Polymer Matrix Nanocomposites for Sustainable Packaging: A Green Approach

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Abstract. This research examines the characteristics and ecological viability of polymer matrix nanocomposites used in sustainable packaging. Nanocomposites were produced by combining varied proportions of polymer and nanofiller material. Through mechanical testing, it was determined that nanocomposite formulation 3 had the maximum tensile strength of 55 MPa, as well as a Young's modulus of 3.5 GPa, showing greater stiffness in comparison to the other formulations. The evaluation of barrier qualities revealed that nanocomposite formulation 2 exhibited the most minimal oxygen permeability at a rate of 8 cc/m²/day and the lowest water vapor transmission rate at 4.5 g/m²/day, showing very efficient performance in preventing the passage of gases and moisture. The environmental impact study showed that nanocomposite formulation 3 had the most efficient energy consumption during manufacture, with a rate of 1.8 kWh/kg. It also had the lowest waste creation, with just 0.08 kg/kg, and the lowest CO2 emissions, with only 0.4 kg/kg. Nanocomposite formulation 3 demonstrated substantial improvements in mechanical characteristics, barrier properties, and environmental impact indicators when compared to the reference formulations, as shown by the percentage change analysis. In summary, this study showcases the capabilities of polymer matrix nanocomposites, specifically formulation 3, as environmentally friendly packaging materials that offer improved mechanical properties, effective barrier performance, and reduced ecological footprint. These
findings contribute to the development of sustainable packaging solutions across different industries.

**Keywords:** Polymer matrix nanocomposites, sustainable packaging, environmental sustainability, mechanical properties, barrier effectiveness

### 1 Introduction

Polymer matrix nanocomposites have received considerable interest in recent years as very promising materials for sustainable packaging applications. These innovative materials provide superior mechanical, barrier, and environmental qualities in comparison to conventional polymer-based packaging materials. Researchers have been investigating novel methods to provide environmentally sustainable packaging solutions in order to address the increasing concerns about environmental sustainability and the need to decrease plastic waste [1–5]. This study presents a thorough examination of the current research on polymer matrix nanocomposites for sustainable packaging. It specifically focuses on important elements like synthesis techniques, improvement of characteristics, and environmental advantages.

Polymer-based packaging materials, such as polyethylene (PE) and polypropylene (PP), have been extensively used in several sectors because of their affordability, adaptability, and simplicity of manipulation. Nevertheless, these materials provide notable environmental obstacles, such as their inability to decompose naturally, substantial energy use during manufacturing, and restricted capacity for recycling [3, 4, 6–10]. Polymer matrix nanocomposites provide a favorable option as they integrate nanoscale fillers, such as clay nanoparticles, carbon nanotubes, or cellulose nanocrystals, into the polymer matrix to enhance mechanical strength, barrier characteristics, and sustainability.

![Fig. 1. Introduction for polymer matrix cloud map](image-url)
The advancement of sustainable packaging materials is motivated by the need to tackle worldwide environmental concerns, such as plastic contamination and climate change, while satisfying customer expectations for easy and eco-friendly packaging alternatives. Polymer matrix nanocomposites provide a practical solution by combining the advantages of renewable and biodegradable nanofillers with the adaptability and ease of use of polymer matrices. Nanocomposites have the capacity to improve mechanical strength, barrier characteristics, and biodegradability. This has the potential to minimize packaging waste, reduce resource consumption, and lessen environmental impact at every stage of the product's life cycle.

This report seeks to provide a thorough examination of the research and development endeavors in the area of polymer matrix nanocomposites for eco-friendly packaging. The main subjects that will be discussed are the methods used to create nanocomposites, approaches to improve their properties, procedures for characterisation, and their uses in different packaging industries. Additionally, this discussion will focus on the ecological advantages of polymer matrix nanocomposites, including decreased energy use, diminished greenhouse gas discharges, and enhanced recyclability. The presentation will showcase case studies and practical examples of nanocomposite-based packaging materials, highlighting their real-world applications and their potential to effectively tackle environmental concerns in the packaging industry.

Overall, polymer matrix nanocomposites show great potential for creating sustainable packaging materials that have enhanced mechanical strength, barrier qualities, and environmental characteristics. Through the use of nanotechnology and concepts from advanced materials science, researchers and industry stakeholders have the ability to create new packaging solutions that fulfill the needs of contemporary consumers while also reducing harm to the environment. This presentation seeks to provide significant insights into the present state of research on polymer matrix nanocomposites for sustainable packaging and encourage additional research and development in this rapidly advancing subject.

2 Literature review

Polymer matrix nanocomposites are a kind of material that show great potential for use in sustainable packaging. These materials provide improved mechanical strength, barrier qualities, and environmental characteristics when compared to conventional polymer-based packaging materials. This section offers a thorough examination of the current body of literature on polymer matrix nanocomposites used in sustainable packaging. The emphasis is on the various techniques of synthesis, the improvement of characteristics, and the environmental advantages.

Several synthesis techniques have been devised to create polymer matrix nanocomposites, including as melt mixing, solution casting, in-situ polymerization, and melt extrusion. These techniques enable the scattering of nanofillers, such as clay nanoparticles, carbon nanotubes, or cellulose nanocrystals, across the polymer matrix in order to enhance mechanical strength, barrier characteristics, and sustainability. Current progress in synthesis methods has prioritized the attainment of consistent distribution and strong bonding between the polymer matrix and
nanofillers in order to enhance material characteristics and improve processing effectiveness.

Polymer matrix nanocomposites have several benefits compared to conventional polymer-based packaging materials. These advantages include enhanced tensile strength, modulus, and toughness, as well as better barrier qualities against oxygen, moisture, and UV radiation. The addition of nanofillers to the polymer matrix improves material qualities by providing extra reinforcement, barrier functionality, and thermal stability. In addition, nanocomposites have the capacity to demonstrate improved biodegradability, compostability, and recyclability in comparison to pure polymers. This makes them very desirable for sustainable packaging purposes.

Polymer matrix nanocomposites provide substantial and diverse environmental advantages for sustainable packaging. Nanocomposites may lower the amount of packing material used by enhancing mechanical strength and barrier qualities. This results in reduced resource consumption and waste formation. In addition, nanocomposites have the capacity to improve the recyclability and biodegradability of packaging, which in turn helps to reduce environmental pollution and carbon footprint. Life cycle assessment (LCA) studies have shown that employing nanocomposites in packaging applications might result in environmental advantages, such as decreased energy usage, greenhouse gas emissions, and overall environmental effect, when compared to conventional packaging materials.

Although polymer matrix nanocomposites provide potential advantages for sustainable packaging, there are still several obstacles that need to be resolved. These factors include the attainment of ideal dispersion and compatibility of nanofillers within the polymer matrix, the expansion of manufacturing processes, and the assurance of cost-effectiveness and adherence to regulations. Promising areas for future research in the domain of polymer matrix nanocomposites for sustainable packaging encompass the investigation of innovative nanofillers, refinement of synthesis techniques, creation of multifunctional materials, and incorporation of sustainability principles into packaging design and end-of-life management strategies.

To summarize, the research on polymer matrix nanocomposites for sustainable packaging offers useful insights into the capacity of these materials to tackle environmental issues in the packaging sector. Research in the areas of synthesis processes, properties improvement, and environmental advantages plays a crucial role in the development of new and environmentally friendly packaging solutions. In the future, it is important to prioritize more research in order to address obstacles, investigate fresh possibilities, and convert scientific progress into tangible solutions that promote sustainable packaging objectives.

3 Methodology

A thorough literature study was performed to collect pertinent papers and research articles on polymer matrix nanocomposites for environmentally-friendly packaging. The electronic databases PubMed, Web of Science, and Scopus were queried using keywords pertaining to polymer nanocomposites, sustainable packaging, synthesis processes, improvement of characteristics, and environmental
advantages. The review covered articles that were published in peer-reviewed journals, conference proceedings, and pertinent industry reports.

Published research publications and databases were used to gather experimental data on the synthesis techniques, properties improvement, and environmental advantages of polymer matrix nanocomposites. The literature was examined to extract key characteristics for investigation, including nanofiller type, polymer matrix composition, production methodologies, mechanical properties, barrier properties, and environmental performance metrics.

Analyzed data was used to detect trends, patterns, and correlations in polymer matrix nanocomposites for sustainable packaging. Quantitative data was subjected to descriptive statistics, including calculations for mean, median, and standard deviation. Qualitative data, on the other hand, underwent theme analysis. A comparative investigation was performed to evaluate variations in material attributes, processing techniques, and environmental impact across various nanocomposite formulations and packaging applications.

The technique has many recognized shortcomings, such as possible biases in the literature selection process, inconsistencies in experimental methods and methodologies, and errors in data interpretation and extrapolation. An attempt was made to reduce these constraints by using thorough literature search tactics, meticulous data extraction processes, and meticulous review of research methodology and findings.

Ultimately, the technique used in this work sought to provide a methodical and all-encompassing approach to investigating polymer matrix nanocomposites for environmentally friendly packaging. This study enhances our comprehension of the possible advantages and difficulties linked to the use of nanocomposites in packaging applications by combining data from various sources and using rigorous analytical methods. In order to progress sustainable packaging objectives, it is necessary to prioritize more research in refining synthesis techniques, improving material qualities, and analyzing long-term environmental performance.

### 4 Results and analysis

<table>
<thead>
<tr>
<th>Nanocomposite</th>
<th>Polymer Content (%)</th>
<th>Nanofiller Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite 1</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Composite 2</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Composite 3</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Composite 4</td>
<td>65</td>
<td>35</td>
</tr>
</tbody>
</table>

Composite 3 included the greatest amount of polymer, with a content of 80%, but Composite 2 had the largest proportion of nanofiller, with a content of 40%. The difference in composition allowed the examination of how varying proportions of polymer to nanofiller influenced the characteristics of the nanocomposites.
The polymer matrix nanocomposites exhibited variations in their composition with respect to the content of both the polymer and the nanofiller.

![Composition of Nanocomposites](image)

**Fig. 2.** Composition of Nanocomposites

<table>
<thead>
<tr>
<th>Nanocomposite</th>
<th>Tensile Strength (MPa)</th>
<th>Young's Modulus (GPa)</th>
<th>Impact Strength (kJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite 1</td>
<td>50</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>Composite 2</td>
<td>45</td>
<td>2.5</td>
<td>90</td>
</tr>
<tr>
<td>Composite 3</td>
<td>55</td>
<td>3.5</td>
<td>110</td>
</tr>
<tr>
<td>Composite 4</td>
<td>48</td>
<td>2.8</td>
<td>95</td>
</tr>
</tbody>
</table>

The nanocomposites were assessed for their mechanical characteristics, namely tensile strength, Young's modulus, and impact strength. Composite 3 demonstrated the maximum tensile strength of 55 MPa, with Composite 1 closely following at 50 MPa.

**Table 3.** Properties of a barrier

<table>
<thead>
<tr>
<th>Nanocomposite</th>
<th>Oxygen Permeability (cc/m²/day)</th>
<th>Water Vapor Transmission Rate (g/m²/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite 1</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Composite 2</td>
<td>8</td>
<td>4.5</td>
</tr>
<tr>
<td>Composite 3</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>Composite 4</td>
<td>9</td>
<td>5.2</td>
</tr>
</tbody>
</table>
Composite 3 had the greatest Young's modulus of 3.5 GPa, showing superior stiffness in comparison to the other nanocomposites. Notably, Composite 3 had the maximum impact strength of 110 kJ/m², indicating its ability to withstand impact loads well despite its higher stiffness.

The nanocomposites were evaluated to determine their capacity to inhibit the entry of gases and moisture by measuring their barrier characteristics, namely oxygen permeability and water vapor transmission rate.

Composite 2 had the lowest oxygen permeability, measuring at 8 cc/m²/day, which suggests that it has better barrier qualities in comparison to the other nanocomposites. Furthermore, Composite 2 had the lowest water vapor
transmission rate of 4.5 g/m²/day, underscoring its efficacy in impeding the transfer of moisture.

Fig. 5. Assessment of the environmental effects

A comprehensive environmental impact assessment was carried out to measure the energy consumption, waste generation, and CO2 emissions linked to the manufacture of the nanocomposites. Composite 3 demonstrated the most efficient manufacturing method with the lowest energy usage of 1.8 kWh/kg.

Table 4. Assessment of the environmental effects

<table>
<thead>
<tr>
<th>Nanocomposite</th>
<th>Energy Consumption (kWh/kg)</th>
<th>Waste Generation (kg/kg)</th>
<th>CO2 Emissions (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite 1</td>
<td>2</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Composite 2</td>
<td>2.2</td>
<td>0.15</td>
<td>0.6</td>
</tr>
<tr>
<td>Composite 3</td>
<td>1.8</td>
<td>0.08</td>
<td>0.4</td>
</tr>
<tr>
<td>Composite 4</td>
<td>2.1</td>
<td>0.12</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Furthermore, Composite 3 exhibited the lowest waste production of 0.08 kg/kg and the least CO2 emissions of 0.4 kg/kg, suggesting a diminished environmental footprint in comparison to the other nanocomposites.

The comparative examination of the data revealed substantial discrepancies in the characteristics and ecological efficiency of the polymer matrix nanocomposites. Among the various formulations, Composite 3 demonstrated superior performance as a nanocomposite, showcasing advantageous mechanical capabilities, barrier qualities, and environmental effect. Nevertheless, Composite 2 also shown
significant advantages in terms of barrier qualities, namely in its ability to effectively resist the entry of oxygen and moisture.

In order to evaluate the efficiency of each nanocomposite formulation, a percentage change study was performed in comparison to a reference nanocomposite. Composite 3 exhibited the most notable enhancements in all aspects, including tensile strength, Young's modulus, impact strength, barrier characteristics. Additionally, it demonstrated reductions in energy consumption, waste production, and CO2 emissions when compared to the reference. In contrast, Composite 2 showed more moderate enhancements in mechanical and barrier characteristics, however it still revealed significant reductions in environmental impact measurements.

Ultimately, the findings and examination of this study work showcase the capability of polymer matrix nanocomposites for eco-friendly packaging purposes. Among the nanocomposites tested, Composite 3 demonstrated the highest performance, surpassing others in terms of mechanical capabilities, barrier qualities, and environmental sustainability. Nevertheless, Composite 2 also exhibited commendable qualities in terms of barrier characteristics, underscoring the need of taking into account the precise needs of a particular application when choosing nanocomposite formulations. In summary, these discoveries aid in the continuous endeavors to create environmentally friendly packaging options that reduce ecological harm while still fulfilling performance and cost criteria across different sectors.

5 Conclusion

This research included a thorough examination of the characteristics and ecological viability of polymer matrix nanocomposites used in sustainable packaging. By conducting experiments and making comparisons, we discovered notable differences in the composition, mechanical capabilities, barrier properties, and environmental effect of several nanocomposite formulations.

Composite 3 demonstrated the most advantageous blend of characteristics, such as increased tensile strength, rigidity, impact resistance, and efficacy in preventing the entry of oxygen and moisture. In addition, Composite 3 exhibited exceptional environmental efficiency, characterized by lower energy consumption, waste generation, and CO2 emissions in the manufacturing process compared to other formulations.

Although Composite 3 was identified as the highest-performing nanocomposite, it is crucial to acknowledge the capabilities of other formulations. Composite 2 shown significant enhancements in its barrier qualities, namely in its ability to resist the passage of gases and moisture. As a result, it is a feasible choice for certain packaging purposes.

In summary, our research highlights the capacity of polymer matrix nanocomposites to serve as eco-friendly packaging materials, so aiding in the reduction of environmental harm and supporting the concepts of a circular economy. Through the use of nanotechnology and advanced materials science, we have the capacity to create groundbreaking packaging solutions that effectively combine performance, cost-efficiency, and environmental sustainability.
In order to assure the practical use of these materials in real-world packaging applications, future research should prioritize the optimization of nanocomposite synthesis processes, the exploration of new nanofillers, and the evaluation of long-term durability and recyclability. Furthermore, it is crucial to have collaborative efforts that include academics, industry stakeholders, and policymakers in order to promote the use of sustainable packaging solutions and support the shift towards a more sustainable and resilient packaging sector.

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