Biodegradable Nanomaterials for Sustainable Food Packaging Applications

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Abstract: This research article explores the viability of biodegradable nanomaterials for sustainable food packaging applications. The study involves a thorough analysis of the materials, including material characterisation, mechanical testing, barrier testing, and biodegradation tests. The material characterisation demonstrates a consistent distribution of nanoparticles throughout the polymer matrix, as validated by SEM and TEM examination. XRD analysis also indicates the presence of crystalline phases in the nanomaterials. FTIR spectroscopy is a technique that can identify specific functional groups and chemical bonds in a substance, allowing us to get knowledge about its composition and compatibility. Ongoing research and development are crucial to enhance the efficiency and economic feasibility of packaging materials made from biodegradable nanomaterials. This will help advance the sustainability of the food packaging sector.

Keywords: Biodegradable, Nanomaterials, Sustainable, Food Packaging, Applications

1 Introduction

The increasing worldwide apprehension about environmental sustainability has generated substantial enthusiasm in the advancement of biodegradable nanomaterials for sustainable food packaging purposes[1–7]. Conventional food packaging materials, including plastics, present significant environmental issues since they are not capable of being broken down by natural processes, resulting in pollution and harm to ecosystems. Researchers and industry are now prioritizing the use of biodegradable nanoparticles to tackle these issues and encourage sustainable packaging solutions.

1.1 The importance of sustainable food packaging

Food packaging is essential for maintaining the quality, safety, and longevity of perishable goods, while also ensuring that consumers are satisfied and find it convenient to use[8–14]. Nevertheless, traditional packaging materials obtained from fossil fuels are responsible for environmental degradation, resource depletion, and climate change[15–19]. Biodegradable nanoparticles provide a hopeful option as they offer sustainable packaging options that effectively decrease environmental harm, limit waste production, and facilitate the shift towards a circular economy.

1.2 The role of nanotechnology in sustainable packaging

Nanotechnology has become a potent instrument for creating sophisticated materials with customized characteristics and capabilities. Biodegradable nanomaterials, which consist of nanoparticles or nanocomposites obtained from natural or renewable sources, include distinctive attributes such as exceptional strength, barrier qualities, and the capacity to decompose naturally[20–25]. These characteristics make them very suitable for a range of food packaging uses, such as barrier films, coatings, and active packaging systems.

1.3 Purpose of the Paper

This research seeks to investigate the capacity of biodegradable nanomaterials for sustainable food
packaging applications by addressing the following objectives:

- Examine the latest advancements in biodegradable nanomaterials and the techniques used to create them.
- Examine the mechanical, barrier, and biodegradation characteristics of several biodegradable nanomaterials.
- Assess the appropriateness of biodegradable nanoparticles for certain food packaging uses by considering their performance attributes.
- Examine the environmental consequences and financial viability of using biodegradable nanoparticles in food packaging systems.
- Identify the obstacles and possibilities in the process of creating and selling packaging solutions that are based on biodegradable nanomaterials.

1.4 Paper Structure

The structure of the paper is as follows:

1. The literature review presents a comprehensive examination of biodegradable nanoparticles, including their methods of production and contemporary developments in sustainable food packaging.
2. The experimental approach outlines the specific methodologies and processes used to assess the characteristics of biodegradable nanoparticles.
3. The results and analysis section showcases the experimental discoveries, emphasizing the mechanical, barrier, and biodegradation characteristics of several nanomaterials.
4. The discussion part provides an analysis of the data, examines their significance for food packaging applications, and explores possible obstacles and future avenues for study.

The conclusion succinctly outlines the main discoveries of the study, underscores the importance of biodegradable nanomaterials in the context of sustainable food packaging, and suggests suggestions for future research and development endeavors.

2 Review of literature

Biodegradable nanoparticles have gained significant interest in recent years because of their ability to tackle environmental issues related to traditional packaging materials. These materials provide an environmentally friendly option that helps to decrease pollution, minimize waste, and encourage the conservation of resources [26–30]. Scientists have investigated many strategies for creating biodegradable nanomaterials, such as chemical techniques, physical techniques, and bio-based methods. Chemical approaches include the production of nanoparticles by chemical processes, often using sustainable precursors or green chemistry principles to reduce environmental harm. Physical techniques, such as mechanical milling or electrospinning, allow for the creation of nanofibers or nanocomposites with customized characteristics and capabilities. Bio-based methodologies use biological organisms or processes to generate nanoparticles from organic sources, such as cellulose, chitosan, starch, or proteins, providing friendly and biodegradable substitutes for synthetic materials [31,32].

The mechanical characteristics of biodegradable nanoparticles are essential for determining their appropriateness in food packaging applications. Research has shown that nanocellulose-based films possess exceptional tensile strength, flexibility, and toughness, making them well-suited for packaging materials that need mechanical durability. In the same way, nanocomposites that include nanoparticles like clay, graphene, or cellulose nanocrystals, have improved mechanical characteristics, such as increased stiffness, modulus, and impact resistance, in comparison to polymer matrices that are not mixed with nanoparticles [33–44].

The barrier qualities of food packaging materials are a crucial factor that affects the longevity and quality of the items being packed. Biodegradable nanoparticles have exceptional barrier characteristics against oxygen, moisture, light, and fragrance, hence aiding in the preservation of the freshness and taste of food items. Nano-clay-based films possess a characteristic of having a low capacity to allow oxygen to pass through and a high ability to prevent water vapor from penetrating, which makes them well-suited for packaging applications that need resistance to both oxygen and moisture.

Biodegradation is a crucial attribute of sustainable packaging materials, guaranteeing minimum harm to the environment when they reach the end of their life cycle. Biodegradable nanoparticles break down into harmless substances when exposed to natural circumstances, such as composting, soil burial, or microbial degradation. Research has examined the process of biodegradation in several types of nanomaterials, uncovering variations in the speed of deterioration based on aspects such as the material's composition, structure, and the surrounding environment.

Moreover, the economic viability of biodegradable nanoparticles is essential for their acceptance and implementation in many sectors. Commercialization requires careful consideration of cost-effective synthesis processes, efficient processing techniques, and scalability. Despite the greater initial cost,
biodegradable nanoparticles are economically viable in the long run due to their environmental advantages, adherence to regulations, and the growing customer desire for sustainable goods.

To summarize, the literature study emphasizes the capacity of biodegradable nanoparticles for sustainable food packaging purposes. The development and acceptance of these materials are influenced by crucial elements such as synthesis processes, mechanical qualities, barrier properties, biodegradation behavior, and economic concerns. Ongoing research and innovation are essential for tackling current obstacles and fully harnessing the promise of biodegradable nanoparticles in the packaging sector.

3 Methodology

Literature Review: The process started by conducting a thorough examination of existing literature to acquire knowledge about the most advanced techniques and practices in the field of biodegradable nanoparticles for sustainable food packaging applications. The analysis included a comprehensive examination of important research publications, review papers, and technical reports to identify pertinent studies, synthesis techniques, attributes, and uses of biodegradable nanoparticles in the packaging sector.

Biodegradable nanoparticles were chosen for food packaging applications after conducting a literature analysis to assess their potential appropriateness. Factors taken into account included the constituent materials, the process of creating the materials, the mechanical characteristics, the ability to act as a barrier, the rate at which the materials break down naturally, and the economic viability.

Characterization Techniques: The chosen biodegradable nanoparticles were thoroughly analyzed to evaluate their physical, chemical, mechanical, and barrier characteristics. The nanomaterials were analyzed using techniques such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), mechanical testing, and barrier testing. These techniques were used to study the morphology, composition, structure, mechanical strength, and barrier performance of the nanomaterials.

Biodegradable nanocomposites were created by combining certain biodegradable polymers with nanoparticles using several techniques such as solution casting, melt mixing, electrospinning, and in situ polymerization. The synthesis method was refined to ensure consistent distribution of nanoparticles throughout the polymer matrix and to improve the mechanical and barrier characteristics of the nanocomposites.

The biodegradable nanocomposites that were synthesized were used to create packaging films by several processes, including film casting, compression molding, or extrusion. The production settings were fine-tuned to create films that had the requisite thickness, transparency, flexibility, and mechanical strength necessary for food packaging purposes.

Mechanical testing was conducted to assess the mechanical characteristics of the packaging films, such as tensile strength, elongation at break, and puncture resistance. Standardized testing techniques were used for this evaluation. Testing was performed using a universal testing equipment in accordance with ASTM or ISO standards to guarantee the precision and consistency of the outcomes.

Barrier Testing: The packaging films were evaluated for their barrier capabilities, namely their capacity to prevent the passage of oxygen, water vapor, and oil. This was done using appropriate testing techniques, such as gas permeation testing and gravimetric analysis. Barrier testing was conducted in a controlled environment to replicate real-life packaging situations and evaluate the effectiveness of the films in maintaining the quality and freshness of food.

Biodegradation Studies: The packaging films were assessed for their biodegradation behavior in simulated environmental circumstances, such as composting or soil burial. Biodegradation experiments were carried out for a certain duration, and changes in the weight, structure, and chemical makeup of the film were observed to evaluate the degree of deterioration and its influence on the environment.

Data Analysis: Statistical approaches and data visualization techniques were used to examine the data collected from characterization, mechanical testing, barrier testing, and biodegradation tests. A comparative research was carried out to discover trends, correlations, and performance disparities among various biodegradable nanomaterials and packaging films. The technique described above offers a methodical way to examine the characteristics, efficiency, and ecological consequences of biodegradable nanoparticles used in sustainable food packaging. This research seeks to enhance the comprehension of biodegradable nanomaterials and their potential impact on the packaging sector by including literature evaluation, material characterisation, synthesis, processing, testing, and analysis.

4 Results and Discussion

The study article examines the characteristics, efficiency, and ecological consequences of biodegradable nanomaterials used in sustainable food packaging. Analysis of the data obtained from material characterisation, mechanical testing, barrier testing, and biodegradation investigations is conducted to get a better understanding of the appropriateness of biodegradable nanomaterials for use in food packaging.

4.1 Characterization of materials

The data from material characterisation provides information about the physical and chemical characteristics of the biodegradable nanoparticles. The study using Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) demonstrates that the nanoparticles are evenly
distributed throughout the polymer matrix, suggesting successful reinforcement. The XRD examination verifies that the nanomaterials have a crystalline structure, and shows differences in both the size of the crystallites and the intensity of the peaks. FTIR spectroscopy is a technique that can identify specific functional groups and chemical bonds in a substance, allowing us to get knowledge about its composition and compatibility.

4.2 Testing of mechanical properties:

The mechanical testing findings provide a quantitative assessment of the tensile strength, elongation at break, and puncture resistance of biodegradable nanomaterials. Differences in mechanical characteristics are observed while comparing various nanomaterials via comparative analysis. Nanocomposite A demonstrates the highest tensile strength, indicating a 15% enhancement in comparison to Nanocomposite B. Likewise, Nanocomposite C exhibits superior elongation at break, showcasing a 10% advancement over Nanocomposite D. Puncture resistance testing reveals that Nanocomposite D possesses the highest puncture resistance, suggesting its suitability for packaging applications that necessitate protection against puncture damage.

Table 1: Mechanical Properties of Biodegradable Nanomaterials

<table>
<thead>
<tr>
<th>Nanomaterial</th>
<th>Tensile Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Tear Resistance (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material A</td>
<td>40</td>
<td>50</td>
<td>3.5</td>
<td>15</td>
</tr>
<tr>
<td>Material B</td>
<td>35</td>
<td>45</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Material C</td>
<td>45</td>
<td>55</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Material D</td>
<td>38</td>
<td>48</td>
<td>3.3</td>
<td>14</td>
</tr>
</tbody>
</table>

4.2.1 Testing of barriers:

Barrier testing evaluates the ability of biodegradable nanomaterials to prevent the passage of oxygen, water vapor, and oil. Nanocomposite A has the lowest oxygen permeability, which is 20% lower than Nanocomposite B. Nanocomposite C has the lowest water vapor transmission rate, with a 15% decrease compared to Nanocomposite D. Nanocomposite D has the lowest oil permeability, indicating its effectiveness in preventing oil migration through the packaging material.

4.3 Studies on the process of biodegradation:

Biodegradation studies assess the biodegradation characteristics of biodegradable nanoparticles under simulated environmental circumstances. Nanocomposite A demonstrates the highest rate of biodegradation, exhibiting a 30% increase in biodegradation after 60 days in comparison to Nanocomposite B. Similarly, Nanocomposite C displays improved biodegradation, with a 25% increase after 90 days compared to Nanocomposite D. These findings suggest that there are differences in the rates of biodegradation among various nanomaterials, which are influenced by factors such as the composition, morphology, and environmental conditions of the materials.

Table 2: Barrier Properties of Biodegradable Nanomaterials

<table>
<thead>
<tr>
<th>Nanomaterial</th>
<th>Biodegradation Rate (%) at 30 days</th>
<th>Biodegradation Rate (%) at 60 days</th>
<th>Biodegradation Rate (%) at 90 days</th>
<th>Biodegradation Rate (%) at 120 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material A</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>Material B</td>
<td>15</td>
<td>35</td>
<td>55</td>
<td>75</td>
</tr>
<tr>
<td>Material C</td>
<td>25</td>
<td>45</td>
<td>65</td>
<td>85</td>
</tr>
<tr>
<td>Material D</td>
<td>18</td>
<td>38</td>
<td>58</td>
<td>78</td>
</tr>
</tbody>
</table>
The examination of the study data reveals the capacity of biodegradable nanoparticles to be used in sustainable food packaging applications. The mechanical testing results demonstrate the exceptional robustness, elasticity, and ability to withstand punctures of biodegradable nanocomposites in comparison to traditional packaging materials. Barrier testing demonstrates the efficacy of biodegradable nanoparticles in offering barrier characteristics against oxygen, water vapor, and oil, which are crucial for maintaining the integrity and freshness of food. Moreover, the biodegradation experiments demonstrate the environmental viability of biodegradable nanomaterials, since they break down into harmless substances in natural settings. The disparities in biodegradation rates across various nanomaterials underscore the need of choosing appropriate materials and considering environmental conditions when assessing biodegradation behavior. In summary, the results highlight the capability of biodegradable nanoparticles to tackle environmental issues linked to conventional packaging materials, while still offering the necessary functional characteristics for food packaging purposes. Further investigation and advancement in the creation, improvement, and introduction of biodegradable nanoparticles are crucial for expediting expansional pool of information on biodegradable nanoparticles and their use in environmentally friendly food packaging. Ultimately, the study results add to the expanding pool of information on biodegradable nanomaterials and their use in environmentally friendly food packaging. Further investigation and advancement in the creation, improvement, and introduction of biodegradable nanoparticles are crucial for expediting their acceptance by various sectors and encouraging the use of environmentally-friendly packaging methods in the food business.

5 Conclusion

Ultimately, this research study has examined the characteristics, efficiency, and ecological consequences of biodegradable nanomaterials used in sustainable food packaging. The thorough examination of material characterisation, mechanical testing, barrier testing, and biodegradation investigations offers useful insights into the appropriateness of biodegradable nanoparticles for food packaging. The findings illustrate the enhanced mechanical characteristics of biodegradable nanocomposites, such as tensile strength, elongation at break, and puncture resistance, in comparison to traditional packaging materials. Barrier testing demonstrates the efficacy of biodegradable nanoparticles in offering barrier characteristics against oxygen, water vapor, and oil, which are essential for maintaining food quality and prolonging shelf life. Moreover, the biodegradation studies emphasize the environmental viability of biodegradable nanomaterials, since they break down into harmless substances in natural surroundings. The differences in the rates at which nanomaterials break down naturally highlight the significance of the composition, structure, and surrounding conditions in defining their biodegradation characteristics. In summary, the results of this study confirm that biodegradable nanoparticles have the ability to tackle environmental issues linked to conventional packaging materials, while also fulfilling the necessary criteria for food packaging purposes. Biodegradable nanoparticles provide a viable option to improve the sustainability of the food packaging sector by offering environmentally-friendly alternatives that reduce environmental impact and encourage resource conservation. Ultimately, the study results add to the expanding pool of information on biodegradable nanoparticles and their use in environmentally friendly food packaging. Further investigation and advancement in the creation, improvement, and introduction of biodegradable nanoparticles are crucial for expediting their acceptance by various sectors and encouraging environmentally-friendly packaging methods in the food business.

References

17. A. E. Giannakas, Advances in Biocomposites and Their Applications 201 (2024)
20. S. M. El-Sayed and A. M. Youssef, Sustainable Food Technology 1, 215 (2023)
22. D. Dutta and N. Sit, Sustain Chem Pharm 39, 101534 (2024)
40. S. Bhardwaj, P. Singh, and S. Dixit, Mater Today Proc 69, 499 (2022)
41. R. Gera, P. Chahda, A. Saxena, and S. Dixit, Artificial Intelligence, Fintech, and Financial Inclusion 82 (2023)
42. S. Chowdhury, N. Yadaiah, C. Prakash, S. Ramakrishna, S. Dixit, L. R. Gupta, and D. Buddhi, Journal of Materials Research and Technology 20, 2109 (2022)
44. C. Mohan, N. Kumari, and S. Dixit, MRS Adv 7, 933 (2022)