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Improving postharvest quality of strawberries with starch-based edible coatings: A literature review

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Abstract

Strawberry (*Fragaria × ananassa*) is a high-value fruit that is highly susceptible to postharvest deterioration due to its high moisture content, rapid respiration rate, soft texture, and vulnerability to microbial spoilage. To address this issue, starch-based edible coatings have emerged as promising biodegradable preservation systems due to their film-forming ability, safety, and compatibility with functional additives. This review aimed to analyze the development of starch-based edible coatings, evaluate the roles of active compounds and reinforcing materials, and identify future research directions. A literature review was conducted by analyzing twenty scientific articles on starch-based coatings for strawberry preservation. The results showed that various starch sources, including cassava, corn, potato, and fruit seed starches, have been effectively used as coating matrices. The addition of active compounds such as propolis, *Aloe vera*, plant extracts, and essential oils enhanced antioxidant and antimicrobial properties, while reinforcing materials like cellulose nanocrystals and metal oxide nanoparticles improved mechanical strength and barrier properties. Overall, starch-based edible coatings demonstrate strong potential as sustainable preservation technologies. Future research should focus on integrating bioactive compounds and nanomaterials to develop more effective and environmentally friendly coating systems.

Keywords: Edible Coating; Starch; Strawberry; Postharvest Preservation; Active Compounds; Nanocomposite; Literature Review.

1. Introduction

Strawberry (*Fragaria × ananassa*) is one of the most economically important horticultural commodities and is widely appreciated by consumers because of its distinctive flavor, attractive appearance, and high nutritional value. Strawberries are recognized as a rich source of vitamin C, phenolic compounds, flavonoids, anthocyanins, and various natural antioxidants that contribute significantly to human health. Despite these nutritional advantages, strawberries are highly perishable fruits due to their elevated moisture content, soft tissue structure, rapid respiration rate, and susceptibility to microbial spoilage. These characteristics result in a relatively short postharvest shelf life, creating substantial challenges in storage, transportation, distribution, and marketing. Previous studies have reported that postharvest deterioration of strawberries is characterized by weight loss, firmness reduction, color changes, depletion of vitamin C and phenolic compounds, and increased microbial activity during storage. Such quality degradation not only causes considerable economic losses but also reduces the nutritional and functional value of the fruit delivered to consumers. Therefore, the development of effective preservation technologies capable of maintaining strawberry

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quality without compromising food safety and sensory attributes has become increasingly important. In this context, polysaccharide-based edible coatings have emerged as one of the most extensively investigated preservation approaches because of their ability to delay deterioration processes during storage (Rahimi, 2024; Warkoyo et al., 2022).

Among the various materials used in edible coating formulations, starch has received considerable attention due to its biodegradability, biocompatibility, edibility, wide availability, low cost, and excellent film-forming properties. Various starch sources have been investigated as coating matrices for strawberry preservation, including cassava starch, sweet potato starch, arrowroot starch, potato starch, avocado seed starch, mango seed starch, litchi starch, corn starch, and buckwheat starch. Numerous studies have demonstrated that starch-based edible coatings effectively reduce weight loss, maintain fruit texture, preserve vitamin C and phenolic compounds, and extend the storage life of strawberries. Gupta et al. (2023) reported that high-amylose starch coatings effectively delayed quality deterioration and extended strawberry shelf life up to 18 days. Similarly, Rahimi (2024) demonstrated that cassava starch-based coatings were more effective than uncoated fruits in preserving firmness, total soluble solids, and vitamin C content. These findings suggest that starch functions not only as a physical protective barrier but also as a medium capable of creating a modified microenvironment that regulates respiration rate and moisture loss. Consequently, starch-based edible coatings have become one of the most promising technologies for modern strawberry preservation systems (Rahimi, 2024).

Recent developments in starch-based edible coating research indicate increasing complexity and innovation in formulation strategies. Early studies primarily employed starch as a single-component barrier material to reduce gas and water vapor transfer. However, contemporary research increasingly focuses on the incorporation of active compounds possessing antioxidant, antimicrobial, and antifungal properties. Finardi et al. (2022) developed a starch-based edible coating enriched with propolis and reported enhanced retention of vitamin C and total phenolic content during storage. Similarly, Carhuavilca-Paredes et al. (2025) formulated a composite coating consisting of mango seed starch, chitosan, and orange peel essential oil, resulting in significant reductions in weight loss and extended shelf life. Gomez-Contreras et al. (2021) further demonstrated that the incorporation of essential oils into sweet potato starch coatings improved both antimicrobial and antioxidant activities. These studies indicate a transition from passive coating systems toward active edible coatings capable of providing additional biological protection against postharvest deterioration. Therefore, a comprehensive understanding of these formulation strategies is essential for identifying current research trends and future directions in starch-based coating technology.

In addition to active compounds, increasing attention has been directed toward the incorporation of reinforcing materials into starch-based edible coating formulations. One of the major limitations of starch films is their hydrophilic nature, which results in relatively poor resistance to water vapor and environmental humidity. To overcome these limitations, numerous studies have developed nanocomposite coating systems through the incorporation of nanoparticles and nanomaterials as reinforcing agents. Filho et al. (2022) demonstrated that cellulose nanocrystals incorporated into arrowroot starch coatings improved the preservation of color, texture, vitamin C, and phenolic compounds in strawberries. Likewise, Alzain et al. (2022) reported that TiO_2 nanoparticles enhanced the mechanical strength and thermal stability of starch-based films. Chitena et al. (2023) also found that ZnO nanoparticles improved antimicrobial activity and increased preservation efficiency. These findings indicate that nanotechnology has become one of the principal research directions in the development of starch-based edible coatings. Nevertheless, the application of inorganic nanoparticles continues to raise concerns regarding food safety and environmental sustainability, highlighting the need for further investigation into safer and more eco-friendly reinforcing materials.

Although research on starch-based edible coatings for strawberry preservation has increased substantially in recent years, available findings remain scattered across diverse studies employing different starch sources, active compounds, reinforcing materials, methodologies, and evaluation parameters. Some studies focus primarily on the utilization of various starch materials, whereas others emphasize the incorporation of natural bioactive substances or nanomaterials. Furthermore, while certain investigations concentrate on evaluating strawberry quality attributes during storage, others focus on the physical, mechanical, and barrier properties of the coating films themselves. Consequently, existing knowledge remains fragmented and does not yet provide an integrated understanding of the overall development of starch-based edible coating technology for strawberries. Moreover, inconsistencies in reported outcomes regarding the effectiveness of different coating formulations highlight the need for a systematic synthesis of the available literature. A comprehensive literature review is therefore necessary to identify effective formulation strategies, evaluate the roles of active compounds and reinforcing materials, and determine existing research gaps that require further investigation. Such an approach is particularly important for advancing scientific understanding and supporting future innovation in this field (Pillai et al., 2024).

Based on these considerations, this study was conducted to critically examine the development of starch-based edible coating formulations, evaluate the contributions of active compounds and reinforcing materials to coating functionality, and identify current research gaps and future innovation opportunities. This review occupies an important position within the existing literature because recent studies have highlighted the growing significance of integrating polysaccharides, natural bioactive compounds, and bio-based nanomaterials in fruit preservation systems. However, comprehensive reviews synthesizing these developments specifically within the context of strawberry preservation remain limited. By systematically analyzing published studies, this review seeks to provide a more comprehensive understanding of the evolution of starch-based edible coating technology. Furthermore, the findings are expected to provide a scientific foundation for the development of more effective, safe, and sustainable coating formulations in future applications. Therefore, this literature review serves not only as a synthesis of previous research findings but also as a conceptual framework for identifying emerging research opportunities in starch-based strawberry preservation.

Accordingly, the objectives of this review are to analyze the development of starch-based edible coating formulation strategies for maintaining strawberry quality and extending shelf life, evaluate the role of active compounds and reinforcing materials in enhancing coating functionality, and identify research gaps, future development directions, and innovation opportunities reported in the literature. To achieve these objectives, the review addresses three principal research questions: (1) How have starch-based edible coating formulation approaches evolved in maintaining fruit quality and extending shelf life during storage according to previous studies? (2) What roles do active compounds and reinforcing materials play in improving the functional characteristics of starch-based edible coatings based on empirical evidence reported in the literature? and (3) What research gaps, development trends, and innovation opportunities remain open in the advancement of starch-based edible coating technologies? These questions provide the foundation for a comprehensive literature synthesis aimed at presenting a clear understanding of the scientific position, technological development, and future prospects of starch-based edible coatings for strawberry preservation.

2. Research Methodology

This study employed a literature review design using a descriptive–qualitative approach to synthesize the development of research concerning the application of starch-based edible coatings for improving postharvest quality and extending the shelf life of strawberries. The review focused on identifying, analyzing, and integrating findings from previous studies related to coating formulations, material characteristics, incorporation of active compounds, utilization of reinforcing materials, and their effects on strawberry quality during storage. The data sources consisted of twenty national and international scientific journal articles that specifically investigated the use of starch-based edible coatings for strawberry preservation. The reviewed studies covered a wide range of starch sources, including arrowroot starch, buckwheat starch, high-amylose starch, potato peel starch, mango seed starch, corn starch, yam starch, litchi seed starch, cassava starch, avocado seed starch, and yellow sweet potato starch. In addition, the analysis included studies incorporating various bioactive compounds such as propolis, *Aloe vera*, essential oils, sungkai leaf extract, lemongrass extract, curry leaf extract, cinnamon extract, and nanocomposite reinforcing materials including nanocellulose, TiO_2, and ZnO nanoparticles. To strengthen the theoretical foundation of the review, one comprehensive review article addressing polysaccharide-based edible coating technology was also included to provide broader conceptual insights into biopolymer-based fruit preservation systems.

The unit of analysis in this study was not human respondents or biological samples but rather scientific articles that fulfilled the predefined inclusion criteria. Articles were included if they specifically discussed starch-based edible coatings for strawberries, described coating formulation methods, evaluated strawberry quality during storage, and were published in accessible peer-reviewed scientific journals. Studies that did not focus specifically on strawberries or did not utilize starch as the primary coating component were excluded from the review process. A structured data extraction form was developed as the primary research instrument to systematically collect relevant information from each article. The extracted information included study title, authors, year of publication, research location, theoretical framework, coating formulation, active compounds, reinforcing materials, research methodology, observed parameters, principal findings, study limitations, and implications for the advancement of starch-based edible coating technology. All extracted data were subsequently organized into a literature synthesis matrix to facilitate comparison, categorization, and identification of recurring patterns across studies.

The data collection procedure was conducted through several systematic stages. The first stage involved identifying potentially relevant articles related to starch-based edible coatings for strawberry preservation. The second stage consisted of screening and selecting articles based on their relevance to the research objectives and compliance with the established inclusion criteria. The third stage involved an in-depth examination of each selected article to obtain detailed information regarding coating formulations, experimental procedures, evaluated quality parameters, and reported outcomes. The fourth stage consisted of extracting and organizing data using a standardized review matrix to ensure consistency across all analyzed studies. Finally, the collected information was synthesized through thematic grouping based on starch source, type of active compound, reinforcing material, coating characteristics, and preservation performance.

Data analysis was performed using content analysis and narrative synthesis approaches. Content analysis was employed to identify major themes, research trends, and recurring findings related to starch-based edible coating development, while narrative synthesis was used to integrate and interpret the findings from different studies into a coherent framework. Through these analytical approaches, the study examined the evolution of coating formulations, evaluated the contribution of active compounds and reinforcing materials to the functional performance of edible coatings, and identified existing research gaps, state-of-the-art developments, innovation opportunities, and future research directions. The results of the analysis were subsequently used to address the three research questions formulated in this review and to provide a comprehensive understanding of the current development and future prospects of starch-based edible coating technology for enhancing strawberry postharvest quality and shelf-life preservation.

3. Results and Discussion

3.1. Distribution and Characteristics of the Reviewed Studies

The literature search and screening process resulted in twenty scientific articles that met the predefined inclusion criteria and were subsequently included in this review (Table 1). The selected publications consisted predominantly of experimental studies and one comprehensive review article addressing polysaccharide-based edible coating technologies for fruit preservation. Most of the reviewed studies were published between 2021 and 2025, indicating that starch-based edible coating applications for strawberry preservation remain an active and rapidly evolving research area. The geographical distribution of the studies covered multiple countries, including Brazil, India, Indonesia, China, Colombia, Mexico, Peru, Afghanistan, Botswana, the United States, Saudi Arabia, and Egypt. This broad geographical representation demonstrates the growing global interest in developing sustainable postharvest technologies capable of reducing quality deterioration and extending strawberry shelf life.

Analysis of the reviewed studies revealed that starch served as the principal film-forming component in all formulations. Various starch sources were investigated, including cassava starch, sweet potato starch, potato peel starch, avocado seed starch, arrowroot starch, litchi seed starch, corn starch, mango seed starch, buckwheat starch, and high-amylose starch. The diversity of starch sources reflects increasing efforts to utilize both conventional and underutilized agricultural resources for edible coating production. Furthermore, several studies incorporated active compounds and reinforcing materials to enhance coating performance, resulting in a wide range of formulation strategies and preservation approaches.

Table 1 Distribution of Starch Sources Used in the Reviewed Studies

No	Starch Source	References
1	Cassava starch	Rahimi (2024); Bohidar et al. (2025)
2	Arrowroot starch	Oliveira Filho et al. (2022); Afriyanti et al. (2021)
3	Potato peel starch	Ardiani et al. (2025); Chitena et al. (2023)
4	Yellow sweet potato starch	Warkoyo et al. (2022)
5	Mango seed starch	Carhuavilca-Paredes et al. (2025)
6	Avocado seed starch	Khairunnisa & Nukatab (2025)
7	Buckwheat starch	Sarker et al. (2025)
8	High-amylose starch	Gupta et al. (2023)
9	Corn starch	Fu et al. (2024); Nur et al. (2021)
10	Litchi seed starch	Castillo-Olvera et al. (2026)
11	Yam Starch	Gomes-Contreras et al. (2021)

3.2. Evolution of Starch-Based Edible Coating Formulations

The literature synthesis revealed a clear progression in starch-based edible coating development from simple formulations toward multifunctional and technologically advanced systems (Table 2). Earlier formulations generally consisted of starch, water, and plasticizers such as glycerol, functioning primarily as physical barriers against moisture and gas transfer. However, recent studies have increasingly incorporated functional additives to enhance coating performance and provide additional preservation mechanisms.

The incorporation of bioactive compounds, natural extracts, essential oils, antioxidants, and nanomaterials has significantly expanded the functional capabilities of starch-based coatings. These modifications are intended to improve barrier properties, antimicrobial activity, antioxidant capacity, and structural stability. Moreover, several studies reported the use of multiple active components within a single coating system, reflecting a shift toward synergistic and multifunctional preservation strategies. Based on formulation characteristics, the reviewed studies can be broadly classified into three major categories: single-starch coatings, starch-based active coatings, and starch-based nanocomposite coatings.

Table 2 Classification of Starch-Based Edible Coating Formulations

Formulation Group	Additional Components
Single starch coating	Plasticizers
Starch + antioxidants	Propolis, ascorbic acid
Starch + plant extracts	Sungkai, cinnamon, curry leaf extracts
Starch + essential oils	Lemongrass, orange peel oil, *Litsea cubeba* oil
Starch + Aloe vera	Aloe vera gel
Starch + nanomaterials	CNC, TiO_2, ZnO

The progressive diversification of coating formulations indicates that current research is moving beyond passive preservation systems toward active and intelligent edible coating technologies capable of providing multiple protective functions simultaneously.

3.3. Application of Active Compounds in Edible Coating Formulations

One of the most prominent trends identified in the reviewed literature is the increasing incorporation of natural active compounds into starch-based edible coating systems (Tabel 3). These compounds were primarily added to improve antimicrobial, antioxidant, and antifungal properties while maintaining the biodegradable and edible characteristics of the coating matrix.

The most frequently reported active compounds included propolis, *Aloe vera*, cinnamon extract, sungkai leaf extract, curry leaf extract, lemongrass extract, orange peel essential oil, and *Litsea cubeba* essential oil. These compounds were typically incorporated directly into coating solutions before application onto strawberry surfaces. The reviewed studies consistently demonstrated that active compounds functioned as supplementary components embedded within the starch matrix rather than replacing the primary film-forming material.

Table 3 Active Compounds Identified in the Reviewed Studies

Active Compound	References
Propolis	Finardi et al. (2022)
Aloe vera	Rahimi (2024); Warkoyo et al. (2022)
Cinnamon extract	Khairunnisa & Nukatab (2025)
Sungkai leaf extract	Ardiani et al. (2025)
Curry leaf extract	Nur et al. (2021)
Lemongrass extract	Afriyanti et al. (2021)

Orange peel essential oil	Carhuavilca-Paredes et al. (2025)
Litsea cubeba essential oil	Fu et al. (2024)

The extensive utilization of natural active compounds demonstrates a growing emphasis on developing edible coatings that provide biological protection in addition to their conventional barrier function.

3.4. Application of Reinforcing Materials in Starch-Based Coatings

The reviewed studies also highlighted the increasing use of reinforcing materials to improve the structural and functional properties of starch-based coatings (Tabel 4). Reinforcing materials were primarily incorporated to enhance mechanical strength, reduce water vapor permeability, improve thermal stability, and increase overall coating effectiveness during storage.

The most commonly reported reinforcing materials included cellulose nanocrystals (CNC), titanium dioxide nanoparticles (TiO_2), and zinc oxide nanoparticles (ZnO). These materials were generally incorporated into coating formulations at relatively low concentrations compared with the starch matrix. Their inclusion resulted in the development of nanocomposite coating systems characterized by improved physical and functional properties.

Table 4 Reinforcing Materials Used in Starch-Based Edible Coatings

Reinforcing Material	**Matrix System**
Cellulose nanocrystals (CNC)	Arrowroot starch
TiO_2 nanoparticles	CMC/Starch
ZnO nanoparticles	Potato peel starch

The increasing incorporation of nanomaterials suggests that nanocomposite technology has emerged as a major research direction in the development of next-generation edible coatings for fruit preservation.

3.5. Strawberry Quality Parameters Evaluated in Previous Studies

The reviewed literature demonstrated substantial variation in the parameters used to evaluate strawberry quality during storage. Nevertheless, several indicators appeared consistently across studies and can be categorized into physical, chemical, microbiological, and material characterization parameters.

The most frequently evaluated fruit quality parameters included weight loss, firmness, total soluble solids, vitamin C content, total phenolic content, antioxidant activity, color attributes, microbial population, decay incidence, and storage life. These parameters were selected because they provide comprehensive information regarding fruit freshness, nutritional quality, consumer acceptability, and microbial stability.

In addition to fruit quality assessments, many studies also characterized coating properties using water vapor transmission rate (WVTR), tensile strength, elongation at break, Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), and X-ray diffraction (XRD). Such analyses were conducted to better understand the relationship between coating structure and preservation performance.

Overall, the reviewed studies adopted a multidimensional evaluation approach, combining fruit quality measurements with material characterization techniques to provide a more comprehensive understanding of coating functionality and effectiveness.

3.6. Summary of Major Findings

The overall synthesis indicates that starch-based edible coating technology has undergone substantial development in recent years. Various starch sources have been successfully utilized as coating matrices and subsequently combined with a wide range of active compounds and reinforcing materials. While starch remained the principal film-forming component in all reviewed studies, recent formulations increasingly incorporated natural bioactive compounds such as propolis, *Aloe vera*, plant extracts, and essential oils to enhance biological functionality.

Furthermore, emerging studies have demonstrated increasing adoption of nanotechnology through the incorporation of cellulose nanocrystals, TiO_2 nanoparticles, and ZnO nanoparticles into starch-based matrices. This trend reflects the transition from conventional edible coatings toward active and nanocomposite coating systems with improved preservation performance.

The most frequently evaluated quality indicators included weight loss, firmness, vitamin C content, total phenolic content, and microbial growth, whereas coating characterization commonly involved FTIR, SEM, XRD, WVTR, and mechanical property analyses. Collectively, the reviewed literature demonstrates considerable diversity in raw materials, formulation strategies, active compounds, reinforcing materials, characterization methods, and quality evaluation parameters. This diversity highlights both the rapid advancement of starch-based edible coating technology and the expanding opportunities for future innovation in strawberry postharvest preservation.

4. Discussion

4.1. Evolution of Starch-Based Edible Coating Formulation Approaches

The findings of this review demonstrate that starch-based edible coating technology for strawberry preservation has undergone substantial evolution, progressing from simple film-forming systems toward multifunctional active and nanocomposite formulations. Early studies primarily focused on the utilization of starch as a standalone matrix capable of forming a semipermeable layer on the fruit surface. In these systems, starch functioned mainly as a physical barrier that reduced moisture loss, limited gas exchange, and moderated respiration processes during storage. This fundamental approach was observed across various starch sources, including cassava starch, arrowroot starch, corn starch, yellow sweet potato starch, potato peel starch, avocado seed starch, mango seed starch, litchi seed starch, high-amylose starch, and buckwheat starch. Despite differences in botanical origin, all starches shared the common objective of creating a protective film capable of slowing postharvest deterioration. Studies by Rahimi (2024) and Warkoyo et al. (2022) further demonstrated that starch-based coatings could effectively reduce weight loss, maintain firmness, preserve soluble solids and vitamin C content, and extend strawberry shelf life. These findings confirm that the initial development of starch-based edible coatings was largely driven by the film-forming capability of starch and its role as a passive protective barrier.

Subsequent developments indicate a transition from passive coatings toward active preservation systems through the incorporation of natural bioactive compounds. The integration of propolis, plant extracts, *Aloe vera*, essential oils, and other natural additives reflects a growing effort to enhance coating functionality beyond simple barrier protection. Studies conducted by Finardi et al. (2022), Afriyanti et al. (2021), Khairunnisa and Nukatab (2025), Ardiani et al. (2025), and Bohidar et al. (2025) consistently demonstrated that bioactive enrichment improved coating performance by providing antioxidant, antimicrobial, and antifungal activities. In these formulations, starch no longer functioned solely as a structural matrix but also acted as a carrier capable of delivering biologically active compounds to the fruit surface. Consequently, edible coatings evolved into multifunctional systems that combined physical protection with biological preservation mechanisms.

Recent research has further expanded formulation complexity through the incorporation of hydrophobic compounds, essential oils, lipid components, and nanomaterials. Such developments address one of the major limitations of starch-based films, namely their hydrophilic nature and relatively poor moisture barrier properties. Studies involving coconut oil, orange peel essential oil, *Litsea cubeba* essential oil, and other lipid-derived compounds reported significant improvements in moisture resistance, fruit firmness retention, color stability, and microbial control. These findings suggest that current formulation strategies increasingly focus on balancing physical, chemical, and biological functionalities within a single coating system. Therefore, the evolution of starch-based edible coatings can be viewed as a continuous process of formulation optimization aimed at maximizing preservation efficiency while maintaining sustainability and food safety.

4.2. Functional Roles of Active Compounds and Reinforcing Materials

The reviewed literature clearly demonstrates that active compounds play a critical role in enhancing the preservation performance of starch-based edible coatings. Most bioactive additives function through antioxidant, antimicrobial, and antifungal mechanisms that complement the physical barrier properties provided by the starch matrix. Propolis, for example, has been reported to preserve vitamin C and phenolic compounds through its antioxidant activity, whereas lemongrass extract, cinnamon extract, sungkai leaf extract, and various essential oils contribute to microbial inhibition and delayed spoilage. Similarly, *Aloe vera* has been widely used because of its combined barrier-enhancing and antimicrobial properties. Collectively, these findings indicate that active compounds are no longer optional additives but have become essential functional components in modern edible coating formulations.

In contrast, reinforcing materials primarily contribute to structural enhancement and performance stabilization. Cellulose nanocrystals (CNC), TiO_2 nanoparticles, and ZnO nanoparticles were identified as the most frequently used reinforcing agents in the reviewed studies. These materials improve tensile strength, thermal stability, water vapor resistance, and overall coating integrity. The incorporation of nanomaterials has also been associated with improved fruit preservation outcomes, including reduced weight loss, enhanced microbial inhibition, and prolonged shelf life. Such findings highlight the complementary relationship between active compounds and reinforcing materials, where the former provides biological functionality and the latter enhances structural performance.

Importantly, the synthesis revealed a clear shift toward multicomponent edible coating systems. In these advanced formulations, starch functions as the primary matrix, active compounds provide biological protection, and reinforcing materials improve mechanical and barrier properties. Examples include formulations combining arrowroot starch, cellulose nanocrystals, carnauba wax nanoemulsions, and essential oils, as well as systems integrating mango seed starch, chitosan, and orange peel essential oil. These studies suggest that optimal preservation performance is generally achieved through synergistic interactions among multiple functional components rather than through the use of starch alone. Consequently, future formulation design should focus not only on selecting suitable starch sources but also on optimizing interactions among matrix materials, active compounds, and reinforcing agents.

4.3. Research Gaps, Future Directions, and Innovation Opportunities

The first major research gap identified in this review concerns the limited integration between material characterization and preservation performance evaluation. Although many studies assessed fruit quality parameters such as weight loss, firmness, vitamin C, total phenolic content, and microbial growth, relatively few simultaneously investigated coating properties through comprehensive analyses including water vapor transmission rate, tensile strength, FTIR, SEM, and XRD. As a result, the relationship between coating microstructure and preservation effectiveness remains insufficiently understood. Future studies should therefore adopt more integrated approaches that directly correlate material characteristics with postharvest performance outcomes.

A second research gap relates to the predominance of natural extracts and inorganic nanoparticles as functional additives, while bio-based nanomaterials remain comparatively underexplored. Although TiO_2 and ZnO nanoparticles have demonstrated significant effectiveness, concerns regarding long-term safety, environmental impact, and regulatory acceptance continue to exist. In contrast, cellulose nanocrystals and other bio-derived nanomaterials offer promising alternatives due to their biodegradability, renewability, and compatibility with biopolymer systems. The increasing interest in bio-nanomaterials suggests a valuable opportunity for future research to develop fully biodegradable and sustainable nanocomposite edible coatings.

A third limitation of the current literature is the substantial variability in storage conditions, evaluation periods, strawberry cultivars, and analytical parameters. Storage durations ranged from a few days to several weeks, while experimental temperatures varied from refrigeration to ambient conditions. Such variability complicates direct comparisons among studies and limits the establishment of universal conclusions regarding formulation effectiveness. Standardized evaluation protocols would therefore greatly enhance the comparability and reproducibility of future research.

From an innovation perspective, the reviewed literature suggests that future developments should focus on creating edible coatings that simultaneously exhibit three key characteristics: biological activity, structural robustness, and environmental sustainability. The integration of renewable starch sources, natural bioactive compounds, and bio-based reinforcing nanomaterials appears particularly promising for achieving these objectives. Such systems align closely with current trends in sustainable food packaging, circular bioeconomy principles, and green postharvest technologies.

4.4. Scientific Significance and Contribution of the Review

The primary contribution of this review lies in its comprehensive synthesis of the current development of starch-based edible coatings for strawberry preservation. By integrating findings from diverse studies, this review provides a clearer understanding of how formulation composition influences preservation performance and postharvest quality maintenance. The findings demonstrate that starch serves as a highly versatile matrix capable of functioning as a standalone coating material, a carrier of bioactive compounds, or a component of advanced nanocomposite systems.

Furthermore, this review establishes a conceptual framework linking coating formulation strategies with strawberry quality outcomes. The synthesis reveals that preservation effectiveness depends not only on the presence of a coating but also on the interactions among starch type, active compounds, reinforcing materials, barrier properties, and application methods. This integrated perspective contributes to a more systematic understanding of edible coating design and provides a scientific basis for future formulation development.

Another important contribution concerns sustainability. The reviewed studies highlight increasing utilization of agro-industrial by-products such as potato peel starch, avocado seed starch, mango seed starch, and litchi seed starch. These findings demonstrate that edible coating technology can simultaneously address postharvest preservation challenges and promote waste valorization within sustainable food systems. Consequently, starch-based edible coatings represent not only a preservation technology but also a promising approach for advancing circular economy principles in the food sector.

4.5. Implications and Limitations of the Study

Theoretical implications of this review suggest that starch-based edible coating technology should be viewed as an interdisciplinary field situated at the intersection of postharvest technology, food material science, biopolymer chemistry, nanotechnology, and sustainability science. The reviewed evidence confirms that coating performance is strongly influenced by formulation design, emphasizing the need to consider starch as a dynamic matrix system rather than merely a film-forming material.

From a practical perspective, the findings provide valuable guidance for researchers and postharvest technology developers in selecting suitable starch sources, active compounds, reinforcing materials, and evaluation parameters. The review also highlights the importance of combining fruit quality assessments with coating characterization analyses to improve understanding of preservation mechanisms and facilitate formulation optimization.

Nevertheless, several limitations should be acknowledged. This review relied exclusively on the selected articles included within the dataset and therefore reflects the scope and focus of the available literature. Additionally, the reviewed studies exhibited considerable heterogeneity in terms of formulation composition, storage conditions, analytical methods, and evaluation parameters. Consequently, the findings were synthesized through narrative analysis rather than quantitative meta-analysis. While this approach limits statistical comparison among formulations, it remains valuable for identifying research trends, conceptual relationships, emerging innovations, and future research priorities. Therefore, the conclusions presented in this review should be interpreted as a conceptual and scientific synthesis rather than definitive evidence supporting a single optimal edible coating formulation for strawberry preservation.

5. Conclusion and Recommendations

This literature review demonstrates that starch-based edible coatings represent a promising and sustainable approach for maintaining strawberry postharvest quality and extending storage life. The reviewed studies showed that a wide range of starch sources, including cassava starch, arrowroot starch, corn starch, sweet potato starch, potato peel starch, avocado seed starch, mango seed starch, litchi seed starch, buckwheat starch, and high-amylose starch, have been successfully utilized as coating matrices for strawberry preservation. Overall, starch-based coatings were consistently reported to reduce weight loss, maintain fruit firmness, preserve vitamin C and phenolic compounds, suppress microbial growth, and prolong strawberry shelf life during storage.

The findings further revealed a clear evolution in formulation strategies from simple starch-based coatings toward active and nanocomposite coating systems. Contemporary formulations increasingly incorporate bioactive compounds such as propolis, *Aloe vera*, lemongrass extract, cinnamon extract, sungkai leaf extract, curry leaf extract, essential oils, and procyanidins to enhance antioxidant, antimicrobial, and antifungal activities. In addition, the incorporation of reinforcing materials, including cellulose nanocrystals (CNC), TiO_2 nanoparticles, ZnO nanoparticles, and chitosan nanoparticles, reflects a growing emphasis on improving mechanical strength, barrier properties, and overall coating functionality. These developments indicate that starch-based edible coating technology is progressively moving toward multifunctional systems capable of simultaneously providing physical protection, biological activity, and enhanced structural performance.

From a scientific perspective, this review contributes to the fields of food technology, postharvest technology, food biomaterials, and sustainable packaging by providing a comprehensive synthesis of formulation developments, active compound applications, reinforcing material utilization, and emerging research trends in starch-based edible coating technology. The review highlights that starch should no longer be viewed merely as a film-forming material but rather as a versatile matrix capable of carrying functional bioactive compounds and reinforcing agents. Furthermore, the increasing utilization of starches derived from agro-industrial by-products demonstrates the potential of edible coating technology to support circular economy principles and sustainable food systems.

Despite the substantial progress achieved in this field, several challenges remain. The reviewed literature revealed considerable variation in storage conditions, experimental designs, evaluation parameters, and coating characterization methods, which limits direct comparison among studies. Moreover, comprehensive relationships between coating structure, physicochemical properties, and preservation performance remain insufficiently explored. Therefore, future studies should integrate strawberry quality assessments with detailed coating characterization analyses, including FTIR, SEM, XRD, water vapor transmission rate (WVTR), tensile strength, elongation at break, antioxidant activity, and antimicrobial activity. Such integrated approaches would provide a deeper understanding of the mechanisms underlying coating performance.

Future research should also prioritize the development of sustainable bio-nanocomposite systems through the utilization of renewable and biodegradable reinforcing materials, particularly nanoscale cellulose derived from agricultural and agro-industrial residues. The integration of starch matrices, natural bioactive compounds, and bio-based nanomaterials offers a promising pathway for developing edible coatings that are active, mechanically robust, environmentally friendly, and commercially applicable. Ultimately, such innovations may contribute significantly to reducing postharvest losses, enhancing food quality and safety, and advancing sustainable food preservation technologies.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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