



## **Active Biopolymer Packaging Infused with Essential Oils: A Review of Material Innovation and Its Integration into Science Education**

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### **Abstract**

The environmental impacts of plastic waste have increased interest in biodegradable food packaging as a sustainable alternative to conventional plastics. Among recent innovations, essential oil-infused biopolymer packaging has attracted attention because it combines active food preservation with environmental sustainability. This systematic literature review aims to synthesize recent developments in essential oil-infused biopolymer packaging and explore its potential as a contextual learning resource in science education. The review followed the PRISMA 2020 framework and employed thematic synthesis to analyze scientific, sustainability, and educational dimensions reported in the literature. The review identified a growing trend toward multifunctional packaging systems through biopolymer blending, essential oil incorporation, encapsulation technologies, and nanomaterial reinforcement. The literature indicates that these systems integrate interdisciplinary scientific concepts, including polymer interactions, antimicrobial activity, diffusion processes, biodegradation, and sustainable material design. The synthesis further revealed that essential oil-infused biopolymer packaging provides an authentic context for inquiry-based, project-based, and sustainability-oriented learning by connecting chemistry, biology, physics, and environmental science with real-world challenges such as plastic pollution and food preservation. The literature also highlights opportunities to develop scientific literacy, critical thinking, problem-solving skills, systems thinking, and sustainability competencies. This review contributes by linking sustainable packaging innovation with science education and highlighting its potential to support interdisciplinary STEM learning and sustainability-oriented education.

### **Keywords:**

Active food packaging; biopolymers; essential oils; sustainability education; STEM learning; systematic literature review

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## **INTRODUCTION**

Plastic-based food packaging plays a central role in modern food systems, yet it also represents one of the most persistent sources of environmental pollution. The global food production and consumption cycle generates large volumes of packaging waste, much of which consists of petroleum-derived, non-biodegradable polymers (Guillard et al., 2018; Varžinskas & Markevičiūtė, 2020). The growing use of synthetic plastics contributes to waste accumulation, ecosystem degradation, greenhouse gas emissions, and health concerns, particularly through improper disposal (Jaya et al., 2022; Narancic et al., 2020; Saravanan et al., 2025). As global plastic production continues to increase, especially for

single-use food packaging, the need for sustainable alternatives has become increasingly urgent (Deshmukh & Gaikwad, 2024; Shaikh et al., 2021; Marangoni Júnior et al., 2021; Sheriff et al., 2025).

Biopolymers derived from renewable resources, such as starch, cellulose, proteins, and lipids, have emerged as promising alternatives because of their biodegradability and lower environmental impact (Huang et al., 2019; Jaya et al., 2022). Recent research has focused on essential oil (EO)–infused biopolymer packaging, which enhances antimicrobial activity, barrier performance, and food shelf life while supporting sustainable packaging development (Asgher et al., 2020; Deshmukh & Gaikwad, 2024; Esteve-Redondo et al., 2024; Huang et al., 2019; Pandey et al., 2024; Shaikh et al., 2021; Song et al., 2022; Yu & Singh, 2023; Zinge & Kandasubramanian, 2020).

Despite these advances, existing reviews have largely focused on material performance and industrial applications, with limited attention to the educational value of EO-infused biopolymer packaging. Because these materials integrate concepts from chemistry, biology, physics, environmental science, and sustainability, they provide authentic contexts for interdisciplinary science and STEM learning. Their use is particularly relevant to sustainability-oriented education, which emphasizes real-world problem-solving, higher-order thinking, and environmental literacy (Dori et al., 2018; Holman & Švejdárová, 2023; Malagrida et al., 2022).

This review addresses this gap by synthesizing recent developments in EO-infused biopolymer packaging from both material science and science education perspectives. Specifically, it aims to (1) synthesize recent technological advances, (2) identify the scientific and sustainability concepts represented in these materials, (3) examine their potential as contextual learning resources for science and STEM education, and (4) propose recommendations for their educational integration. By bridging sustainable packaging research and science education, this review provides a conceptual foundation for sustainability-oriented interdisciplinary learning.

The review addresses four research questions: (RQ1) What recent developments in EO-infused biopolymer packaging have been reported? (RQ2) What scientific concepts and sustainability dimensions are represented in these innovations? (RQ3) How can these materials be used as contextual learning resources in science and STEM education? and (RQ4) What opportunities and challenges exist for integrating them into sustainability-oriented science learning?

## **METHODS**

This study employed a Systematic Literature Review (SLR) design guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) framework to ensure transparency, rigor, and reproducibility throughout the review process (Page et al., 2021). A systematic review approach was considered appropriate as the study aimed to synthesize existing evidence on essential oil–infused biopolymer packaging and examine its potential relevance to science education. Systematic reviews provide a structured method to identify, evaluate, and synthesize research findings while minimizing selection bias and enhancing the reliability of conclusions. A systematic literature search was conducted in Scopus, Web of Science, and Google Scholar, selected for their broad coverage of peer-reviewed research in materials science, environmental science, food technology, and science education. The search combined terms related to essential oils, biopolymers, biodegradable packaging, and sustainability education using Boolean operators. The review was limited to peer-reviewed journal articles published in English

between 2010 and 2024 to ensure coverage of recent developments in sustainable packaging and sustainability-oriented science education. Studies were included if they investigated biopolymer-based food packaging, incorporated essential oils or plant-derived bioactive compounds, reported relevant material properties (e.g., physicochemical, antimicrobial, barrier, biodegradation, or sustainability characteristics), or discussed educational or sustainability implications. Eligibility was restricted to peer-reviewed journal articles published in English. The exclusion criteria comprised conference abstracts, editorials, book chapters, theses, non-peer-reviewed publications, and studies focusing on petroleum-based packaging. Studies were also excluded when they lacked sufficient methodological or conceptual information or when full-text access was unavailable.

Study selection followed the PRISMA framework, including identification, screening, eligibility assessment, and inclusion. After removing duplicates, titles and abstracts were screened against the eligibility criteria, followed by full-text assessment of potentially relevant articles. Studies meeting all predefined criteria were included in the final synthesis. The selection process is illustrated in the PRISMA flow diagram (Figure 1).

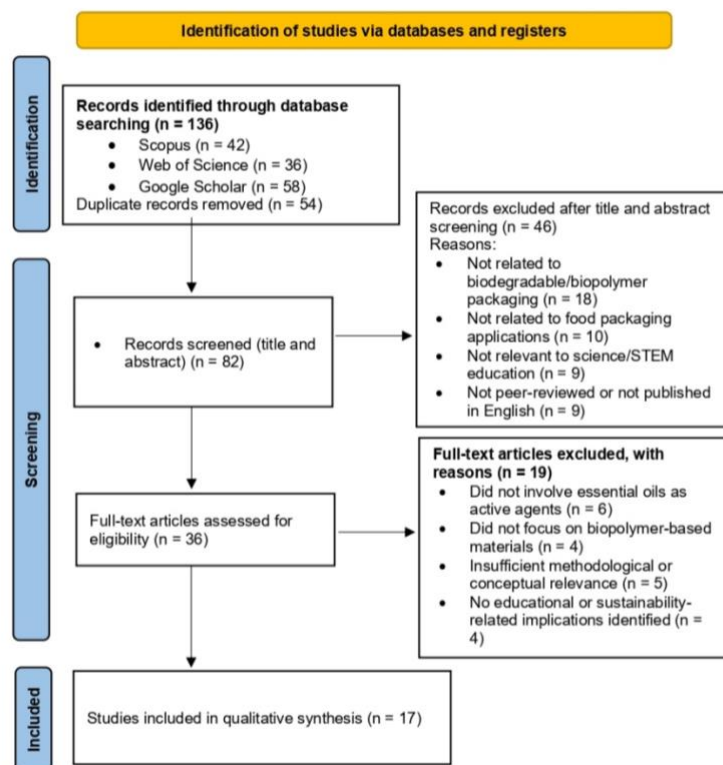


Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion process of studies on essential oil-infused biopolymer packaging and its educational potential.

The database search yielded 136 records, including 42 from Scopus, 36 from Web of Science, and 58 from Google Scholar. After removing 54 duplicate records, 82 articles remained for title and abstract screening. A total of 46 records were excluded during screening because they did not meet the predefined scope of the review. Subsequently, 36 full-text articles were assessed for eligibility. Nineteen studies were excluded for

methodological or conceptual reasons, resulting in 17 studies being included in the final qualitative synthesis.

### **Data Extraction**

A structured data extraction form was developed to ensure consistency during the review process. Information extracted from each study included publication information (author(s), year, country), type of biopolymer material, essential oil or bioactive compound used, functional properties reported, packaging applications, sustainability-related aspects, educational relevance or potential learning applications. The extracted data were organized into a review matrix to facilitate comparison across studies.

### **Data Analysis**

Data were analyzed using a thematic synthesis approach to identify recurring concepts across the included studies. The analysis involved three stages: (1) descriptive coding of material characteristics, packaging functions, and sustainability features; (2) analytical coding to identify broader conceptual themes; and (3) synthesis into two overarching domains: (a) scientific and technological aspects (e.g., antimicrobial activity, barrier properties, biodegradability, and sustainable material development) and (b) educational aspects (e.g., contextual learning, inquiry- and project-based learning, STEM integration, and sustainability education). The review sought to develop conceptual insights into the potential interconnections between sustainable packaging innovation and science education, rather than to produce statistically generalizable findings.

### **Trustworthiness and Quality Assurance**

Review quality was enhanced by following the PRISMA 2020 guidelines, applying predefined eligibility criteria, using a standardized data extraction matrix, and conducting iterative comparisons across studies to strengthen consistency and analytical validity.

### **Limitations of the Review**

This review was restricted to English-language, peer-reviewed journal articles and excluded grey literature, which may have constrained the breadth and scope of the evidence considered, particularly in relation to sustainable packaging research. In addition, because educational applications of essential oil-infused biopolymer packaging remain limited, some educational implications were derived conceptually rather than from classroom-based studies. Nevertheless, the review offers a comprehensive synthesis of the existing evidence while advancing a conceptual framework for integrating sustainable packaging innovation into science and STEM education.

## **RESULTS & DISCUSSION**

### **Results**

The findings are organized according to the four research questions (RQ1–RQ4), with detailed study characteristics presented in **Supplementary Tables S1 and S2**. Across the 17 included studies, four major trends emerged: (1) a shift from conventional biodegradable films to multifunctional active packaging systems; (2) increasing use of essential oils as controlled-release bioactive agents; (3) greater emphasis on sustainability through biodegradability, circular economy, and plastic waste reduction; and (4) limited integration of these innovations into science and STEM education, highlighting an important research gap.

**RQ1: The recent developments and characteristics of essential oil–infused biopolymer packaging reported in the literature.**

The reviewed studies demonstrate significant advances in biopolymer-based active packaging, particularly through polymer blending, composite formulation, and the incorporation of essential oils. Frequently used biopolymers include starch, cellulose, chitosan, alginate, PLA, and PHA, each contributing distinct mechanical, barrier, antimicrobial, and biodegradation properties (Asgher et al., 2020; Guillard et al., 2018; Narancic et al., 2020). Starch-based films are commonly studied due to their abundance and low cost, but they show limitations in mechanical strength and moisture resistance (Samrot et al., 2022). These findings are consistent with prior studies (Atarés & Chiralt, 2016; Rosenboom et al., 2022), but this review further highlights their increasing use in multifunctional composite systems designed for active packaging applications.

A key technological trend is the transition from single-component films to multifunctional composite systems incorporating plasticizers, nanofillers, and encapsulated essential oils. These innovations improve mechanical properties, enhance barrier performance, enable controlled release of bioactive compounds, and extend food shelf life. Table 1 summarizes the major biopolymers, their characteristics, recent technological developments, and applications in essential oil–infused active packaging.

Table 1. Characteristics of Biopolymers Used in EO-Based Packaging

| Biopolymer   | Source                          | Main Function                                                   | Trend                               | Reference(s)                                                          |
|--------------|---------------------------------|-----------------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------------|
| Chitin       | Crustacean shells               | Used as precursor for chitosan-based active films               | Biodegradability                    | Roy et al. (2023); Jaya et al. (2022)                                 |
| Chitosan     | Deacetylated chitin             | To enhance antimicrobial performance                            | EO active film                      | Atarés & Chiralt (2016); Huang et al. (2019)                          |
| Cellulose    | Plant biomass                   | Nanocellulose-reinforced films with encapsulated essential oils | nanocomposite                       | Marinho (2025); Zinge & Kandasubramanian (2020)                       |
| Alginate     | Brown seaweed                   | Multilayer films incorporating EO nanoemulsions                 | Oxygen barrier and active packaging | Benavides et al. (2012); Atarés & Chiralt (2016)                      |
| Starch       | Crops and agricultural residues | To improve flexibility and shelf-life performance               | blended films                       | Shaikh et al. (2021)                                                  |
| Cyclodextrin | Starch-derived                  | Encapsulation and stabilization of volatile essential oils      | Controlled release carrier          | Velázquez-Contreras et al. (2022)                                     |
| PLA          | Fermented biomass               | EO-loaded PLA composites for improved antioxidant activity      | sustainable packaging               | Narancic et al. (2020); Rosenboom et al. (2022); Shaikh et al. (2021) |

Overall, the findings indicate that recent developments in EO-infused biopolymer packaging are characterized by the integration of essential oils, encapsulation technologies, nanofillers, and polymer blending strategies. These innovations have facilitated the transition from conventional biodegradable films toward multifunctional active packaging

systems with improved mechanical properties, controlled-release behavior, and enhanced food preservation performance.

***RQ2: Scientific Concepts and Sustainability Dimensions Represented in Essential Oil–Infused Biopolymer Packaging***

The reviewed studies indicate that essential oil–infused biopolymer packaging incorporates scientific concepts from multiple disciplines. Chemistry concepts include polymer interactions, antioxidant activity, and controlled-release mechanisms (Samir et al., 2022). Biological concepts are represented through antimicrobial activity and biodegradation processes (Asgher et al., 2020). Physics concepts involve diffusion, mass transfer, and barrier properties that regulate the movement of gases, moisture, and bioactive compounds within packaging systems (Benavides et al., 2012).

In addition to scientific concepts, the literature highlights several sustainability dimensions, including the use of renewable resources, biodegradability, waste reduction, circular economy practices, and sustainable food preservation (Jiao et al., 2024). These findings indicate that EO-infused biopolymer packaging combines scientific innovation with sustainability-oriented applications. Table 2 summarizes the main scientific concepts and sustainability dimensions identified in the reviewed studies.

Table 2. Scientific concepts and sustainability dimensions represented in essential oil–infused biopolymer packaging

| Domain         | Concept/Dimension           | Application and Educational Relevance                                    | Supporting References                                                         |
|----------------|-----------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Chemistry      | Polymer interactions        | Biopolymer–EO interactions for material design and intermolecular forces | Atarés & Chiralt (2016); Fasihi et al. (2019); Zinge & Kandasubramanian, 2020 |
| Chemistry      | Antioxidant activity        | Phenolic compounds for food preservation and redox chemistry             | Calo et al. (2015); Mishra et al. (2020); Pandey et al. (2024)                |
| Chemistry      | Controlled release          | Diffusion-controlled EO release and transport kinetics                   | Atarés & Chiralt (2016); Guillard et al. (2018)                               |
| Biology        | Antimicrobial activity      | Microbial inhibition and food safety                                     | Calo et al. (2015); Rathod et al. (2021)                                      |
| Biology        | Biodegradation              | Microbial decomposition and biological recycling                         | Guillard et al. (2018); Kwon et al. (2020)                                    |
| Physics        | Diffusion and mass transfer | Mass transfer, permeability, and structure–property relationships        | Guillard et al. (2018); Atarés & Chiralt (2016)                               |
| Physics        | Barrier properties          | Plant-based materials for sustainable resource use                       | Atarés & Chiralt (2016); Fasihi et al. (2019)                                 |
| Sustainability | Renewable resources         | Biodegradable alternatives to conventional plastics                      | Guillard et al. (2018)                                                        |
| Sustainability | Waste reduction             | Renewable and recyclable material systems                                | Kwon et al. (2020); Guillard et al. (2018)                                    |

| Domain         | Concept/Dimension             | Application and Educational Relevance                                    | Supporting References                                  |
|----------------|-------------------------------|--------------------------------------------------------------------------|--------------------------------------------------------|
| Sustainability | Circular economy              | Shelf-life extension with reduced environmental impact                   | Guillard et al. (2018); Zinge & Kandasubramanian, 2020 |
| Sustainability | Sustainable food preservation | Biopolymer–EO interactions for material design and intermolecular forces | Mishra et al. (2020); Pandey et al. (2024)             |

Overall, the findings demonstrate that EO-infused biopolymer packaging integrates interdisciplinary scientific concepts and sustainability dimensions, providing a foundation for its application in science and STEM education.

### ***RQ3. Utilization of Essential Oil–Infused Biopolymer Packaging as a Contextual Learning Resource***

The reviewed studies indicate that essential oil–infused biopolymer packaging provides an authentic context for learning interdisciplinary scientific concepts. The development and production of active biopolymer packaging involve concepts from chemistry (polymer interactions and antioxidant activity), biology (antimicrobial mechanisms and biodegradation), physics (diffusion and barrier properties), and environmental science (sustainable materials and waste reduction).

Several studies suggest that these packaging systems can be incorporated into project-based, inquiry-based, and problem-based learning activities. The design, production, and evaluation of biopolymer films can provide students with opportunities to engage in scientific inquiry, analyze data, address complex problems, and make sustainability-oriented decisions. **Table 3** summarizes the educational potential of EO-infused biopolymer packaging across different scientific domains and learning contexts.

Collectively, the findings suggest that EO-infused biopolymer packaging offers a meaningful context for connecting interdisciplinary scientific concepts with real-world sustainability challenges in science education. Its application in inquiry-based and project-based learning environments provides opportunities to develop scientific literacy, critical thinking, problem-solving skills, and sustainability awareness. Based on the thematic synthesis of the reviewed studies, an evidence-based framework was developed to illustrate the integration of EO-infused biopolymer packaging into science learning (Figure 2).

The framework was not developed as an independent conceptual model but was derived from recurring themes identified across the reviewed literature. Three major dimensions emerged from the synthesis: The scientific foundations of biopolymer packaging systems, the technological mechanisms of active packaging, and the pedagogical integration in science education. Material-related components were synthesized from studies on biopolymer properties, essential oil functionality, and sustainable packaging systems, whereas educational components were derived from studies emphasizing inquiry-based, project-based, problem-based, and sustainability-oriented learning approaches.

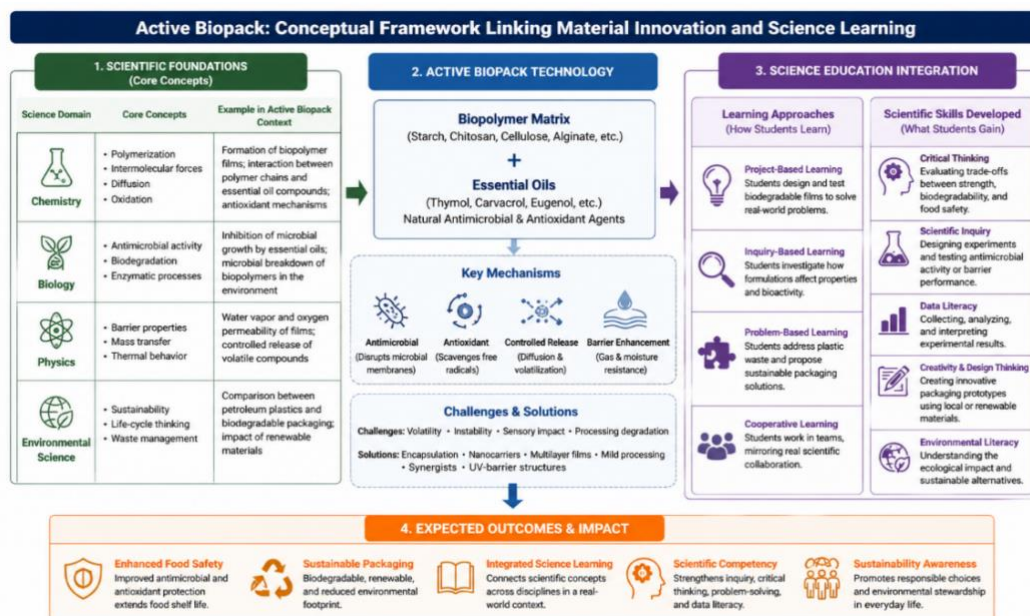


Figure 2. Evidence-based synthesis framework of essential oil–infused biopolymer packaging integration into science learning derived from systematic literature review findings.

#### ***RQ 4. Opportunities and Challenges Exist for Integrating These Innovations Into Interdisciplinary and Sustainability-Oriented Science Learning***

The reviewed studies identified both opportunities and challenges associated with integrating essential oil–infused biopolymer packaging into science and sustainability education. The identified opportunities are largely associated with the interdisciplinary nature of the topic, its relevance to contemporary environmental challenges, and its potential to facilitate student-centered learning approaches. The main challenges concern implementation constraints, limited empirical evidence, and the absence of established curricular frameworks.

Overall, the findings indicate that EO-infused biopolymer packaging provides a promising interdisciplinary context for sustainability-oriented science learning. However, further research is needed to develop instructional frameworks, classroom implementation models, and assessment strategies that support its effective integration into science and STEM education.

### ***Discussion***

#### **Advances in Essential Oil–Infused Biopolymer Packaging**

The findings indicate a clear shift from single-component biopolymer films toward multifunctional composite systems incorporating essential oils, plasticizers, nanofillers, and encapsulation technologies. This trend addresses the limitations of biodegradable packaging, including poor mechanical strength, moisture sensitivity, and limited stability, as reported in previous studies (Atarés & Chiralt, 2016; Guillard et al., 2018; Rosenboom et al., 2022). Unlike earlier reviews, the present synthesis highlights the integration of multiple modification strategies within a single system to simultaneously improve packaging performance and sustainability. The complementary use of chitosan, cellulose, and starch further reflects a transition from simple material substitution to performance-oriented design that enhances food preservation, biodegradability, and controlled-release functionality.

### **Scientific Concepts and Sustainability Dimensions**

The reviewed studies demonstrate that EO-infused biopolymer packaging integrates concepts from chemistry, biology, physics, and environmental science within a single technological system. While previous research often examined antimicrobial activity, polymer interactions, or barrier properties separately (Calo et al., 2015; Mishra et al., 2020; Pandey et al., 2024), this review shows how these concepts collectively support sustainable material innovation. Renewable resources, biodegradability, waste reduction, and circular economy principles consistently emerged, reinforcing the importance of evaluating packaging materials based on both technical performance and life-cycle sustainability (Jiao et al., 2024).

### **Educational Potential of EO-Infused Biopolymer Packaging**

A major contribution of this review is the identification of EO-infused biopolymer packaging as a contextual resource for science and STEM education. Beyond food preservation, these materials naturally integrate multiple scientific disciplines and support inquiry-, project-, and problem-based learning. This finding aligns with evidence that authentic, context-based learning improves conceptual understanding and student engagement (Chow et al., 2017; Toth et al., 2014). By combining antimicrobial testing, material characterization, data analysis, and environmental evaluation into a single learning sequence, sustainable packaging provides an authentic context for developing scientific literacy, systems thinking, and sustainability awareness.

### **Opportunities and Challenges for Educational Integration**

EO-infused biopolymer packaging offers authentic opportunities for interdisciplinary and sustainability-oriented science learning by connecting scientific concepts to real-world environmental issues. However, classroom implementation remains limited because most studies emphasize material development rather than instructional practice. Additional challenges include variability in material formulations, laboratory resource requirements, and the absence of curriculum-aligned instructional frameworks. Future research should therefore prioritize empirical classroom studies and the development of practical teaching models.

### **Theoretical and Practical Implications**

This review bridges sustainable packaging research and science education by integrating perspectives from material science, sustainability, and educational research. The findings provide educators and curriculum developers with an interdisciplinary context for teaching scientific concepts through sustainability issues while encouraging collaboration among researchers, educators, and industry to promote environmental awareness and sustainable innovation.

### **Study Limitations and Future Research**

This review is limited to English-language, peer-reviewed journal articles published between 2010 and 2024 and relies on qualitative thematic synthesis rather than quantitative meta-analysis. Consequently, the findings identify conceptual patterns rather than effect sizes. In addition, evidence on educational implementation remains limited because most studies focus on material development and food packaging applications. Future research should strengthen this emerging field through classroom interventions and quantitative evaluations to validate the educational value of EO-infused biopolymer packaging.

## CONCLUSION

This review synthesizes recent advances in essential oil-infused biopolymer packaging and highlights its potential for science education. Recent developments emphasize the integration of essential oils, encapsulation technologies, and composite biopolymers to enhance packaging functionality while promoting sustainability through biodegradability, renewable resources, and circular-economy principles. The findings suggest that these innovations provide authentic contexts for inquiry-, project-, and sustainability-oriented science learning by integrating concepts from chemistry, biology, physics, and environmental science. However, broader educational implementation is limited by the lack of classroom-based evidence and curriculum-aligned instructional frameworks. This review bridges sustainable packaging research and science education by identifying interdisciplinary learning opportunities and sustainability concepts embedded in these materials. Future research should focus on empirical classroom validation and the development of instructional frameworks to support their integration into science and STEM education.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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