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Additives for sustainable fruit packaging: A systematic review

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ABSTRACT

Fruit packaging plays a crucial role in preserving quality, ensuring safety, extending shelf life, and reducing postharvest waste. This study systematically reviewed 316 studies conducted in 34 countries over the past six years to evaluate the role of additives in improving the structural and functional properties of packaging and their efficiency in maintaining fruit quality. The review focuses on three main packaging methods: direct fruit coating, fruit wrapping, and alternative approaches. A total of 83 types of chemical, physicochemical, biological, mechanical, and sensory tests were analyzed to assess the performance of these packaging systems. Key findings reveal innovations in active, edible, functional, intelligent, and sustainable packaging, with an emphasis on environmental sustainability and food safety. Notable additives, such as glycerol, essential oils, natural extracts, Tween, nanocellulose, silver nanoparticles, zinc oxide, and calcium chloride, demonstrated the ability to enhance film and coating properties, including elasticity, antimicrobial activity, and UV protection. These advancements contribute to the extension of shelf life across various fruit species, addressing global challenges in reducing food waste. This review highlights the systematic identification of trends, gaps, and opportunities in additive applications for fruit packaging, offering insights for the development of sustainable and effective packaging solutions. By consolidating diverse findings, this study provides a foundation for future innovations in the field, aligning with growing consumer demand for environmentally responsible and efficient postharvest technologies.

1. Introduction

Fresh fruits are indispensable in the daily diet of people around the world due to their taste and nutritional properties (Küçük et al., 2023). However, ripening, senescence, and pathogen infection, after harvest, often result in quality loss and significant waste (de Matos Fonseca et al., 2021; Heras-Mozos et al., 2021; Nian et al., 2023; Pavinatto et al., 2020). These challenges highlight the urgent need for innovative strategies that can effectively address the high perishability of fruits and reduce post-harvest losses, which currently account for substantial economic and environmental impacts worldwide.

Fruit and vegetable packaging plays an essential role in maintaining quality, reducing waste, and enhancing global food safety (Parente et al., 2023). The application of films and coatings is a valuable strategy that provides additional protection to intact or minimally processed fruits and vegetables. These materials form a semipermeable barrier, reducing fruit metabolic activity and water loss, as well as inhibiting microbial adhesion and growth (Abdalla et al., 2023; Dalei et al., 2023), while also offering protection against mechanical damage (Bremenkamp et al., 2021). Moreover, the development of active and intelligent packaging has gained attention in recent years, enabling not only physical protection, but also functionalities such as antimicrobial activity and monitoring fruit freshness.

Various materials have been considered for the development of films and coatings, including synthetic polymers and biopolymers (Galus et al., 2020). However, pure polymers often exhibit insufficient physicochemical properties, requiring the incorporation of additives to confer additional package functionalities. Additives such as essential oils ensure antimicrobial activities and improve the organoleptic attributes of packaged fruits (Belili et al., 2024; Yang, Goksen, et al., 2023; Zhang,

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Zhang, et al., 2022), while glycerol enhances the elastic behavior of the films (Atta et al., 2021). Copper oxide particles can provide UV protection, mitigating the degradation of antioxidants and the loss of nutrients (da Costa et al., 2024). Recent advancements in nanotechnology have also introduced new additives, such as nanocellulose and metallic nanoparticles, which improve barrier properties, mechanical strength, and biodegradability, demonstrating their potential in sustainable packaging applications.

The addition of materials for packaging may include compounds such as plasticizers, thickeners, crosslinkers, texturizers, antimicrobial agents, and antioxidants (Rahman et al., 2024; Sani et al., 2021), which positively influence the performance of fruit packaging materials. These compounds not only extend shelf life, but also address growing consumer demand for sustainable and environmentally friendly solutions in food preservation.

Unlike previous studies primarily focused on natural-origin additives for food packaging (Kaur et al., 2023), this review systematically explores a variety of additives used in films and coatings, with a specific focus on fruits. Therefore, this study aimed to gather and evaluate the main information obtained in the last six years on the use of additives to improve the structural and functional properties of packaging, as well as their efficiency in maintaining the postharvest quality of fruits. By consolidating findings from 316 studies, across 34 countries, this review provides a comprehensive overview of recent innovations, highlights key trends in additive applications, and identifies opportunities for further advancements in sustainable fruit packaging.

2. Research methodology overview

In order to gather relevant evidence, this study employed a systematic literature review (SLR), a rigorous methodology that defines clear research objectives and questions. The SLR process includes the systematic identification, screening, selection, analysis, and interpretation of data, adhering to strict inclusion and exclusion criteria.

2.1. Purpose and research question

Research on films and coatings for fruit packaging is expanding, focusing on analyzing additives to extend shelf life, maintain quality, and ensure food safety. While several reviews exist, no studies have applied a SLR to this topic. This research addresses this gap by exploring the diverse purposes of additives in fruit packaging. The objective is to identify the most commonly used additives in films and coatings and evaluate their impact on quality, food safety, and shelf life through the research questions: *What are the most commonly used additives in fruit packaging, and how do they influence quality, food safety, and shelf life?*

2.2. Data search strategy

For our systematic literature review, initiated on January 22, 2024, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. Using Science Direct, Scopus, and Web of Science, we applied the search terms "Fruit AND Packaging AND Preservation AND (Coating OR Film)" to cover various aspects of fruit packaging and preservation. The review focused exclusively on published studies available in these databases, avoiding unpublished data or external inquiries. This approach ensured a robust collection of relevant scientific evidence for thorough analysis and synthesis.

2.3. Study selection

The selected studies followed a rigorous methodology with inclusion criteria requiring search terms in the title, abstract, or keywords; publication in English; mention of at least one additive used in packaging; and the use of films and coatings on fruits. Exclusion criteria removed abstracts, conferences, editorials, books, review articles, case reports, articles unavailable for download, and studies published before January 2019. Two independent investigators (AGP and DFMN) screened titles and abstracts, with a third (GLAM) resolving any disagreements. Full-text analyses excluded studies not meeting the criteria, ensuring methodological consistency without employing additional search methods.

2.4. Data extraction and processing

Data collection was conducted using a predefined form to extract the first author's name, journal title, publication year, study location (country and primary affiliation), and study methodology. This included details on fruit types, processing stages, material usage methods, packaging composition, additive types and functions, tests performed on packaged fruits, and key physical, chemical, biological, mechanical, and sensory analyses. Microsoft Office Excel® was used for data processing and analysis.

2.5. Methodological quality assessment

A checklist was developed to evaluate the methodological quality of the studies, focusing on identifying additives used in films and coatings for fruit packaging. Each selected article was assessed based on eight criteria: 1) purpose of fruit usage, 2) evaluation techniques for packaged fruit, 3) additive purpose, 4) additive incorporation methodology, 5) functional performance of additives, 6) fruit shelf life, 7) properties of packaged fruits, and 8) packaging form. Studies that addressed all these aspects were deemed to have higher methodological quality.

3. Results and discussion

3.1. Summary of study selection, distribution, and quality

In the study selection process, a total of 1206 publications were initially identified, which were distributed across the databases as follows: 776 in Scopus, 276 in Web of Science, and 154 in Science Direct (Fig. 1). The initial screening involved applying various filters, which resulted in the exclusion of 286 studies based on document type (Fig. 1). Additionally, 193 studies were excluded for not falling within the defined period of interest, 31 for not being in the required language, and 267 for being indexed in multiple databases (Fig. 1). During the detailed screening stage, 74 additional studies were excluded, leaving a total of 355 studies considered for full evaluation (Fig. 1). After a thorough review of these studies, 316 were ultimately included in the analysis, following the exclusion of 39 studies that did not meet the established inclusion criteria (Fig. 1).

This thorough selection process not only ensured the inclusion of high-quality publications, but also highlighted a consistent growth trend in the number of studies focused on additives for fruit packaging. These 316 studies, distributed across 34 countries, demonstrated a steady increase in research activity from 2019 to 2024, with the peak of publications occurring in 2023, representing more than one-third of the analyzed research (n = 112, 35.44 %) (Fig. 2). Although the review of studies was finalized on January 22, 2024, that year already accounted for 12.34 % of the total publications, indicating the potential for significant growth by the end of the analyzed period (Fig. 2).

China has the largest number of studies, totaling 183 studies (57.91 %), followed by Brazil (n = 22, 6.9 %), India (n = 21, 6.6 %), Vietnam (n = 11, 3.48 %), and Iran (n = 10, 3.1 %) (Fig. 2). This distribution reflects a clear interest in research on additives used in films and coatings for fruits. Other countries, such as Italy, Mexico, Thailand, Canada, and Spain, show a variation of 4–7 studies over the years, without a dominant year for these countries (Fig. 2). Countries like Chile, Egypt, the United States, Greece, Japan, Malaysia, Turkey, South Korea, Saudi Arabia, and other countries have a smaller contribution, ranging from 1 to 3 studies over the years (Fig. 2).

China leads in research production on additives in fruit packaging

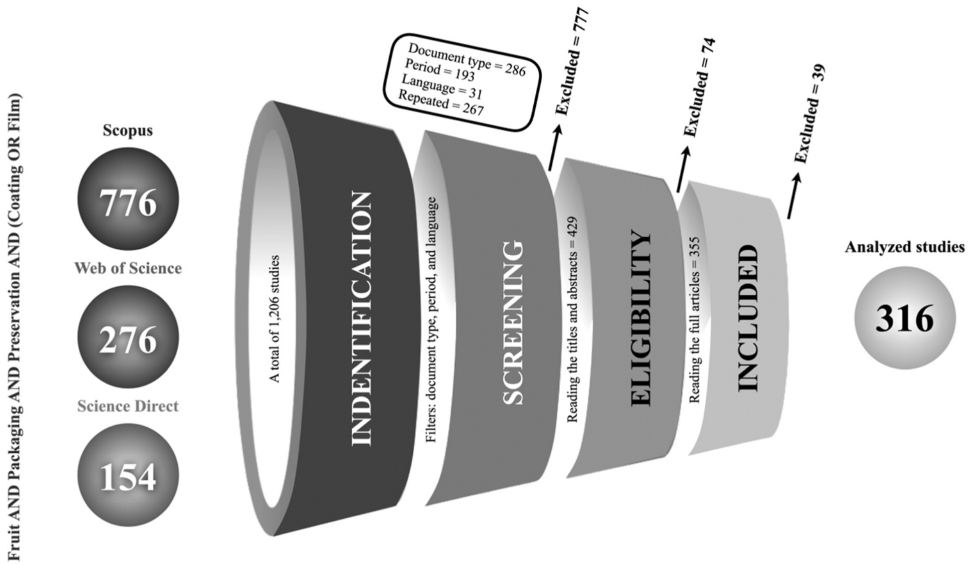


Fig. 1. PRISMA flow diagram of the study identification and selection process.

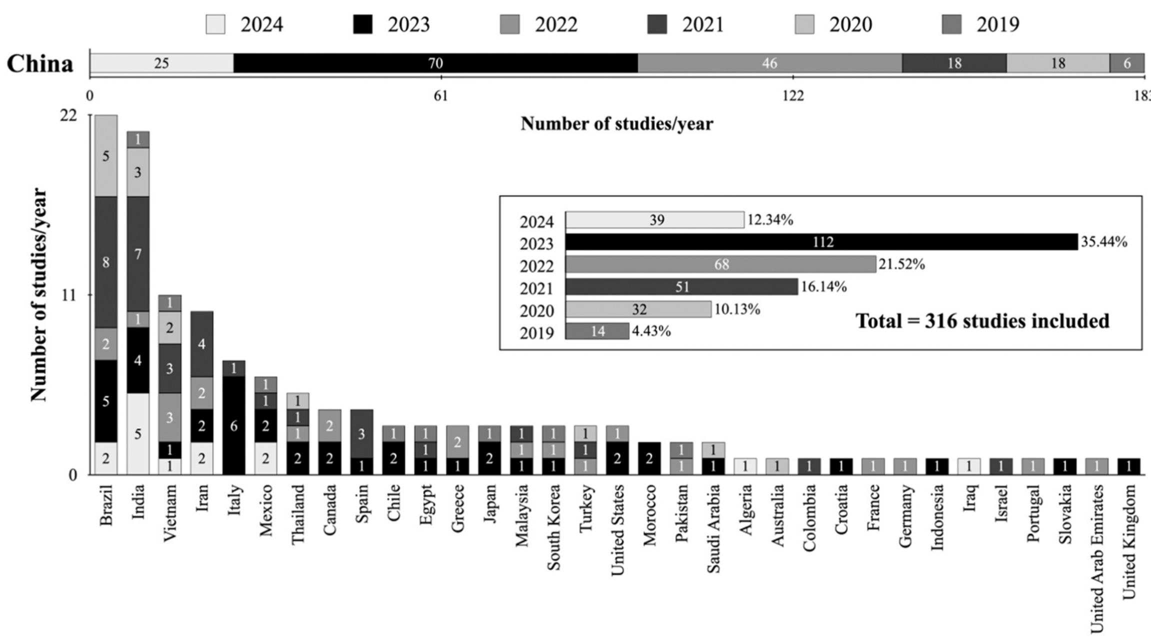


Fig. 2. Distribution of studies by country and year of publication. Highlighting China's contribution and yearly summaries.

and has had significant contributions over the years. Brazil and India follow as the next largest contributors. China, India, and Brazil also stand out in global fruit productivity (Abrol, 2015), an activity highly dependent on soil type, climate, temperature of the cultivation area, as well as the agricultural technologies used (Lv et al., 2024; Łysiak & Szot, 2023). The combination of fertile soil, favorable climatic conditions, and advanced technologies makes these countries leaders in productivity, which may justify the increased interest and relevance in the use of additives in fruit packaging.

Analyzing the publications over the years, it is observed that Asian countries, such as China, India, Vietnam, and Iran, have recently increased their study output (Fig. 2). On the global stage, Asia is the leading fruit-producing region, showing significant growth in recent decades (FAO, 2021). In contrast, scientific production in countries like Canada and Egypt has remained stable for several years, while it has declined in others, such as Italy, Mexico, and Thailand (Fig. 2). This increased focus on research, particularly in Asia, aligns with the growing global demand for fresh and healthy products, which has fueled interest in innovations in fruit packaging.

Studies on fruit packaging have gained prominence due to the increasing demand for fresh and healthy products and the need to reduce food waste (Nunes et al., 2023). The food industry is constantly seeking new ways to extend the shelf life of fruits, while maintaining their nutritional and sensory properties (Boninsegna et al., 2023; Chen, Brennan, et al., 2023; Hu, Liu, et al., 2022; Pateiro et al., 2021). Fig. 3 presents an analysis of the methodological quality of the studies included to evaluate the use of additives in fruit packaging. This analysis is crucial as it allows for a multidimensional study of how clarity in objectives, methodology descriptions, and statistical analysis, among other factors, contribute to the safety and reliability of this review.

All studies had clearly defined objectives and evaluated the shelf life of fruits, showing a consistent focus on this aspect, which indicates a

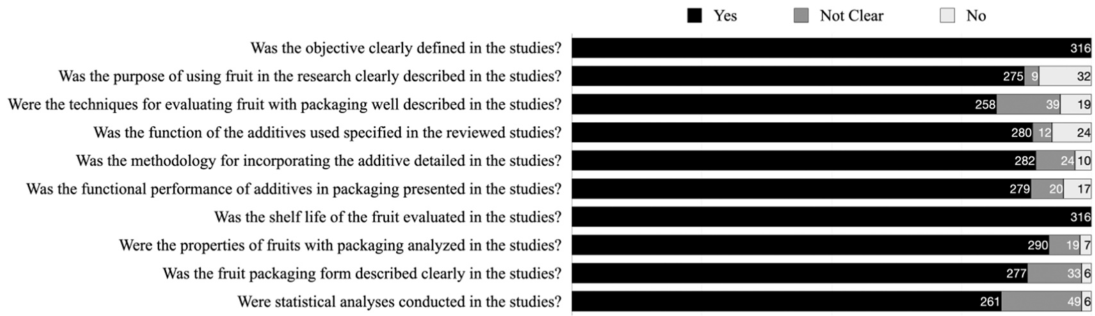


Fig. 3. Methodological compliance assessment to verify if the study quality criteria were observed (Yes, Not Clear, No).

purpose-driven approach in the research (Fig. 3). The high degree of clarity in these aspects is a strength, suggesting that most studies are well-targeted at providing practical and applicable information. Furthermore, the assessment of shelf life is particularly critical, as it determines the effectiveness of packaging in prolonging the quality and freshness of fruits (Bodana et al., 2024; Goswami et al., 2024; Sharma et al., 2024).

The majority of studies (87 %) clearly described the purpose of using the fruits, with only 3 % of the studies being unclear on this aspect and 10 % failing to provide an adequate description (Fig. 3). This is an area for improvement, as a lack of clarity on the purpose can lead to misinterpretations of the results and misleading comparisons between different studies.

In 81 % of the studies, the techniques used were well described, while 12 % did not present the techniques and 6 % did not provide clear descriptions (Fig. 3). The function of the additives was clearly specified in 88 % of the studies, with 4 % being unclear and 8 % not mentioning the function (Fig. 3). In 88 % of the studies, the methodology for incorporating the additives was detailed, while 8 % did not provide these details and 3 % lacked clear descriptions (Fig. 3). The functional performance of the additives was presented in 88 % of the studies, with 6 % showing uncertainty and 5 % failing to present this information (Fig. 3). Although these data indicate a positive trend, the presence of uncertainties and lack of detail in a significant proportion of the studies suggests the need for standardization and greater rigor in methodological descriptions.

The properties of the packaged fruits were analyzed in 92 % of the studies, with 6 % lacking clarity and 2 % failing to analyze them adequately (Fig. 3). The form of packaging was clearly described in 88 % of the studies, with 10 % providing unclear descriptions and 2 % failing to describe the packaging adequately (Fig. 3). Statistical analyses were conducted in 83 % of the studies, while 16 % of the studies left these analyses unclear, and 2 % did not conduct statistical analyses (Fig. 3).

Overall, the results of the methodological quality assessment show that the majority of the evaluated studies were clear and comprehensive regarding their objectives, methodologies, functions and performances of additives, as well as the evaluation of fruit shelf life. However, some areas, such as the description of assessment techniques and the conduct of statistical analyses, showed more uncertainty. These findings may be valuable in identifying areas that require greater attention or standardization in future research on additives in fruit packaging. Therefore, clearer guidelines for methodologies and improvements in statistical analysis standards are recommended to enhance the quality and reliability of studies on fruit packaging.

3.2. *Overview of packaged fruit studies*

According to the principles of respiration rate and ethylene biosynthesis during the ripening process, fruits can be categorized as climacteric or non-climacteric (Fukano & Tachiki, 2021; Kou et al., 2021). Climacteric fruits exhibit peaks in respiration rate and ethylene biosynthesis during ripening (Liu et al., 2015), while non-climacteric fruits do not show significant increases in these rates (Chen et al., 2020). This distinction is crucial for selecting appropriate packaging solutions tailored to the physiological characteristics of each fruit type. Among the included studies (n = 316), 51 evaluated more than one type of fruit, indicating the effects of packaging additives on different fruits (Fig. 4). Of the total sample, 198 studies utilized additives in packaging for climacteric fruits, while 194 studies did the same for non-climacteric fruits. Although there are more studies on climacteric fruits, the greater diversity of non-climacteric fruits highlights their significance in the market, with 28 species of non-climacteric fruits compared to 24 species of climacteric fruits.

Fruits such as strawberries, grapes, cherries, and citrus are classified as non-climacteric and therefore do not ripen after harvest. In contrast, fruits like bananas, tomatoes, apples, and mangoes are climacteric, continuing to ripen even after being harvested. Despite this distinction, both groups are susceptible to deterioration caused by fungi, yeasts, and bacteria. Additionally, they undergo changes such as weight loss, reduction in firmness, and alterations in other physicochemical characteristics (Kowsalya et al., 2019; Maurizzi et al., 2023; Xu et al., 2023; Zhang, Zhang, et al., 2023; Zidan et al., 2023). Therefore, the application of appropriate films and coatings is essential for both groups, as these solutions act as semipermeable barriers, reducing respiration rates, microbial growth, and moisture loss, ultimately extending the shelf life of the packaged fruits.

3.2.1. *Strawberries*

Strawberries are a prominent focus of research on non-climacteric fruits, with 97 studies dedicated to their packaging and preservation. In 2022, global strawberry production exceeded 9.5 million tons, spanning all continents except Antarctica, with China leading as the largest producer, followed by the United States, Mexico, Turkey, and Spain (FAO, 2024). This significant production volume and global distribution highlight the urgent need for tailored packaging solutions to address strawberries' high perishability and susceptibility to quality degradation during postharvest handling. Physicochemical changes, such as weight and flesh firmness loss, significantly impact their marketability and shelf life, making strawberries a priority in packaging research focused on innovative technologies to preserve quality. Additionally, breeding programs have aimed to develop new strawberry varieties with superior adaptability to diverse environmental conditions, improved organoleptic traits, and extended postharvest life, further emphasizing the importance of advanced packaging solutions to complement these agricultural advancements (Zeist & Resende, 2019).

3.2.2. *Bananas*

Bananas stand out as the most extensively studied climacteric fruit, with 43 studies specifically addressing their packaging requirements (Fig. 4). Globally, bananas are among the most cultivated, traded, and consumed fruit, playing a vital role in ensuring food and nutritional security (FAO, 2024; Maseko et al., 2024). As a climacteric fruit,

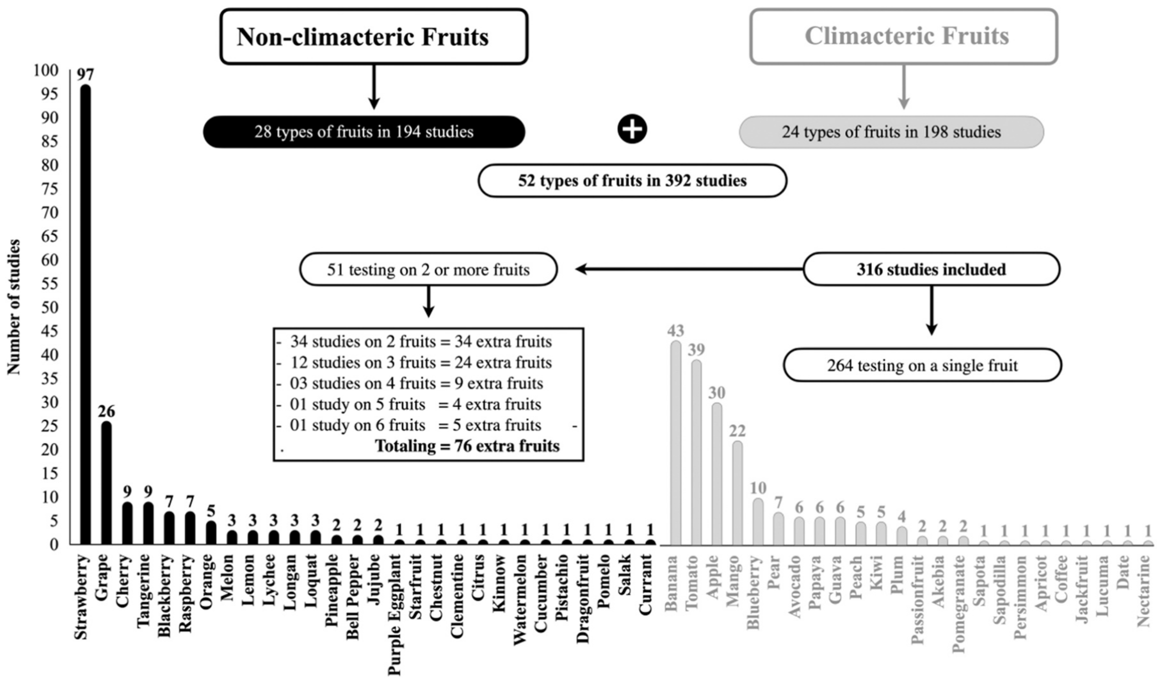


Fig. 4. Distribution of studies on climacteric and non-climacteric fruits.

bananas exhibit an increase in respiration rate after harvest, which intensifies metabolic activity, resulting in accelerated ripening and significant postharvest quality deterioration (Gang et al., 2024; Jung et al., 2020). This physiological behavior presents substantial challenges for preservation, necessitating the application of advanced packaging technologies. These strategies often involve the integration of additives designed to reduce respiration rates, decelerate ripening processes, and maintain the physicochemical and sensory attributes during storage and transportation. The prevalence of research focused on bananas underscores their essential contribution to global food systems, emphasizing the urgency of developing effective postharvest management practices to mitigate losses and align with market demands.

3.2.3. *Forms of fruit utilization in packaging studies*

The consideration of climacteric and non-climacteric fruit quality preservation during storage and transportation extends to the different forms in which fruits are utilized in research. Two primary categories were identified: whole fruits and minimally processed fruits (Fig. 5). The majority of studies (n = 264, 83.54 %) focused on whole fruits, reflecting their prevalence in the fresh fruit market. In contrast, a smaller proportion (n = 42, 13.29 %) addressed minimally processed fruits, while only a limited number (n = 10, 3.16 %) included both forms. This emphasis on whole fruits aligns with their simpler handling, storage requirements, and longer shelf life compared to minimally processed counterparts.

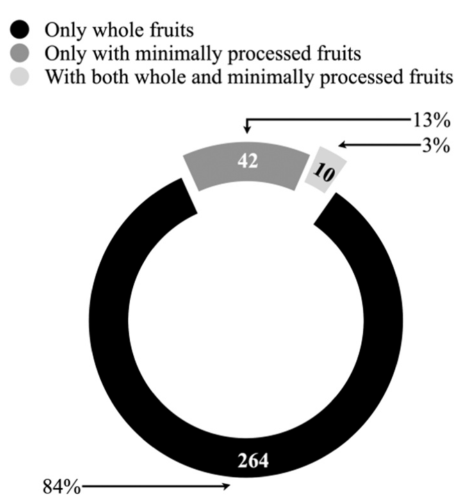


Fig. 5. Distribution of studies on fruit packaging considering whole fruits, minimally processed fruits, and both.

Despite the growing market for minimally processed fruits (Gomes et al., 2023; Prakash et al., 2018), whole fruits continue to dominate due to their ease of storage, intact cellular structure, and resistance to physicochemical changes and microbial decay (Kang et al., 2023; Li, Jiang, et al., 2023; Li, Guo, et al., 2023; Mao et al., 2024; Perera and Smith, 2013; Prakash et al., 2018). However, the increasing demand for ready-to-eat options highlights the need for further research on packaging solutions tailored to minimally processed fruits. These solutions are essential to address their unique vulnerabilities and to support this expanding segment of the fruit market, ensuring quality and extending shelf life under these specific conditions.

3.3. *Innovations and base materials and additives in fruit packaging*

The data reviewed from 316 studies indicate a total of 447 instances of packaging material usage (Fig. 6). The predominance of chitosan, mentioned in 102 out of the 447 uses, highlights its exceptional characteristics, such as non-toxicity, low cost, commercial availability, excellent film-forming properties, and bioactive and biodegradable nature (Bagher et al., 2020; Liu et al., 2020; Nguyen et al., 2023). Starch and polyvinyl alcohol (PVA), each with 35 mentions (Fig. 6), also stand out for their film-forming properties and compatibility with natural additives, making them valuable in various packaging solutions (Belili et al., 2024; Garavand et al., 2022; Paredes et al., 2023). The distribution of multiple material usage in the studies reveals a growing trend in exploring specific combinations to optimize properties such as water behavior, mechanical properties, gas barrier performance, and interactions with the packaged product (Fu et al., 2024; Gang et al., 2024; Pan et al., 2023; Shen et al., 2022; Zhou, Cheng, et al., 2021). Among the studies, 201 were conducted with a single material, 101 with two, 12

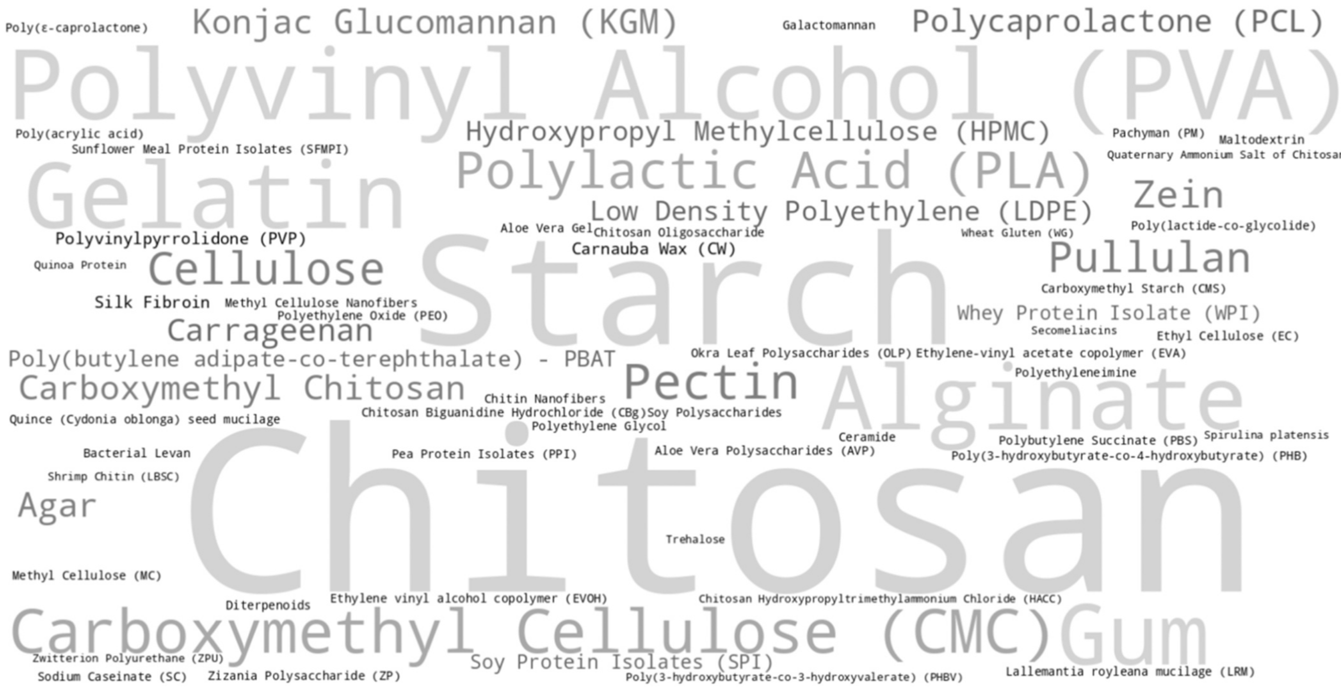


Fig. 6. A word cloud of materials visualizes the frequency of use of different base materials in packaging.

with three, and only 2 with four different materials (Fig. 6). This trend reflects a focus on simpler combinations while exploring material synergies to address specific preservation challenges.

The diversified use of natural gums such as guar, arabic, acacia, locust bean, xanthan, Konjac, Tara, lacquer, and gellan, as well as various starch sources like arrowroot, potato, cassava, corn, and pine seed, also deserves attention (Fig. 6). These natural materials are increasingly explored for their potential to enhance biodegradability and align with sustainability objectives. Less conventional materials have been investigated for their unique properties, including carnauba wax, ceramide, diterpenoids, secomeliacins, and the disaccharide trehalose (Fig. 6). Carnauba wax provides water resistance and shine to packaging materials (Choi et al., 2019; Phothisuwan et al., 2021), while ceramide prevents moisture loss (Nian et al., 2022). Diterpenoids and secomeliacins possess antioxidant and antimicrobial properties (Ahmed et al., 2022). Trehalose protects against thermal stress and dehydration, maintaining food integrity under adverse conditions (Kuczyńska-Wiśnik et al., 2024). The use of these materials highlights the search for innovative, natural-based alternatives for sustainable packaging development.

Chitosan has emerged as an innovative and sustainable material with the potential to transform the preservation and commercialization of fresh foods. Its ability to combine structural and functional properties, such as antimicrobial and antioxidant activities, makes it a preferred material for fruit coatings. These films significantly extend shelf life by reducing respiration rate and delaying the growth of microorganisms (Benavides & Franco, 2023; Nayak et al., 2024; Zhao, Wang, Li, Lei, et al., 2023). Moreover, being biodegradable, these packaging materials do not contribute to plastic waste, meeting the growing demand for sustainable and environmentally responsible packaging solutions (El Mouzahim et al., 2023; Nayak et al., 2024; Preethi et al., 2021).

The diversity of materials used in packaging manufacturing ($n = 68$), including natural and synthetic biopolymers, reflects a clear trend of innovation toward more functional and environmentally friendly solutions (Fig. 6). The growing interest in biopolymers demonstrates a shift towards integrating biodegradability with high-performance characteristics. While most studies employed a single material, a significant number explored synergies between two or more ($n = 115$), which often results in unique properties such as enhanced mechanical characteristics, biocompatibility, and the ability to form functional films that extend the shelf life of fresh fruit (Guo et al., 2024; Nayak et al., 2024; Yang, Liu, et al., 2023).

Building on this exploration of material synergies, the analysis of additives used in fruit packaging identified 226 different types of materials applied. Fig. 7 illustrates the diversity and distribution of these additives, highlighting the wide range of options explored in the studies. Notably, the majority of studies focused on the use of one to three different additives, with 74 studies opting for a single additive, 114 utilizing two, and 83 applying three. This distribution suggests a practical approach to achieve effective packaging functionality with simplified formulations.

A detailed analysis shows that most of the studies are concentrated in a small group of additives, with only eight types accounting for more than 50 % of occurrences (Fig. 7). These include glycerol, oils, natural extracts, Tween, nanocellulose, silver nanoparticles, zinc oxide, and calcium chloride, which have demonstrated effectiveness in improving packaging properties, particularly in active and functional applications.

Among these additives, glycerol stands out as the most frequently cited plasticizer, appearing in 172 studies. Its primary function is to enhance the flexibility and elasticity of materials, while improving elongation at break resistance and response to external pressure on films (Atta et al., 2021; Dang et al., 2024). These properties are crucial for biodegradable packaging, which requires greater malleability to compete with conventional petroleum-based polymers.

The widespread use of glycerol in scientific literature highlights its effectiveness and compatibility with both natural and synthetic polymers. Beyond its role as a plasticizer, it is particularly valuable in biodegradable coatings for fruits and flexible seals in packaging. Studies have shown that biopolymer-based films plasticized with glycerol can reduce moisture loss, delay ripening, and extend shelf life in fruits such as oranges, tomatoes, and bananas, helping to maintain quality and minimize waste.

Like glycerol, other additives play key roles in functional packaging formulations. Natural extracts (47 studies) and essential oils (46 studies) rank second and third in frequency of use, respectively. These terms encompass a variety of compounds, each with distinct properties. Natural extracts are valued for their bioactive functions, such as antioxidant

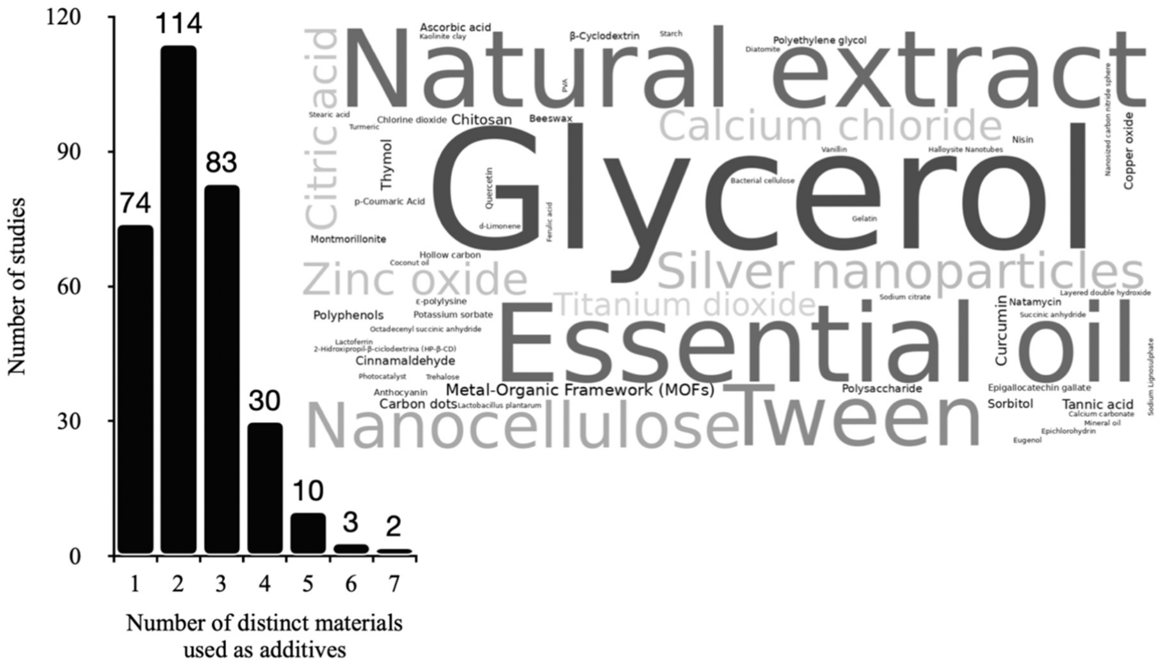


Fig. 7. Overview of additive materials in fruit packaging: Diversity and distribution.

and antimicrobial effects, which contribute to food preservation (Dai et al., 2022; Li, Guo, et al., 2023; Paredes et al., 2023). Their growing application reflects the increasing demand for natural alternatives that enhance both functionality and consumer acceptance of packaging.

The application of natural extracts in coatings for plums, strawberries, and blackberries has proven effective in extending shelf life by reducing microbial spoilage and fungal growth. Additionally, these extracts help preserve sensory attributes such as color, texture, and flavor, ensuring better postharvest quality. Their potential as a sustainable alternative for fruit preservation is reinforced by studies highlighting their antimicrobial and antioxidant properties.

The diversity within this category highlights the wide range of possible applications, making these compounds a frequent choice in studies focused on innovation and sustainability. Among the bioactive extracts cited in the literature, those derived from leaves, peels, fruits, seeds, and propolis stand out (Choi et al., 2019; Nguyen et al., 2022; Pu et al., 2024; Vargas-Torrico et al., 2022; Zidan et al., 2023).

In addition to bioactive extracts, essential oils have gained prominence in food packaging due to their antimicrobial and antioxidant properties. They are widely used to inhibit microbial growth, while acting as natural antioxidants (Belili et al., 2024; Zhou, He, et al., 2021). One of their key advantages is their ability to control spoilage and extend shelf life. Essential oils from oregano, thyme, cinnamon, and clove contain bioactive compounds such as carvacrol, thymol, and eugenol, which have demonstrated effectiveness against a broad spectrum of bacteria and fungi (Belili et al., 2024; Nur Hanani et al., 2023; Shi et al., 2023; Yin et al., 2019).

The application of essential oils in packaging has been tested in coatings for dates, mangoes, and guavas, as well as in direct contact with blackberries inside conventional packaging. These studies showed that essential oils not only preserved the physical and chemical characteristics of the coated fruits, but also provided a protective effect on nearby blackberries, demonstrating their broad-spectrum antimicrobial activity. This dual action, direct and indirect protection, reinforces their potential for use in active and multifunctional packaging systems, which is particularly relevant given the high susceptibility of fruits to microbial deterioration.

Furthermore, the antioxidants present in essential oils play a crucial role in protecting against oxidation (Hosseinifarahi et al., 2023; Poongavanam et al., 2023; Rusková et al., 2023). By slowing oxidative processes, these compounds help maintain fruit freshness, extend shelf life, and ensure that fruits reach consumers with high quality.

Tween, cited in 29 studies, is a surfactant widely used to stabilize emulsions and facilitate the incorporation of hydrophobic substances into aqueous matrices (Chau et al., 2024; Goswami et al., 2024; Triunfo et al., 2023). By reducing surface tension between immiscible liquid phases, it promotes the formation of homogeneous and stable mixtures over time. Its versatility in different formulations makes it an effective component for stabilizing complex and sensitive emulsions. Additionally, Tween enhances the dispersion of bioactive compounds, such as vitamins, antioxidants, and antimicrobial agents (Pateiro et al., 2021), improving the functional properties of packaging films and extending product shelf life. Its application in coatings for pomelos, tangerines, peaches, apricots, and nectarines has demonstrated that, as an emulsifier, Tween enables the formation of uniform and effective coatings that help preserve the postharvest quality.

The application of Tween in combination with other bioactive compounds has improved coating adhesion to fruit surfaces, reducing moisture loss, microbial growth, and oxidation. These findings highlight its importance as an essential component in edible coating formulations, especially for fruits that are highly sensitive to storage and transportation conditions. Beyond emulsifiers like Tween, structural reinforcement additives such as nanocellulose have gained attention in food packaging due to their ability to enhance mechanical properties and barrier performance. Cited in 22 studies, nanocellulose stands out for its high mechanical strength, biodegradability, and large surface area, making it ideal for producing reinforced materials and films with optimized characteristics (Kang et al., 2021; Qin et al., 2023; Tang et al., 2023). Its nanoscale structure enables efficient interaction with other matrix components, improving mechanical resistance, functionality, and UV barrier properties.

The increasing use of nanocellulose in biocomposites and smart packaging reflects the growing demand for sustainable and high-performance materials. By integrating advanced functionalities with environmental responsibility, nanocellulose offers an innovative alternative for improving packaging durability and efficiency (Begum et al., 2023; Rashvand et al., 2023; Wongthanaroj et al., 2022).

Packaging incorporating nanocellulose has been tested in various applications, including the wrapping of raspberries and strawberries, the coating of bananas, strawberries, and apples, and as a flexible seal in blueberry containers. These studies demonstrated that nanocellulose effectively protects fruits from physical damage, moisture loss, and microbial contamination. Additionally, its use as a flexible seal in blueberry packaging has shown promise in maintaining fruit quality and freshness, highlighting its versatility across different packaging formats.

Silver nanoparticles, cited in 19 studies, and zinc oxide, mentioned in 14, are widely recognized for their potent antimicrobial properties and are frequently used in active packaging to inhibit the growth of pathogenic and spoilage microorganisms (Guerra et al., 2023; Kowsalya et al., 2019; La et al., 2021; Zhang, Zhang, et al., 2023; Zhang, Jiang, et al., 2023). Their incorporation into packaging has been tested on both climacteric fruits (mango, banana, and cherry tomato) and non-climacteric fruits (lemon and strawberry), demonstrating significant effectiveness in extending shelf life by reducing microbial contamination.

For instance, in highly perishable strawberries, packaging enriched with silver nanoparticles significantly delayed microbial growth. In mangoes, bananas, and cherry tomatoes, active packaging helped reduce respiration rates and premature ripening. The proven efficacy of these materials justifies their recurrent use in research, particularly for applications aimed at extending food safety and quality.

Furthermore, the versatility of silver nanoparticles and zinc oxide allows their integration into various packaging matrices (Francis et al., 2022; Guo et al., 2020; Kalia et al., 2021; Nguyen et al., 2021; Zhang, Wang, et al., 2022; Zhang, Zhang, et al., 2022; Zhang, Yang, et al., 2022). Their application supports innovations in the food packaging sector, meeting the growing market demand for efficient, safe, and sustainable solutions.

Calcium chloride, cited in 13 studies, plays a crucial role as a crosslinking agent, enhancing the stability and mechanical strength of various matrices (Boninsegna et al., 2023; Wang et al., 2023; Yang, Liu, et al., 2023; Yang, Fei, et al., 2023; Yang, Goksen, et al., 2023; Yang, Zhou, et al., 2023; Yang, Li et al., 2023). In addition to improving mechanical properties, calcium chloride contributes to the structural integrity and durability of packaging materials, making it an essential additive in multiple applications (Senturk Parreidt et al., 2018).

Its effectiveness in enhancing texture and moisture barrier properties makes calcium chloride particularly valuable in edible films and coatings. Studies have shown that packaging incorporating calcium chloride has been tested in coatings for clementines, bananas, kiwis, and strawberries, demonstrating its ability to preserve postharvest fruit quality. These findings reinforce its potential as a functional additive in edible packaging, providing an effective solution for preserving fruits with diverse physiological characteristics. However, further research is needed to assess the safety and efficacy of calcium chloride applications, ensuring that excessive migration into food does not occur. It is essential to maintain its benefits without compromising consumer health or environmental sustainability.

While conventional additives like calcium chloride continue to play a critical role in edible coatings, research is increasingly focusing on innovative materials that can further enhance packaging performance and sustainability. Although most studies concentrate on a limited number of materials, there is growing interest in versatile additives that offer bioactivity, biocompatibility, and alignment with current demands for sustainability, innovation, and food safety (Fig. 8).

Additionally, research is exploring less conventional materials, such as Metal-Organic Frameworks (MOFs) and carbon nanodots, due to their potential to enhance packaging functionality. MOFs have gained attention for their ability to act as nanocarriers for bioactive compounds, improve absorption capacity, and provide antimicrobial activity in films and coatings (Nian et al., 2022, 2023; Tavassoli et al., 2024; Wang et al., 2023). Carbon nanodots, in addition to their antimicrobial properties, enhance gas and moisture barrier performance, enable the integration of sensors to monitor fruit quality, and improve film strength and flexibility, making packaging more durable and sustainable (Li, Yang, et al., 2023; Zhao, Wang, Li, Lei, et al., 2023; Zhao, Wang, Li, Guo, et al., 2023; Shen, Yan, et al., 2024; Shen, Yang, et al., 2024). These materials represent the frontier of packaging innovation, offering advanced functionalities while addressing environmental concerns.

In line with these advancements, the analysis of packaging

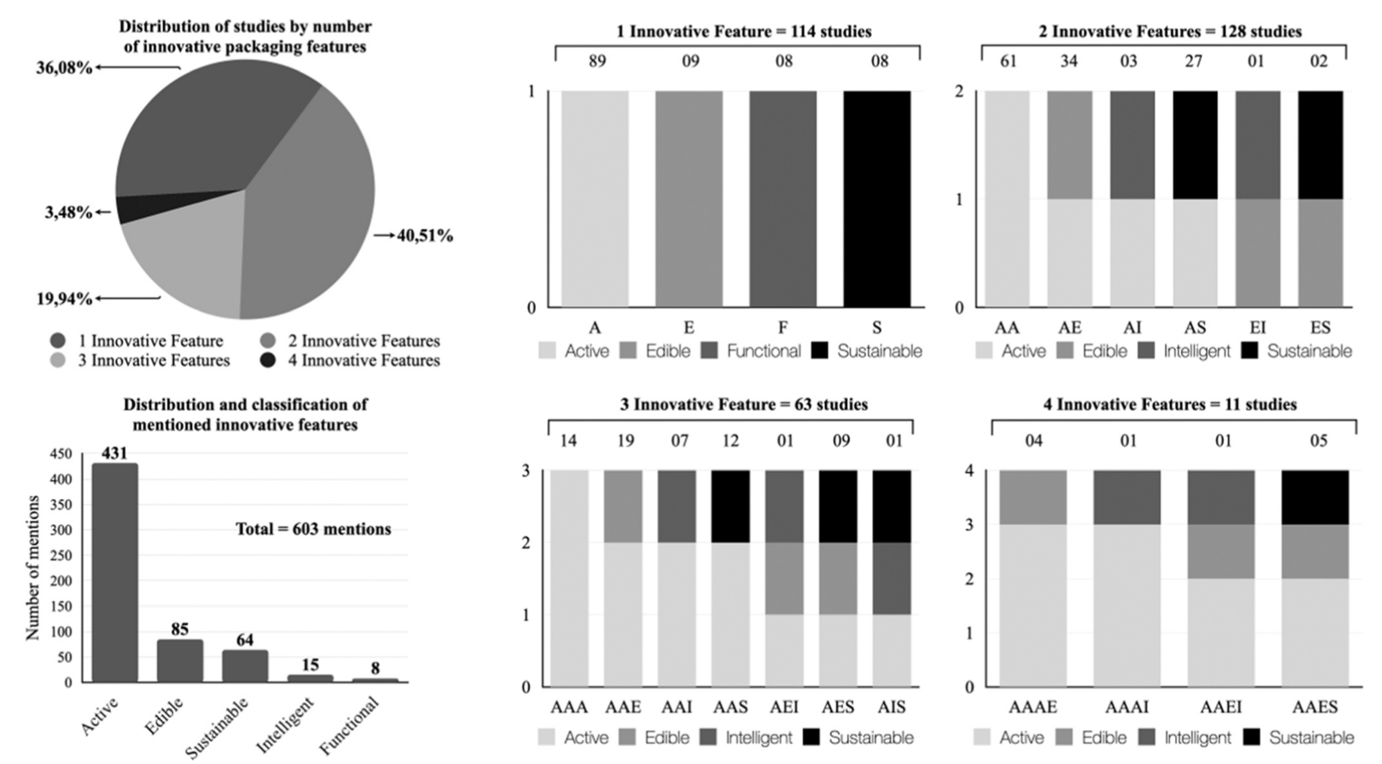


Fig. 8. Profile of the innovative packaging features (active, edible, functional, intelligent and sustainable) presented in the studies, including combinations.

innovation across the different studies included reveals important trends regarding the research focus and the development of new technologies in this field. Fig. 8 provides a detailed overview of how active, edible, functional, intelligent, and sustainable packaging are being explored, both individually and in combination, reflecting diverse research efforts.

The distribution of studies by the number of innovative features indicates that most studies focus on investigating one or two features at a time (Fig. 8). With 40.51 % of the studies analyzing only one feature and 36.08 % focusing on two (Fig. 8), it becomes evident that the approach to packaging innovation often prioritizes simplicity and specificity. In other words, most studies concentrate on isolated innovations or limited combinations, while few dedicate efforts to creating solutions that integrate multiple innovations simultaneously. This trend likely reflects the technical challenges and complexity involved in developing multifunctional packaging solutions.

The analysis of mentions of innovative features highlights the predominance of active packaging, which was mentioned 431 times in the analyzed studies (Fig. 8). This significant number underscores its priority in research and development, reflecting the growing demand for solutions that actively ensure food safety and quality. Among the main active properties, antimicrobial functions, including antibacterial and antifungal activities, and antioxidant properties stand out (Belili et al., 2024; Pu et al., 2024; Wu et al., 2024). Additionally, features such as anti-browning, atmospheric modification, ethylene reduction, and self-healing were also mentioned in the studies (Preethi et al., 2021; Singkhonrat et al., 2023; Vargas-Torrico et al., 2022; Xie et al., 2022). These functionalities emphasize the versatility of active packaging in addressing various challenges related to food preservation.

On the other hand, sustainable and edible packaging also appears frequently, albeit on a smaller scale (Fig. 8). This trend suggests a growing concern about the environmental impact of packaging and a shift toward alternatives that minimize waste, while maintaining functionality (Costa et al., 2024; Gang et al., 2024; Phothisuwan et al., 2021; Yakoubi et al., 2023). The intelligent features (I) of packaging, with 15 mentions (Fig. 8), are generally associated with monitoring the condition of fruits. These innovations include technologies such as CO_2 monitoring and responsive packaging (Yang, Zhou, et al., 2023; Yuan et al., 2024; Zhao, Jia, et al., 2022), which can interact with the environment and provide feedback on product quality and safety. These solutions aim not only to protect food but also to enhance the consumer experience by ensuring that the product is in optimal condition for consumption. Regarding functional (F) characteristics, they had only 8 mentions and are related to convenience, handling, or overall packaging efficiency (Kang et al., 2021; Yang, Fei, et al., 2023). The limited mentions of functional and intelligent features highlight potential areas for further research and development.

In studies exploring only one feature, active packaging is predominantly focused on, being the main subject of 89 of the 114 studies analyzed (Fig. 8). These packages, which aim to extend shelf life and improve food safety, represent a strong trend towards solutions that actively interact with their contents or the external environment (Chau et al., 2024; Francis et al., 2022; Rusková et al., 2023; Zhang, Wang, et al., 2022). Their widespread application underscores the relevance of active technologies in addressing key issues in food preservation.

When it comes to combining two innovative features (n = 128), dual-active packaging stands out, with 61 mentions (Fig. 8). These solutions incorporate a combination of antibacterial, antifungal, antioxidant, and/or ethylene removal activities, demonstrating their versatility and effectiveness in maintaining food quality (de Matos Fonseca et al., 2021; Sun et al., 2023; Xiao et al., 2024; Xu et al., 2023). Additionally, the combination of active and edible packaging was explored in 34 studies (Fig. 8), suggesting a growing interest in solutions that combine edible functionality with active protection (Guo et al., 2024). Packaging that combines active and sustainable features was mentioned in 27 studies (Fig. 8), indicating efforts to merge food preservation capabilities with reduced environmental impact (Francis et al., 2022; Liao et al., 2023).

On the other hand, combinations of active and intelligent features, as well as combinations between other features (such as edible, functional, and sustainable), are less common. This suggests significant technical challenges in integrating these functionalities and/or a research focus that prioritizes specific technological solutions. The complexity of developing packaging that efficiently and economically combines multiple functions may explain this trend. However, these combinations represent an area with considerable potential for future advancements.

Combinations involving three innovative features appear relatively frequently, being recorded in 63 studies (Fig. 8). This demonstrates that, while challenging, there is a growing interest in exploring multifunctional packaging solutions. In these cases, active features continue to predominate, reinforcing the importance of these technologies in the development of innovative packaging. However, combinations involving four features remain less frequent, with 11 mentions (Fig. 8), reflecting the technical complexity associated with these innovations (Correa-Pacheco et al., 2019; Zhao, Jia, et al., 2022). This trend indicates that, while progress has been made in integrating multiple functionalities, there is still significant room for research. Future efforts could focus on overcoming these challenges to develop increasingly sophisticated and efficient packaging solutions.

3.4. Analytical approaches and packaging usage in fruit studies

Chemical, physicochemical, biological, mechanical, and sensory tests were identified across the 316 included studies, totaling 83 different types of analyses conducted on packaged fruits. Table 1 presents only the tests that were performed in more than 10 studies, highlighting the frequency of these analysis types in the scientific research. Among these, weight loss emerged as the most frequently performed test, emphasizing its critical role in assessing fruit quality.

Weight loss, observed in approximately 76.3 % of the studies, was the predominant test conducted (Table 1), underscoring its importance in monitoring fruit quality. Weight loss is directly related to carbon (CO_2) and water loss from the fruit, which can lead to wilting, reduced freshness, and deterioration in quality (Maurizzi et al., 2023; Wu et al., 2024). In that case, efficient packaging must effectively reduce fruit respiration rate and carbon (CO_2) loss, as well as inhibit fruit transpiration and water loss. Therefore, weight loss is a crucial indicator of the effectiveness of fruit packaging, providing valuable information on the maintenance of fruit quality, freshness, and shelf life (Bodana et al., 2024; Dharini et al., 2024; Nur Hanani et al., 2023). Moreover, weight loss is also associated with visual appearance, as fruits that lose weight often appear wilted and less attractive, which can negatively impact consumer acceptance.

The fruit appearance was the second most commonly used test, being performed in approximately 67.1 % of the studies (Table 1). This criterion, based on the evaluation of color, shine, and fruit integrity, is one of the main factors used by consumers to judge quality (Vargas-Torrico et al., 2022; Yang et al., 2022; Yuan et al., 2024). Maintaining an attractive appearance is a fundamental goal in the use of additives in packaging, directly reflecting the effectiveness of these technologies in satisfying the consumers. As appearance plays a central role in consumer acceptance, its evaluation complements other tests related to internal quality parameters.

Soluble solids, or Brix values, measured in approximately 43.7 % of the studies (Table 1), represent one such internal quality parameter. These values provide crucial information on the quality, maturity, and flavor of the fruits. The evaluation of soluble solids is essential to determine whether the packaging used is effective in maintaining or enhancing sugar content during storage (Choi et al., 2019; Hu, Gong, et al., 2023). Together with appearance, Brix values offer insights into both external and internal fruit quality, because it is considered a fruit ripening stage index.

Firmness and texture tests, conducted in about 43.4 % of the studies

Table 1
Prevalence of key analytical tests in studies on packaged fruits.

Analysis	Studies	Analysis	Studies	Analysis	Studies
Weight loss	241	pH	59	Browning Parameters	21
Food appearance	212	Phenolic content	43	Malonaldehyde (MDA) content	20
Soluble solids (SS)/ Brix values	138	Antioxidant analysis	38	Concentration of CO2 or O2	19
Firmness/ Texture	137	Toughness/ Hardness	36	Sensory quantitative descriptive analysis (QDA)	19
Color analysis/ Pigmentation	101	Decay Parameters	34	Rot Parameters	18
Acidity/ Titratable acidity	98	Enzyme activity	30	Sugar Parameters	16
Microbial assessment	75	Respiratory rate	28	Anthocyanin content	14
Vitamin C/ Ascorbic acid	61	Flavor, texture, taste, and overall acceptability	26	Ethylene gas production	11

(Table 1), are also essential to ensure the quality and freshness of the fruits, providing a satisfactory sensory experience (Choi et al., 2019; Nguyen et al., 2020; Phothisuwan et al., 2021). These attributes complement the evaluation of soluble solids, as texture and firmness directly influence consumer satisfaction and the perception of freshness. Therefore, both the assessment of soluble solids and firmness contribute to monitoring and ensuring the high fruit quality to consumers.

Color/pigmentation analysis, present in approximately 32.0 % of the studies (Table 1), is a visual indicator of fruit ripeness. The color of fruits is a crucial characteristic for consumers, significantly influencing first impressions and purchasing decisions (Vadiveloo et al., 2019). Fruits with vibrant and uniform colors are perceived as fresher and of higher quality, which enhances their market attractiveness and acceptance. Effective packaging technologies that maintain the natural color of fruits play a vital role in meeting consumer expectations, improving visual appeal, and boosting sales outcomes (Liao et al., 2023; Nian et al., 2022; Ranganath, 2022). Color analysis complements other sensory and chemical evaluations by linking appearance with consumer perceptions of quality.

Titratable acidity was analyzed in approximately 31.0 % of the studies, and pH in about 18.7 % of the studies (Table 1), both being fundamental parameters for determining the flavor and microbiological stability of fruits (Tyl, 2024). Titratable acidity plays a crucial role in fruit quality, directly influencing its flavor, texture, and preservation (Xu et al., 2012). Adequate acidity levels ensure a balance between sweetness and acidity, resulting in a more pleasant taste. Additionally, acidity contributes to the preservation of fruit shelf life by inhibiting spoilage and microbial activity. pH also influences flavor and microbiological stability, with lower pH resulting in a more acidic taste and greater pathogen inhibition, while higher pH can result in a sweeter taste and poorer preservation (Tyl, 2024). Therefore, both titratable acidity and pH are determinants in assessing fruit ripeness and overall quality.

Microbial evaluation, conducted in approximately 23.7 % of the studies (Table 1), is essential for ensuring food safety, controlling quality, and extending the shelf life of packaged fruits. This analysis focuses on identifying and controlling pathogenic and spoilage microorganisms, ensuring that packaging solutions meet regulatory standards while preventing waste and preserving product characteristics (Karanth et al., 2023). The inclusion of microbial assessments enhances the reliability of packaging technologies in maintaining food safety and quality.

The analysis of vitamin C (ascorbic acid), present in about 19.3 % of the studies (Table 1), determines the nutritional value of fruits and evaluates the impact of storage conditions on nutrient stability. Ascorbic acid is highly sensitive to temperature variations, with significant losses observed during thermal fluctuations. Assessing vitamin C levels is crucial not only for ensuring nutritional adequacy, but also for understanding the efficacy of packaging in preserving fruit nutrients throughout storage (Okafor et al., 2024). This parameter, alongside other chemical and microbial evaluations, underscores the multidimensional benefits of effective fruit packaging solutions.

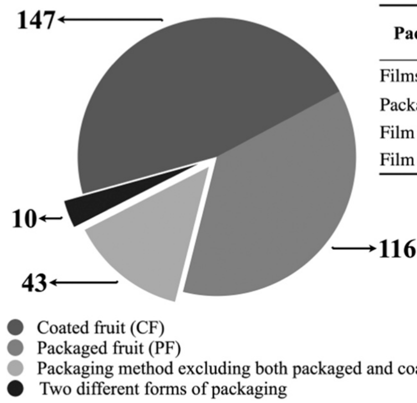
Other important tests were performed, though by a smaller number of studies. Among them, phenolic content (13.6 %), antioxidant analysis (12.0 %), strength/hardness (11.4 %), degradation parameters (10.8 %), enzymatic activity (9.5 %), respiration rate (8.9 %), quantitative descriptive sensory analysis (QDA) (6.6 %), decay parameters (5.7 %), sugar parameters (5.1 %), anthocyanin content (4.4 %), and ethylene gas production (3.5 %) were noteworthy (Table 1). Like the previously mentioned tests, these methods are essential for determining different aspects of quality, food safety, nutritional value, and sensory acceptability of packaged fruits, significantly contributing to improvements in packaging processes, storage, and shelf life extension, ensuring product integrity and freshness until it reaches the final consumer (Armghan Khalid et al., 2022).

Building on these insights, Fig. 9 illustrates the detailed analysis of the 316 included studies on fruit packaging methods. The analysis categorizes the studies into four main categories, supplemented by two additional tables that address articles employing more specific methods for testing materials as well as those utilizing two forms of packaging on one or more fruits.

Studies that opted for fruit coatings (CF) represent the majority, totaling 147 studies (Fig. 9). These studies investigate the effects and benefits of coatings applied directly to the fruits. This outcome reflects the growing relevance and interest in coating applications due to the various benefits this technique can offer. Fruit coatings are generally easy to apply, enhance the shine of the fruits, improve their aesthetic appearance, and prolong their freshness (Blancas-Benitez et al., 2022). The category of studies that developed packaging involving fruits (PF) encompasses 116 studies. These studies focus on the protection and preservation of fruits wrapped in films, ensuring their safety and integrity (Dharini et al., 2024; Hosseinifarahi et al., 2023). This focus underscores the critical importance of effective packaging in maintaining fruit quality from harvest to consumption.

Both coatings and film packaging have been extensively studied for their potential positive effects on food preservation and quality (Bianchi et al., 2021). The application of these materials acts as a barrier against moisture loss (Kang et al., 2023; Nayak et al., 2024), slows down the ripening process (Gang et al., 2024; Ma et al., 2023; Yan et al., 2023), protects against mechanical damage (Dai et al., 2022; Sun et al., 2023), and prevents microbial contamination (Barrino et al., 2023; Nur Hanani et al., 2023). Although both methods offer effective solutions for fruit preservation, the choice between them should consider the specific needs of the fruit and the context of use, such as the type of fruit and storage conditions (Liyanapathiranage et al., 2023).

Another 43 studies analyzed packaging methods that do not fit into the first two categories of coated or wrapped fruits (PMEPCF). These methods include innovative approaches, such as applying films to the top opening of conventional packaging, sealing it tightly ($n = 26$) (Sun et al., 2022; Zeinali et al., 2021). The films used in this context function as barriers to moisture and gases (O2 and CO2), preserving fruit quality



Packaging method excluding both packaged and coated fruit	Number of studies*
Films related to another package's covering	26
Packaging that received a coating	10
Film inside another package, with or without fruit contact	8
Film in contact with a part of the fruit	4

*The five studies where PMEPCF was one of the two different packaging forms were quantified.

Two different forms of packaging	Number of studies
CF / PF	5
CF / PMEPCF	4
PF / PMEPCF	1

Fig. 9. Distribution of packaging usage methods, highlighting studies using two different forms and categorizing less common methods.

and extending its shelf life (Dang et al., 2024; Li et al., 2022; Yuan et al., 2024). In other cases, edible films were placed inside the packaging, with or without direct contact with the fruit (n = 8) (Cheng et al., 2023; Zhang, Zhang, et al., 2022), being advantageous in controlling the internal atmosphere, reducing oxidation and microbial activity (Cheng et al., 2023; Shi et al., 2023). Some methods involve applying films to specific parts of the fruit (n = 4), providing additional protection in areas vulnerable to deterioration (Liang et al., 2022; Shen et al., 2022). Additionally, some studies explored the use of conventional packaging with additional coatings (n = 10), which may incorporate antimicrobial or antioxidant agents, conferring active characteristics to the packaging and extending the product's shelf life (Cai et al., 2022; Huang et al., 2023). These subcategories explore flexible and promising approaches to fruit preservation in different contexts and storage conditions.

The smallest category evaluated two distinct packaging methods, comprising 10 studies (Fig. 9). These studies investigated the efficacy of using two packaging methods. In three studies, the authors compared these methods on grapes, apples, and strawberries (Huang et al., 2022; Sganzerla et al., 2021; Xu et al., 2024). Comparing different packaging methods is crucial to assessing their efficacy and understanding the interactions between the packaging material and the fruit. Performance comparison allows for determining which method better preserves quality and freshness, identifying packaging practices that can extend the fruit's shelf life. Furthermore, these studies reveal how different materials interact with the fruit, which is essential for optimizing packaging and ensuring that the fruit maintains its organoleptic attributes during storage. Given that fruits possess varied intrinsic characteristics, such as moisture levels, respiration rates, and susceptibility to mechanical damage, these properties should be considered when evaluating packaging methods' effectiveness. This approach helps to determine the most effective method for each fruit type, adapting the packaging to their specific needs.

The analysis of the relationship between fruit type (climacteric or non-climacteric) and packaging type reveals varied uses for both PF and CF packaging. Both fruit types are used in the categories of packaged (PF) and coated (CF) fruits, suggesting that the need for ripening control and preservation is not exclusive to one type of packaging. This indicates that factors such as specific fruit properties and coating objectives play a crucial role in choosing the type of packaging.

Regarding the level of processing and packaging type, whole fruits are more commonly used with PF and CF packaging, which can be attributed to the need to protect the fruit's integrity and control ripening and water loss (Eldib et al., 2020; Muñoz-Almagro et al., 2021; Rashvand et al., 2023; Shen et al., 2024). Minimally processed fruits are also packaged, although less frequently. For these, protection against oxidation and dehydration (Jiang et al., 2022; Kahramanoglu, 2021; Magri et al., 2023) may be the primary concern, influencing the choice of packaging type.

3.5. Focus areas and impact on shelf life in fruit packaging studies

The reviewed studies have been categorized based on their primary areas of focus: Environmental Sustainability (ES), Food and Nutritional Security (FNS), Food Preservation (FP), Food Quality (FQ), and Material Development (MD) (Table 2). This categorization not only highlights the volume of research dedicated to each area, but also reveals the intersections between these themes, providing a more comprehensive view of trends within the packaging industry.

It is noted that the majority of the studies, a total of 146, focus exclusively on Food Preservation (FP) (Table 2). The significant interest in this focus indicates that preservation remains a central priority in research, suggesting a relevant concern with extending the shelf life of food, which is crucial for combating waste and ensuring food security in a global context of increasing demand for resources (Chen, Chang, et al., 2023; Zhao, Tian, et al., 2022).

Beyond the isolated focus on preservation, some combinations of study areas also stand out. For example, 37 studies combine Environmental Sustainability with Food Preservation (ES/FP), while another 36 explore the link between Food Preservation and Material Development (FP/MD) (Table 2). These combinations reveal a growing interest in connecting food preservation with aspects of sustainability and material innovation (Athir et al., 2020; Guerra et al., 2023; Mouzahim et al., 2023; Zhou, Cheng, et al., 2021). This reflects an important trend in research, where sustainability is no longer seen as an add-on, but rather as an integral component of preservation strategies, and material innovation is viewed as key to addressing contemporary challenges in the food packaging industry.

There are also studies that address multiple areas simultaneously, such as the 18 studies that combine Environmental Sustainability, Food and Nutritional Security, and Food Preservation (ES/FNS/FP) (Table 2). These data suggest that research is adopting a more holistic approach, recognizing that complex challenges in the food industry require solutions that consider multiple dimensions, such as the need to preserve food without compromising sustainability and ensuring food security in

Table 2
Distribution of studies by focus areas and their combinations.

Focus of the Study	Study Number	Focus of the Study	Study Number
FP	146	ES/ FNS/ FP	18
FQ	3	ES/ FP/ MD	6
ES/ FP	37	ES/ FP/ FQ	5
FP/ MD	36	FNS/ FP/ MD	5
FNS/ FP	25	FNS/ FP/ FQ	4
FP/ FQ	25	FP/ FQ/ MD	2
ES/ FQ	1	ES/ FNS/ FP/ FQ	1
ES/ MD	1	FNS/ FP/ FQ/ MD	1

Environmental sustainability (ES)/ Food and nutritional security (FNS)/ Food preservation (FP)/ Food quality (FQ)/ Material development (MD) a global scenario (Gang et al., 2024; Min et al., 2021; Qin et al., 2023). Based on this understanding, this trend is positive, as it reflects an evolution in scientific thinking, where different areas of knowledge are integrated to develop more comprehensive and effective solutions.

On the other hand, some areas, such as Food Quality (FQ) and Material Development (MD), appear less frequently when analyzed in isolation (Table 2). This may indicate that these areas, while important, still offer opportunities for future research. The low incidence of studies focused exclusively on food quality, for example, may suggest the need for greater focus in this area, particularly on how it can be integrated with other dimensions, such as preservation and sustainability. However, it is essential to emphasize the importance of not only considering the number of studies in each category, but also how they interrelate to form a broader and more integrated picture of research on fruit packaging. This more comprehensive analysis allows us to better understand emerging trends and identify areas that may benefit from increased attention in the future, contributing to the development of more sustainable and innovative solutions in the global food supply chain.

While these observations highlight areas that may benefit from greater research focus, particularly in integrating food quality and material development with other critical dimensions, understanding the practical implications of these studies is equally important. In this context, Fig. 10 presents an analysis of the reported shelf life across the 316 included studies that investigated packaged fruits. Two comparative approaches were identified in addition to evaluating fruits with the tested packaging: unpackaged fruits and fruits packaged with other conventional or alternative packaging. The intersections between these groups detail how the comparisons were made and how many articles clearly reported the number of shelf life days for each combination.

Of the 316 studies analyzed, 168 compared fruits packaged with the tested packaging against unpackaged fruits; of these, 116 articles explicitly reported the shelf life (Fig. 10). This direct comparison allows for evaluating the packaging's effectiveness in prolonging the freshness and quality of the fruits, as well as identifying the packaging's impact on reducing losses and waste. It was observed that the shelf life of packaged fruits was significantly longer than that of unpackaged fruits, due to physical protection against damage and contamination, and the control of critical environmental factors. Packaging contributes to moisture retention (Hadimani et al., 2023), limits oxygen exposure (Yuan et al., 2023), provides microbiological protection (Parven et al., 2020), and regulates gases such as ethylene (Xuan et al., 2019; Yuan et al., 2023), slowing down ripening and deterioration. Additionally, packaging can protect against light and temperature variations, preserving quality and extending the fruits' shelf life (Fu et al., 2024).

Another 84 articles focused exclusively on evaluating fruits with the packaging under study, without comparisons to other packaging or the absence thereof (Fig. 10). Of these, 78 studies clearly reported the shelf life, demonstrating a particular interest in evaluating specific packaging characteristics, such as ethylene adsorption, water solubility, mechanical, thermal, antioxidant, antimicrobial, and gas barrier properties (Jiang et al., 2020; Nian et al., 2023; Yuan et al., 2021; Zhou, Cheng, et al., 2021).

Additionally, 21 studies compared the performance of the packaging under study with conventional or alternative packaging; 18 of these clearly reported the shelf life, with a significant extension observed in fruits packaged with the new solution (Fig. 10). This result suggests advantages of the new packaging over existing ones. These comparisons are crucial for determining whether the new packaging offers real benefits, such as better quality preservation, greater efficiency (Nian et al., 2022), sustainability (Wei et al., 2021), or active functionalities (de Matos Fonseca et al., 2021). Thus, in addition to contributing to the selection of more functional preservation methods, these analyses can guide the development of packaging using sustainable materials, reducing environmental impact, and adding value to the food industry.

In a total of 43 studies, a comprehensive analysis compared fruits under three conditions: unpackaged, with conventional or alternative packaging, and with the new packaging under study. Of these studies, 20 clearly reported the effective shelf life of the fruits (Fig. 10). This comparison provides a complete view of the relative effectiveness of each packaging method, allowing the identification of the solution that offers the best performance in terms of quality preservation and extension of the fruits' shelf life. Moreover, this analysis helps to highlight performance patterns and identify the most effective packaging characteristics.

In the studies analyzed, unpackaged fruits showed the poorest performance in terms of shelf life and quality preservation, highlighting the importance of packaging in the protection and conservation of fresh produce (Hu, Liu, et al., 2023; Nayak et al., 2024; Yang, Li, et al., 2023). Fruits packaged in conventional or alternative solutions demonstrated superior performance, offering a level of protection that helped to prolong the freshness and integrity of the fruits (Li, Yang, et al., 2023; Zhang, Hu, et al., 2024; Zhang, Wang, et al., 2024). However, the new packaging under study stood out, showing the best overall performance, surpassing both unpackaged fruits and those conventionally packaged. This superiority suggests that the new packaging solution may bring significant improvements in terms of efficiency and effectiveness in fruit

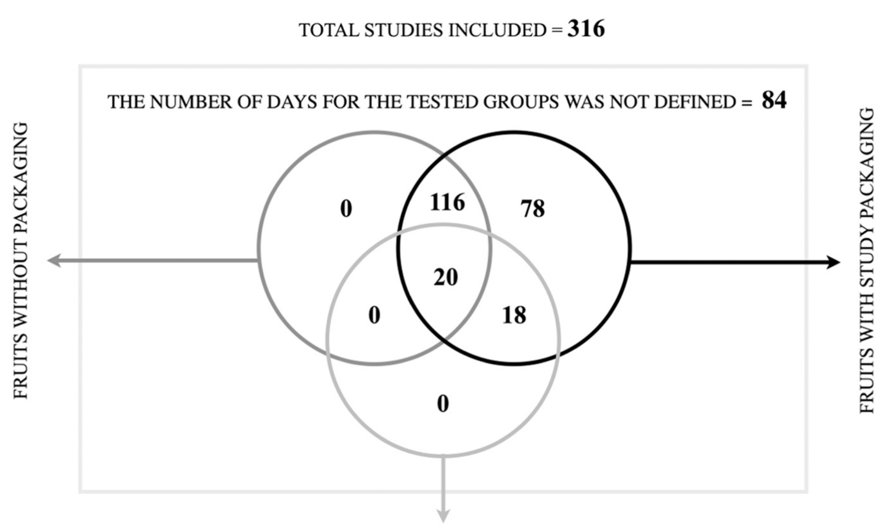


Fig. 10. Comparative analysis of shelf life in packaged fruits reported in studies.

preservation.

In terms of efficiency, the packaging under study may employ materials or technologies that maximize fruit protection with less reliance on scarce resources, potentially reducing costs and increasing sustainability (Liang et al., 2022; Zhang, Zhang, et al., 2023). In terms of effectiveness, the packaging may slow down ripening, minimize deterioration, and maintain the nutritional and sensory quality of the fruits for longer periods (Hu, Gong, et al., 2023; Nayak et al., 2024; Xu et al., 2023). These characteristics confirm the potential of the new packaging solution as a more advanced alternative, offering benefits that surpass those of conventional packaging.

However, many articles (n = 84) did not provide complete information on the packaging's performance, resulting in gaps that may hinder a comprehensive analysis of the results (Fig. 10). These studies often conduct multiple tests and report the number of days per test but fail to consolidate these data into a clear and overall outcome. This means that a packaging may perform well in one specific type of test, but it may not show the same efficacy in another. This inconsistency in reported data makes it difficult to evaluate the real effectiveness of packaging over time and to identify performance patterns. Consequently, the interpretation of the benefits of certain packaging solutions may be compromised, highlighting the need for more standardized methodologies and clearer reporting so that studies can provide more useful and applicable conclusions. Despite these gaps, the available data allow the identification of trends and the comparison of the effectiveness of different packaging, guiding more effective packaging practices and directing future more comprehensive research. Therefore, we recommend that future studies rigorously detail, clearly and objectively, the shelf life for all tested conditions, allowing for a more robust and accurate analysis.

4. Conclusions

The study of fruit packaging plays a vital role in meeting the growing demand for fresh and nutritious food, while simultaneously reducing waste and promoting sustainable practices. Innovations in this field benefit the entire fruit industry, consumers, and the environment by ensuring fruit quality and safety throughout the supply chain. The selection of additives and materials for films and coatings must be carefully tailored to the specific postharvest characteristics of each fruit, as well as the unique storage and transportation conditions. Given the significant variability in fruit physiology, customized packaging solutions for individual genotypes are essential to ensure optimal preservation and extended shelf life, avoiding generic approaches.

This review provides a comprehensive overview of additive use, offering valuable insights for advancing packaging technologies. By highlighting the role of these additives in extending the postharvest life of fruits, the study supports innovations that combine high-performance features with food safety. Key additives, such as glycerol, essential oils, natural extracts, Tween, nanocellulose, silver nanoparticles, zinc oxide, and calcium chloride, are analyzed in terms of their distinct roles and contributions. Evaluating these additives not only for their effectiveness, but also for their safety is critical to comply with regulatory standards and minimize potential risks to human health.

The findings of this study hold significant practical value for the fruit packaging industry. Strategically applying these insights can enhance packaging efficiency, reduce losses, and ensure consumers receive high-quality fruit. However, limitations remain, such as inconsistencies in the quality of reviewed studies and the lack of precision in quantifying postharvest preservation efficiency. Addressing these gaps requires further research to validate additive performance under practical conditions and explore economic assessments to evaluate the cost-benefit ratio of packaging solutions.

5. Future perspectives

Future research must prioritize the development of packaging systems that integrate multifunctional features, such as active, intelligent, and sustainable properties, while maintaining affordability. The challenges of designing packaging solutions tailored to specific fruit needs, storage environments, and market demands should be at the forefront of innovation. Addressing these gaps will enable the fruit packaging industry to adopt more effective and scalable solutions for global markets.

Another critical priority is the evaluation of safety throughout the entire lifecycle of packaging technologies, from material development to consumer. Ensuring these technologies meet safety standards is essential for building trust and encouraging widespread adoption. Further research should focus on testing these technologies under real-world conditions to validate their effectiveness, safety, and environmental impact.

Economic feasibility also requires attention, as cost-effective solutions are essential for both fresh and processed fruit sectors. Packaging systems that balance high performance, sustainability, and affordability will drive greater adoption and innovation in the industry. By addressing these challenges, fruit packaging technologies can continue to evolve, fostering innovations that uphold food quality, safety, and sustainability in an increasingly competitive global market.

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CRediT authorship contribution statement

Angelucia Gonçalves Parente: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Caroliny de Souza:** Investigation, Data curation. **Fernanda Silva Ferreira:** Investigation, Data curation. **Henrique Sátiro Gama e Silva:** Investigation, Data curation. **Sérgio Tonetto de Freitas:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Gabriela Lemos de Azevedo Maia:** Investigation, Data curation. **David Fernando de Morais Neri:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foohum.2025.100534.

Data availability

The datasets produced throughout the present investigation are accessible upon reasonable request from the corresponding author.

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