study emphasizes the critical role of MAP in controlling microbial spoilage in vegetables and fruits, ensuring postharvest safety.	Future research should integrate MAP with antimicrobial treatments to reduce spoilage across various crops.
(Gallagher *et al.*, 2003) **in European Food Research and Technology**	34	The effect of dairy and rice powder addition on loaf and crumb characteristics of gluten-free bread	Gluten-free bread, MAP, dairy powder, rice starch, shelf life, staling	Investigated how MAP and dairy powder can be combined to extend the shelf life of gluten-free bread, preserving both texture and taste.	Research could explore MAP's impact on other gluten-free products, improving both taste and storage stability.

(Chrysargyris *et al.*, 2018) **in Frontiers in Plant Science**	56	Effects of Salinity on Tagetes Growth, Physiology, and Shelf Life of Edible Flowers Stored in Passive Modified Atmosphere Packaging	Salinity stress, Tagetes growth, MAP, antioxidant compounds, flower storage	Demonstrated the benefits of passive MAP in extending shelf life of Tagetes flowers under salinity stress, by reducing weight loss and microbial spoilage.	Future research could explore optimal MAP conditions for various flower species under stress conditions like salinity.
(Mohi Alden *et al.*, 2019) **in Computers and Electronics in Agriculture**	91	Quality and Shelf-life Prediction of Cauliflower under Modified Atmosphere Packaging Using Artificial Neural Networks and Image Processing	Cauliflower, MAP, shelf-life prediction, artificial neural networks, gas composition	Used MAP and artificial neural networks (ANNs) to predict the shelf life of cauliflower based on gas composition and color changes.	Future research could apply ANN-based MAP models to optimize packaging for other perishable crops.
(Villalobos *et al.*, 2014) **in Postharvest Biology and Technology**	88	Use of Equilibrium Modified Atmosphere Packaging for Preservation of 'San Antonio' and 'Banane' Breba Crops (Ficus carica L.)	MAP, Equilibrium, fig storage, gas composition, microbial control	Investigated equilibrium MAP with microperforated films to preserve breba figs by controlling O2 and CO2 levels and minimizing microbial growth.	Future studies should assess MAP for other fig varieties and explore other fruit crops using similar packaging technologies.
(Mashabela, Mahajan and Sivakumar, 2019) **in Food Packaging and Shelf Life**	67	Influence of Different Types of Modified Atmosphere Packaging Films and Storage Time on Quality and Bioactive Compounds in Fresh-Cut Cauliflower	MAP, fresh-cut cauliflower, bioactive compounds, storage time, glucosinolates, antioxidants	Analyzed the impact of MAP films on bioactive compounds like glucosinolates in fresh-cut cauliflower, demonstrating the role of MAP in maintaining nutritional quality.	Future research could examine MAP integration with other preservation techniques to enhance the bioactive compound retention in other vegetables.
(Vithu, Dash and Rayaguru, 2019) **in Food Reviews International**	122	Post-Harvest Processing and Utilization of Sweet Potato: A Review	Sweet potato, post-harvest processing, storage, bioactive compounds, utilization	Discussed how MAP helps extend the shelf life of sweet potato by slowing down respiration and reducing microbial spoilage.	Future research should investigate how MAP can be integrated with other preservation methods to enhance sweet potato storage.

Table.4 Most Frequently Occurring Keywords in MAP Research for Horticultural Product Preservation

Frequency	Keywords
>20	Modified Atmosphere Packaging (21)
16-20	Food storage (19), food packaging (18)
11-15	Packaging (14), shelf life (12), crops (11), fruits (11)
6-10	Food preservation (10), carbon dioxide (9), atmosphere (8), quality control (8), modified atmosphere (7), oxygen (7), packaging materials (7), chemistry (6)

Figure.1 Annual publication of Modified Atmosphere Packaging

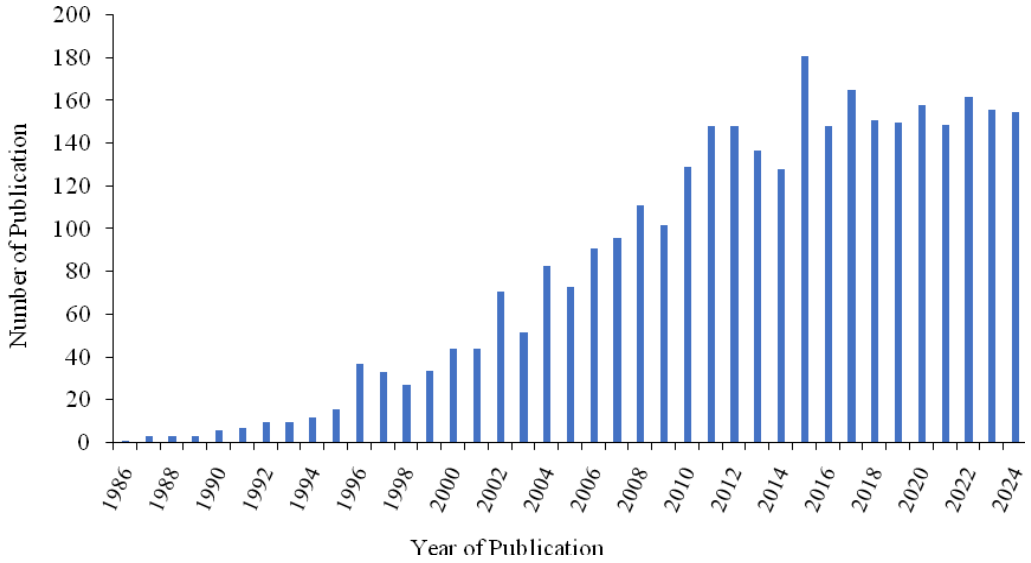


Figure.2 Diagram of PRISMA. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analysis

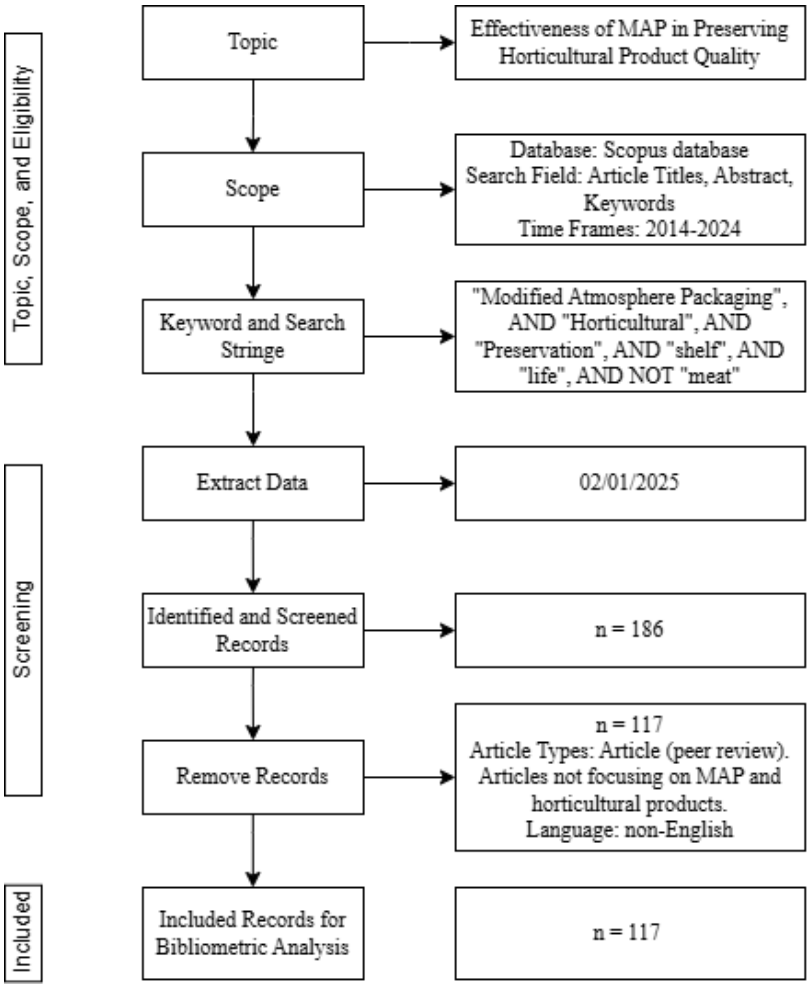


Figure.3 Most Contributive Countries in Modified Atmosphere Packaging (MAP) Research

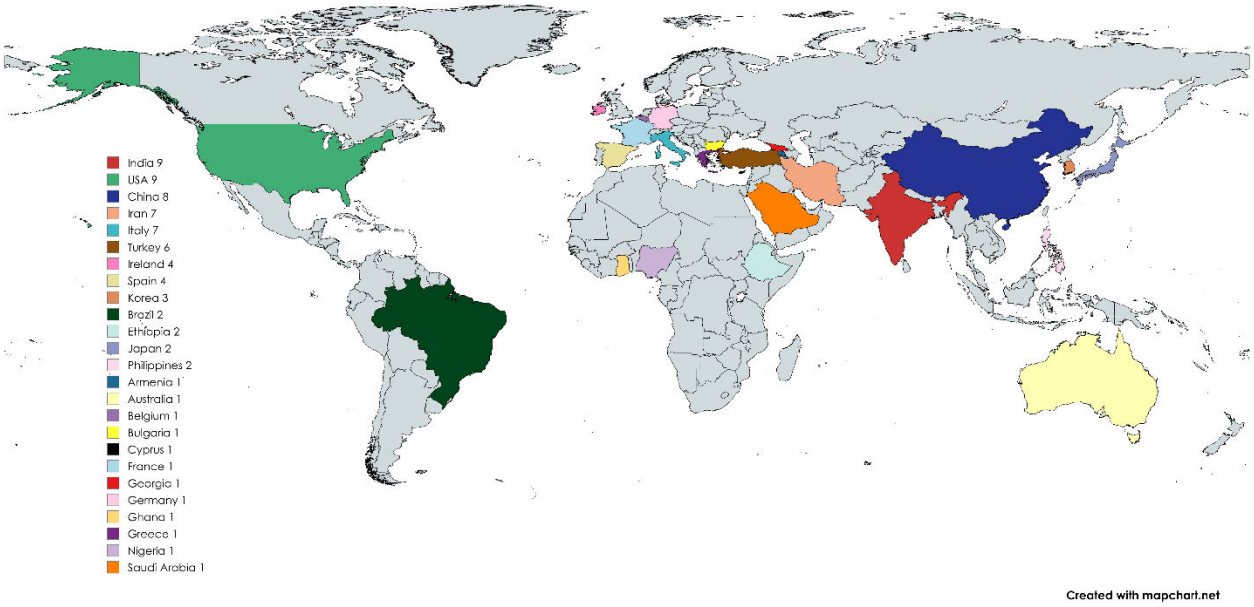


Figure.4 Development of the MAP Research Topic Over the Years

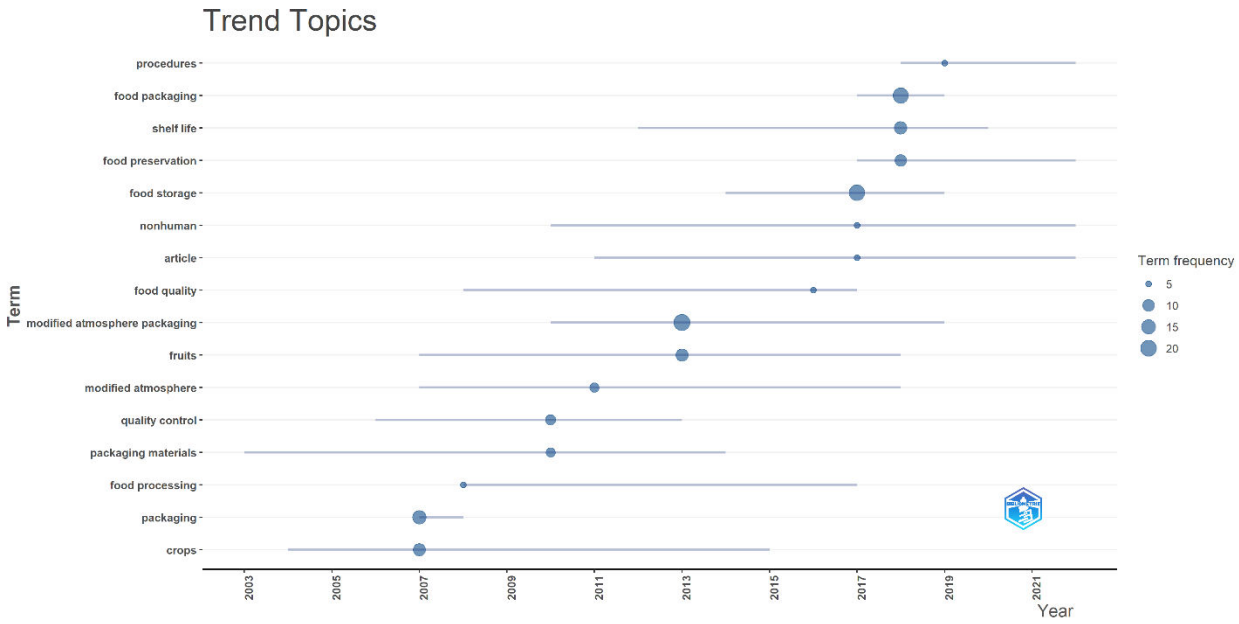


Figure.5 Conceptual Structure Map (Factorial Analysis) of Keywords on the Topic of MAP Research

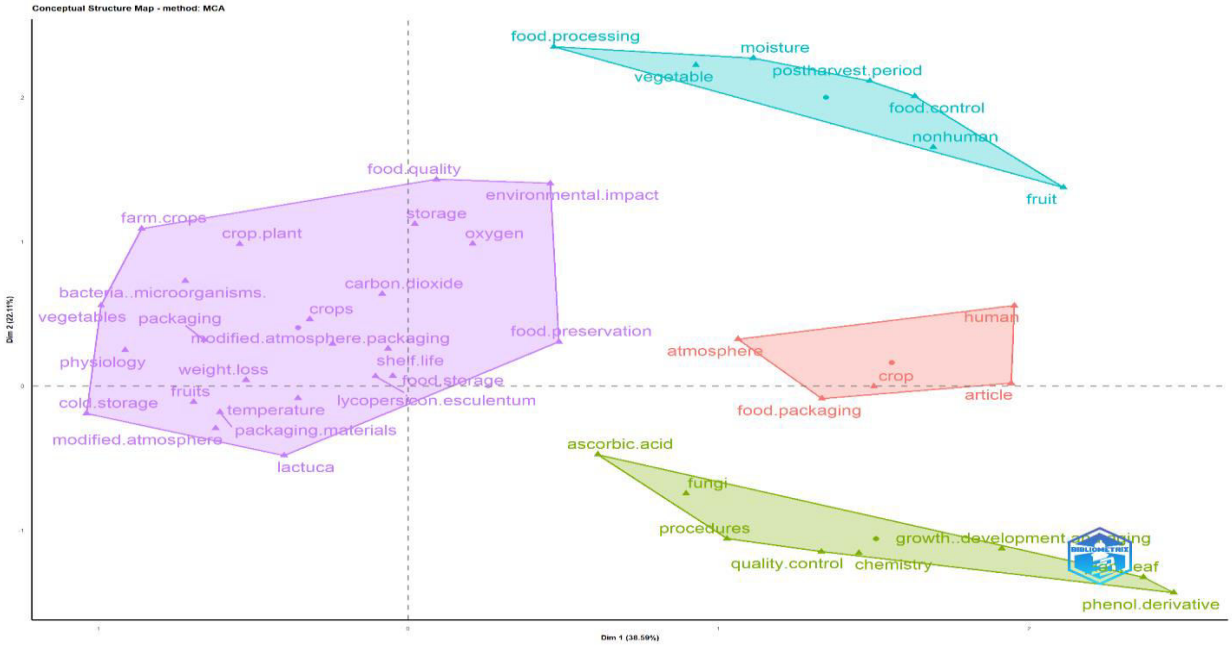
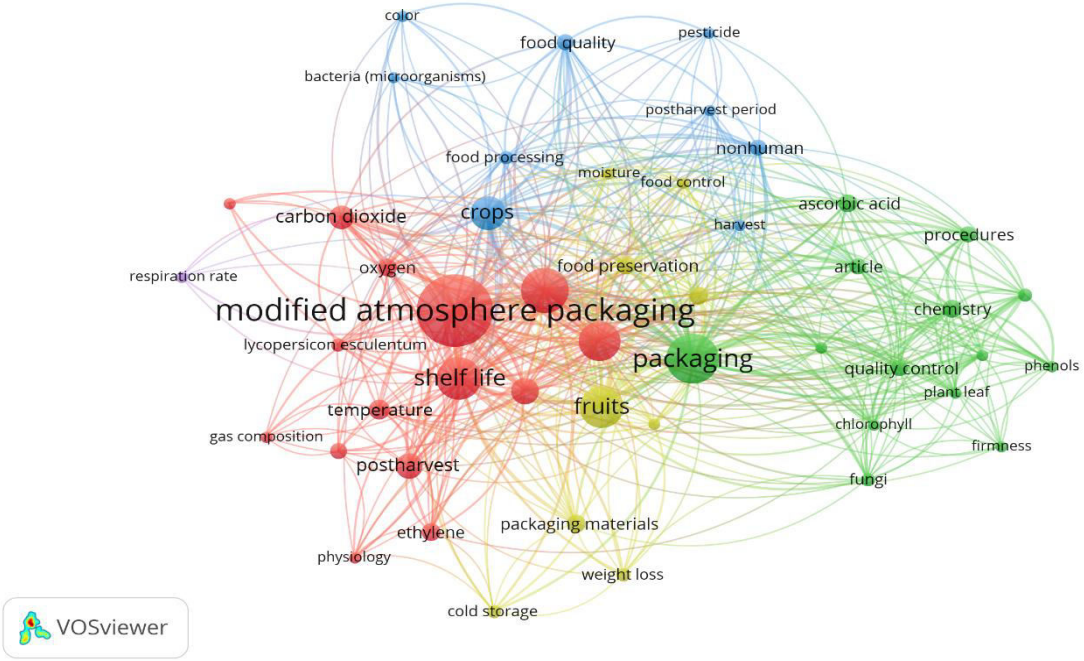


Figure.6 Network Visualization of Keywords in the Topic of Modified Atmosphere Packaging



Additionally, research on cooperative models for farmers to share MAP resources and policy recommendations for supporting smallholder farmers could help address these barriers and make MAP a more viable option globally (Perry *et al.,* 2019; Marku, 2024). The bibliometric analysis not only highlights the growing interest in MAP but also reveals exciting developments in technology that could significantly enhance its effectiveness. The rising

number of publications and increasing citations related to MAP innovations, such as smart packaging, AI integration, and sustainable materials, signals a strong trend towards technological advancements in this field.

The keyword co-occurrence maps and citation analysis in the bibliometric study indicate that sustainability and smart packaging solutions have emerged as dominant themes in recent years, suggesting that future research will likely focus on these cutting-edge innovations.

For example, smart packaging technologies, which integrate sensors to monitor and adjust environmental conditions in real-time, are rapidly gaining traction in the MAP research landscape. This is particularly significant as it could address the current limitations of MAP, which relies on static gas compositions and environmental conditions that are difficult to optimize across diverse crops (Yousefi *et al.,* 2019; Firouz, Mohi-Alden and Omid, 2021; Vasuki *et al.,* 2023). The bibliometric analysis shows that keywords like sensor technology and real-time monitoring have become increasingly prevalent in recent research, reflecting growing interest in dynamic MAP systems. This trend is evidenced by the rising frequency of keywords such as "sensor technology" and "real-time monitoring" in recent studies, indicating a shift towards dynamic MAP systems that can better respond to the needs of perishable goods (Alam *et al.,* 2021; Firouz *et al.,* 2021; Vasuki *et al.,* 2023). For instance, smart packaging can facilitate the communication of critical information regarding food quality and safety, thus extending shelf life and minimizing waste (Guerraf, 2024; Pereira, 2024). The integration of printed electronics and other advanced materials into packaging systems is also enhancing the functionality of smart packaging, allowing for better monitoring of food conditions (Liao *et al.,* 2019; Lydekaityte and Tambo, 2019).

Additionally, biodegradable materials are emerging as an important area of research. The bibliometric data shows an uptick in studies related to eco-friendly packaging solutions, indicating a shift towards sustainability in food preservation (Salgado *et al.,* 2021; Amin *et al.,* 2022; Jafarzadeh *et al.,* 2023). The global trend towards reducing plastic waste and promoting sustainable practices in packaging has been a driving force behind the development of biodegradable MAP films and other plant-based polymers. However, these technologies are still in the early stages, and further research is needed to scale these materials for widespread use.

The integration of AI-based systems with MAP technology is another promising trend. The bibliometric analysis reveals a growing body of research on artificial intelligence and machine learning models used to predict the optimal storage conditions for various horticultural products. These AI systems could improve the precision of MAP by adjusting parameters such as temperature, humidity, and gas concentrations based on real-time data, making MAP more efficient and adaptable (Khan *et al.,* 2023). Finally, the combination of MAP with other preservation methods—such as ozone treatment or high-pressure processing (HPP)—is gaining attention as a way to further extend shelf life and preserve the nutritional quality of fresh produce. The bibliometric analysis highlights recent studies exploring these synergies, which could offer more holistic solutions to postharvest preservation challenges (Deshwal and Panjagari, 2022).

This systematic literature network analysis, using the Scopus database, reveals key relationships among MAP-related keywords and their impact on preserving the quality and extending the shelf life of horticultural products. Despite growing research on MAP, there remains a limited focus on its intersection with critical issues like food security and environmental sustainability. The review of the top fifteen studies highlights diverse methodologies and research focuses, primarily on gas control, temperature management, and innovative packaging materials. The bibliometric analysis provides valuable insights into major research trends, emphasizing MAP's role in controlling atmospheric conditions to slow respiration rates. Author-based networks reveal collaboration patterns and historical developments in the field, underscoring MAP's increasing importance in food preservation. However, challenges remain in optimizing MAP for small-scale farms and overcoming the economic and logistical barriers to its widespread adoption. Future research should explore the integration of MAP with alternative preservation methods and focus on the development of more sustainable packaging technologies, such as biodegradable materials and eco-friendly films. Addressing these challenges will help scale MAP's impact, reduce food waste, and contribute to a more sustainable global food system

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Author Contributions

Sri Handayani Nofiyanti: Conceptualization, Writing - Original Draft; Usman Ahmad: Methodology, Supervision; Yuvita Lira Vesti Arista: Investigation, Resources, Formal Analysis; Michael Alexander Hutabarat: Validation, Visualization; Muhammad Rizqi: Administration, Editing

Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflict of Interest The authors declare no competing interests.

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