Global Journal of Science and Technology (GJST)

An experimental view - Development of Smart Plant-Based Bioplastics Reinforced with Nanocellulose and Natural Plant Extracts for Sustainable Food Packaging

[1]Manali Kumari, [2]Avshesh Kumar

[1,2]Department Of Botany T.D.P.G.College, Jaunpur Affliated To VBSP University, Jaunpur(222002).

ABSTRACT

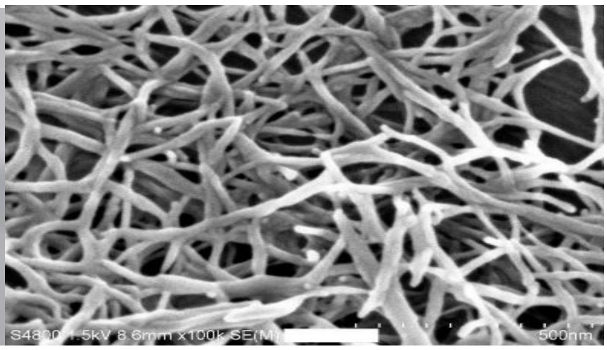
Sustainable food packaging materials are desperately needed due to the growing amount of plastic waste derived from petroleum. In order to improve their mechanical, barrier, antibacterial, and antioxidant qualities, this research attempts to create intelligent plant-based bioplastic films supplemented with nanocellulose and natural plant extracts. Plant extracts like neem, tulsi, and clove were added to starch-based bioplastic sheets that contained glycerol as a plasticizer and were reinforced with nanocellulose. The produced films were assessed for their efficacy in food packaging applications as well as their physicochemical, mechanical, biodegradation, and antibacterial qualities. The findings show that while natural plant extracts increased antibacterial activity and prolonged the shelf life of packaged foods, nanocellulose enhanced film strength and stability. These intelligent bioplastic films promote sustainable food preservation and the ideas of a circular bioeconomy by providing a biodegradable and environmentally friendly substitute for traditional plastic packaging.

KEYWORDS
Biodegradable films, antimicrobial packaging, active packaging, bioplastics, nanocellulose, plant extracts, sustainable food packaging, and circular bioeconomy. Greetings.

ARTICLE HISTORY
Received: 27 April 2026
Accepted: 15 May 2026
Published: 30 June 2026

CITATION
Kumari, K., (2026). An experimental view - Development of Smart Plant-Based Bioplastics Reinforced with Nanocellulose and Natural Plant Extracts for Sustainable Food Packaging, *Journal of Science and Technology (GJST)*, 2(2), 141-151. https://doi.org/10.65523/gjst.2026.v2.i2.18

1. Introduction



Due to their non-biodegradable nature, excessive buildup in landfills and seas, and contribution to greenhouse gas emissions, the widespread use of petroleum-based plastics in food packaging has raised serious environmental concerns. Only a small portion of the more than 400 million tons of plastic

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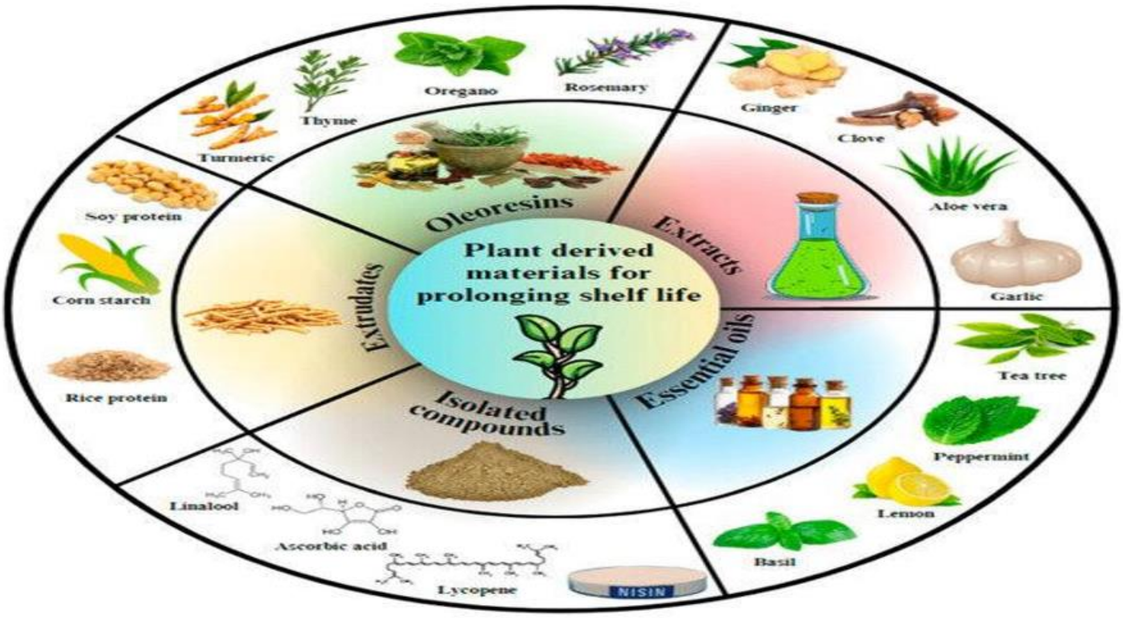
generated worldwide each year is successfully recycled, with about 36% of it being utilized for packaging. Therefore, it is imperative to provide renewable, biodegradable, and sustainable alternatives that can lessen plastic pollution without sacrificing the safety and quality of food (Li et al., 2015; Wang et al., 2024).



Since plant-based bioplastics are made from renewable biomass including starch, cellulose, pectin, proteins, and other natural polymers, they have become one of the most promising environmentally acceptable alternatives to traditional plastics. These substances can lessen reliance on plastics made from fossil fuels and are biodegradable and biocompatible. However, pure bioplastic films typically have weak mechanical strength, excessive moisture sensitivity, and insufficient barrier qualities, which restrict their practical use in food packaging. As a result, enhancing their functional properties through bioactive modification and reinforcement has grown in importance (Ahankari et al., 2021; Xu et al., 2024).

Because of its remarkable mechanical strength, high crystallinity, low density, biodegradability, and wide surface area, nanocellulose has garnered a lot of scientific interest among different reinforcing materials. In order to promote waste valorization and support the circular bioeconomy, nanocellulose can be recovered from renewable agricultural residues including banana pseudostems, sugarcane bagasse, rice straw, wheat straw, and other lignocellulosic wastes. Tensile strength, thermal stability, flexibility, and oxygen and water vapor barrier qualities are all much enhanced when nanocellulose is added to plant-based polymer matrices, increasing the suitability of biodegradable films for food packaging applications (Ren et al., 2024; Wang et al., 2024).

Using natural plant extracts is another interesting method for creating cutting-edge food packaging materials. Phenolic chemicals, flavonoids, tannins, and essential oils are abundant in medicinal plants like neem (Azadirachta indica), tulsi (Ocimum tenuiflorum), clove (Syzygium aromaticum), green tea

(Camellia sinensis), turmeric (Curcuma longa), and pomegranate peel. Strong antibacterial and antioxidant properties of these phytochemicals prevent foodborne pathogens from growing, lessen lipid oxidation, and maintain the nutritional value and sensory appeal of packaged foods. Active food packaging, which improves food safety while lowering the use of artificial preservatives, is made possible by the inclusion of these naturally occurring bioactive substances into biodegradable films (Wang et al., 2024; Qin et al., 2024).

The potential of plant-based bioplastics has been further enhanced by the development of smart food packaging. Through antibacterial activity, antioxidant release, moisture regulation, and intelligence sensing capabilities, smart packaging technologies enhance food preservation in addition to offering physical protection. According to recent research, nanocellulose-based composite films with natural plant extracts have better mechanical performance, better barrier qualities, increased biodegradability, and multifunctional qualities that make them appropriate for next-generation sustainable packaging technologies (Jacob et al., 2024; Xu et al., 2024).

Thus, the goal of this research is to create intelligent plant-based bioplastics for sustainable food packaging that are reinforced with nanocellulose and natural plant extracts.

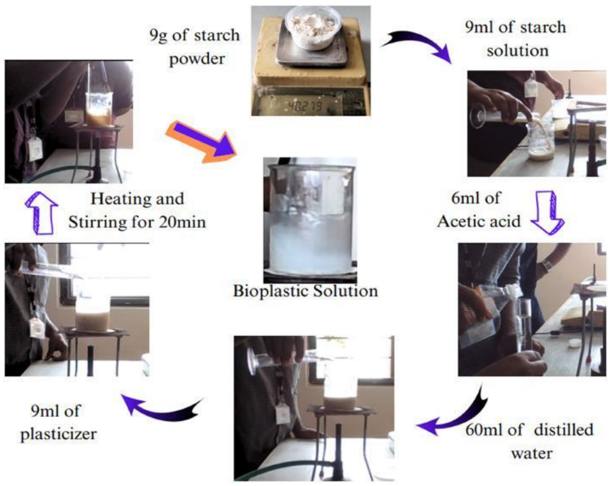
It is anticipated that the produced bioplastic films will prolong the shelf life of packaged food items while demonstrating enhanced physicochemical, mechanical, thermal, antibacterial, antioxidant, and biodegradation capabilities. The development of eco-friendly packaging materials and the worldwide shift to a sustainable circular bioeconomy are both aided by this research.

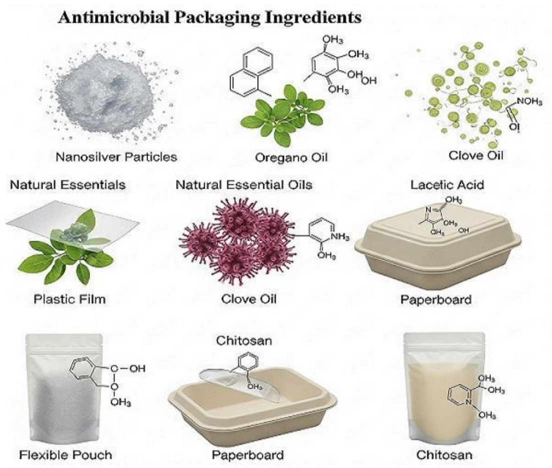
Extensive research on biodegradable packaging materials made from renewable resources has been prompted by the growing environmental issues surrounding plastic waste. Because they are renewable, biodegradable, and have a smaller environmental impact than petroleum-based plastics, plant-based bioplastics made from starch, cellulose, pectin, and other natural polymers have become viable substitutes.

Nevertheless, these biopolymers' low barrier qualities, high moisture sensitivity, and poor mechanical strength limit their commercial use in food packaging. In order to improve the functional characteristics of plant-based polymers, scientists have concentrated on adding natural bioactive chemicals and reinforcing them with nanocellulose (Ahankari et al., 2021; Wang et al., 2024). Because of its high tensile strength, good crystallinity, biodegradability, low density, and huge specific surface area, nanocellulose has emerged as one of the most promising reinforcing materials. It may be separated from renewable agricultural wastes including sugarcane bagasse, rice straw, wheat straw, and banana pseudostems, which supports the circular bioeconomy and encourages the valuation of agricultural waste. According to a number of studies, adding cellulose nanocrystals (CNCs) or cellulose nanofibers (CNFs) to starch-based bioplastics greatly enhances their tensile strength, thermal stability, flexibility, oxygen barrier qualities, and water resistance, making them more appropriate for use in food packaging (Xu et al., 2024; Wang et al., 2024).

The use of natural plant extracts in biodegradable films to create active and intelligent food packaging materials has also received a lot of interest in recent years. Phenolic chemicals, flavonoids, tannins, and essential oils are abundant in plant extracts derived from neem (Azadirachta indica), tulsi (Ocimum tenuiflorum), clove (Syzygium aromaticum), turmeric (Curcuma longa), green tea (Camellia sinensis), and pomegranate peel.

Strong antibacterial and antioxidant qualities of these phytochemicals prevent foodborne infections, lessen oxidative degradation, and preserve the nutritional value of packaged foods. It has been demonstrated that adding them to biopolymer matrices greatly increases the shelf life of meat, dairy, and fresh produce while reducing the need for artificial preservatives (Sheibani et al., 2024).



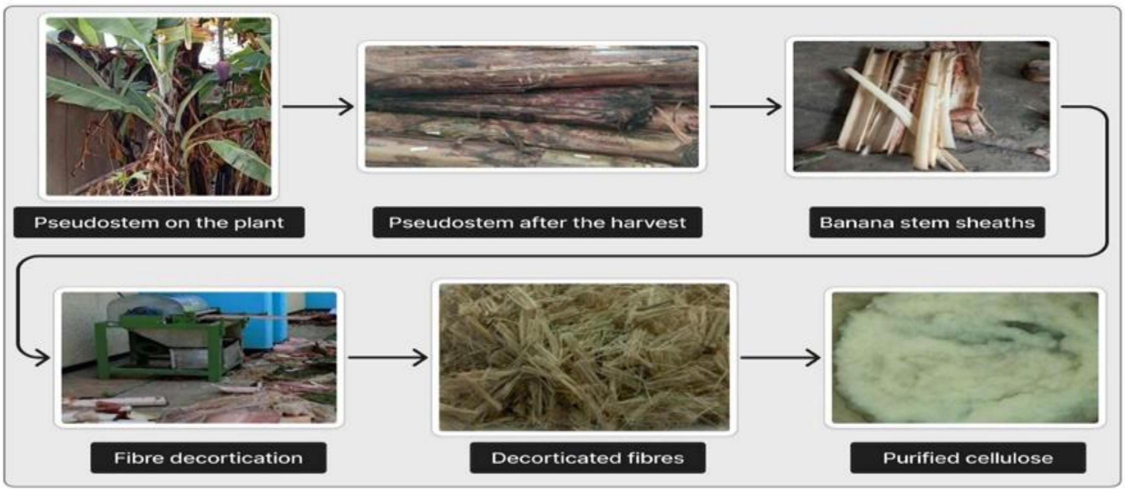


The use of biodegradable packaging materials has been further extended by the idea of smart food packaging. Smart packaging technologies actively maintain food quality, check freshness, and react to environmental changes in addition to providing physical food protection. According to recent studies, composite films made of nanocellulose and natural plant extracts offer better mechanical performance, improved barrier qualities, antibacterial activity, antioxidant capacity, and biodegradability. They are promising candidates for next-generation sustainable food-packaging technologies because of these multipurpose qualities (Nath et al., 2024; Qin et al., 2024).

Relatively few research have concurrently combined nanocellulose reinforcement and natural plant extracts into a single multifunctional plant-based bioplastic system, despite significant advancements. The majority of earlier research has concentrated on either increasing the mechanical performance of biodegradable films or separately strengthening their bioactive qualities. To maximize formulation, compatibility, long-term stability, and industrial scalability, more experimental research is necessary. According to Jacob et al. (2024) and Wang et al. (2024), creating smart plant-based bioplastics reinforced with nanocellulose and natural plant extracts is a promising approach to creating high-performance, biodegradable, and ecologically friendly packaging materials that can take the place of traditional petroleum-based plastics in the food industry.

Research Methodology

In order to create intelligent plant-based bioplastic films reinforced with nanocellulose and natural plant extracts for environmentally friendly food packaging, an experimental research design was used.



1. Raw Material Gathering

- Clove buds, neem leaves, tulsi leaves, banana pseudostem, glycerol, and corn starch were gathered from nearby sources.
- Analytical-grade compounds were utilized.

2. Removal of Nanocellulose

- The fibers from banana pseudostems were cleaned, dried, and treated with sodium hydroxide ($NaOH$).
- Acid hydrolysis and bleaching were used to produce nanocellulose.

3. Making Plant Extracts

- Clove, tulsi, and neem were dried in the shade and ground into powder.
- Concentrated plant extracts were obtained by filtering the granules after they were extracted using 70% ethanol.

4. Making Bioplastic Films

- In distilled water, corn starch was dissolved.
- The plasticizer was glycerol.
- The starch solution was mixed with plant extracts (2%) and nanocellulose (1%, 3%, and 5%).
- The solution casting process was used to heat, stir, pour into Petri dishes, and dry the slurry.

5. Experimental Interventions

- T_2: Glycerol + Starch (Control)
- T_2: 1% Nanocellulose + Control
- T2: 3% Nanocellulose + Control
- T2: 5% Nanocellulose + Control
- T_2: T_2 + Extract from Neem
- T_2: Tulsi Extract + T_2
- T_2: T_2 + Extract from Cloves

6. Bioplastic Film Characteristics

- Physical characteristics: water solubility, transparency, moisture content, and thickness.
- Tensile strength and elongation at break are examples of mechanical characteristics.
- XRD, SEM, and FTIR structural analysis.
- Thermogravimetric analysis (TGA) for thermal stability.

7. Evaluation of Biology

- The agar diffusion method was used to measure antimicrobial activity against.
- Escherichia coli and Staphylococcus aureus.
- The DPPH radical scavenging assay was used to measure antioxidant activity.

8. Research on Biodegradation

- For sixty days, bioplastic films were buried in the ground.
- To assess biodegradability, percentage weight loss was measured on a regular basis.

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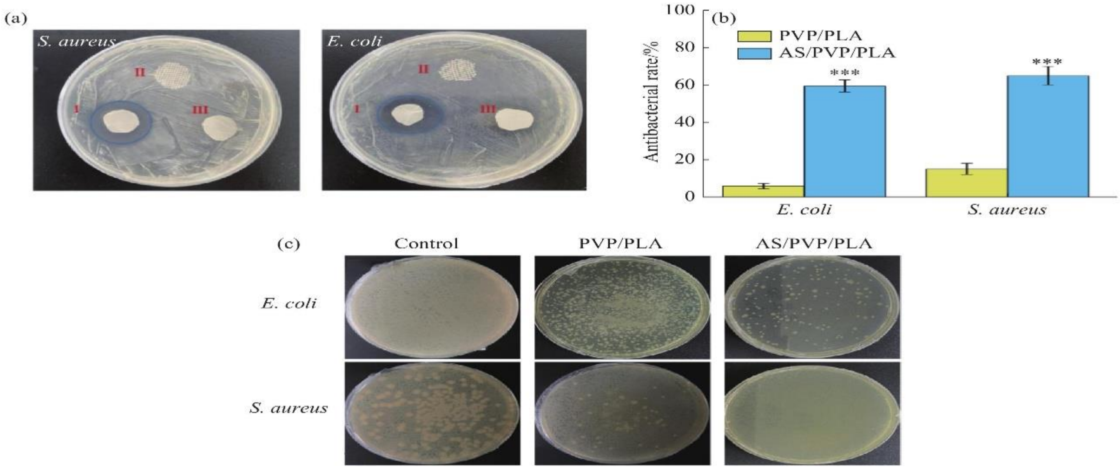
9. Use of Food Packaging

- The created bioplastic films were used to wrap fresh tomatoes.
- During storage, shelf-life, weight loss, microbiological growth, and visual quality were tracked.

10. Analysis of Statistics

- Every experiment was carried out in triplicate.
- One-way ANOVA was used to evaluate the data at a significance threshold of $p < 0.05$.

Results and Discussion



When compared to the control film, the created smart plant-based bioplastic films reinforced with nanocellulose and natural plant extracts showed notable improvements in mechanical, barrier, and biological properties. The addition of clove extract (T_4) showed the highest antibacterial and antioxidant properties, whereas the addition of 3% nanocellulose (T_2) offered the best balance between strength and flexibility. The created bioplastic films successfully decreased weight loss and microbiological deterioration, prolonging shelf life, according to food-packaging testing using fresh tomatoes. These results imply that sustainable, biodegradable, and active packaging materials appropriate for food applications can be created by combining nanocellulose with natural plant extracts.

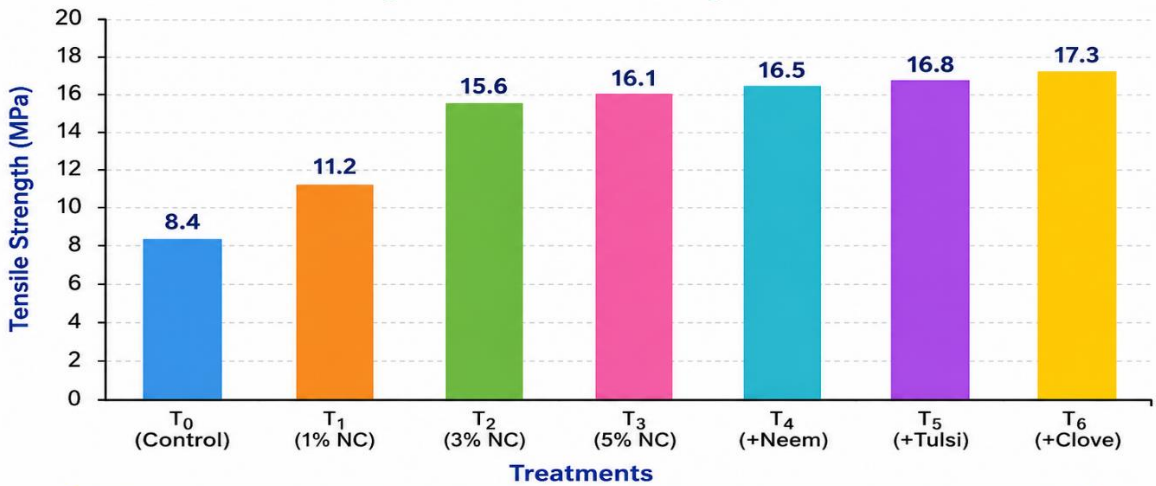
Table 1. Experimental Results of Smart Plant-Based Bioplastic Films

Treatment	Tensile Strength (MPa)	Water Vapor Permeability (g/m²/day)	Antimicrobial Zone (mm)	Antioxidant Activity (%)	Biodegradation (%)	Shelf Life (Days)
T_0 (Control)	8.4	18.5	0	15	72	7
T_1 (1% NC)	11.2	16.4	0	18	75	8
T_2 (3% NC)	15.6	13.2	0	22	78	10
T_3 (5% NC)	16.1	12.8	0	23	80	10
T_4 (3% NC + Neem)	16.5	12.1	14	76	82	12
T_5 (3% NC + Tulsi)	16.8	11.8	17	81	84	13
T_6 (3% NC + Clove)	17.3	10.9	22	91	87	14

Graph 1. Tensile Strength of Bioplastic Films (MPa)

Tensile strength of different bioplastic treatments

Higher values indicate stronger films.



Observation: Tensile strength increased steadily with nanocellulose reinforcement, reaching the highest value in T_6 (17.3 MPa).

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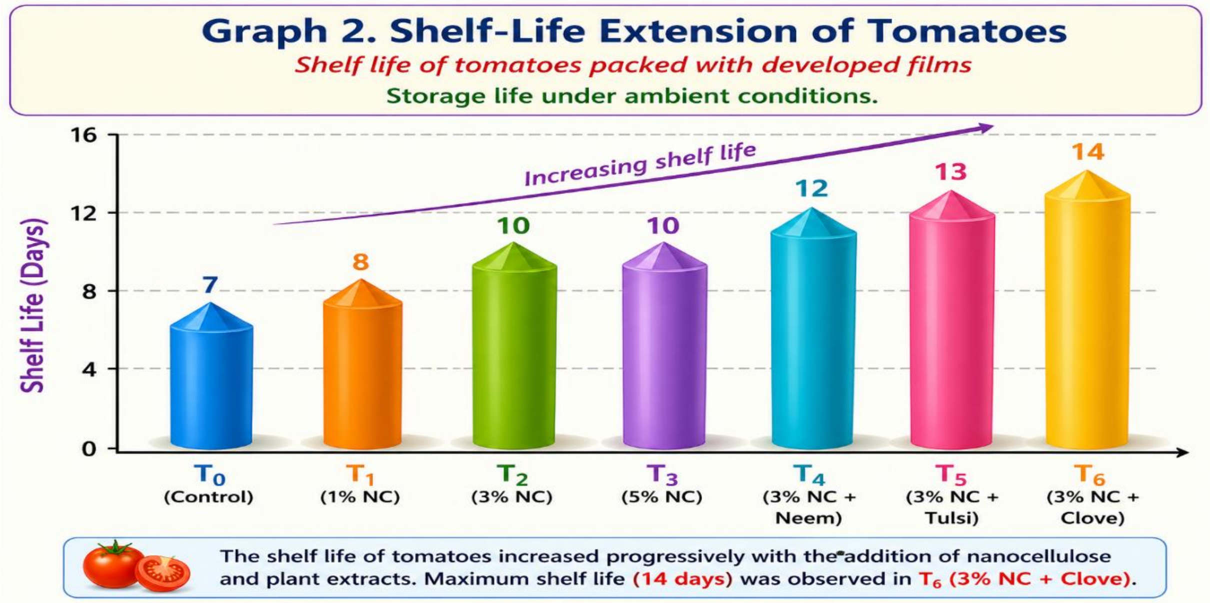

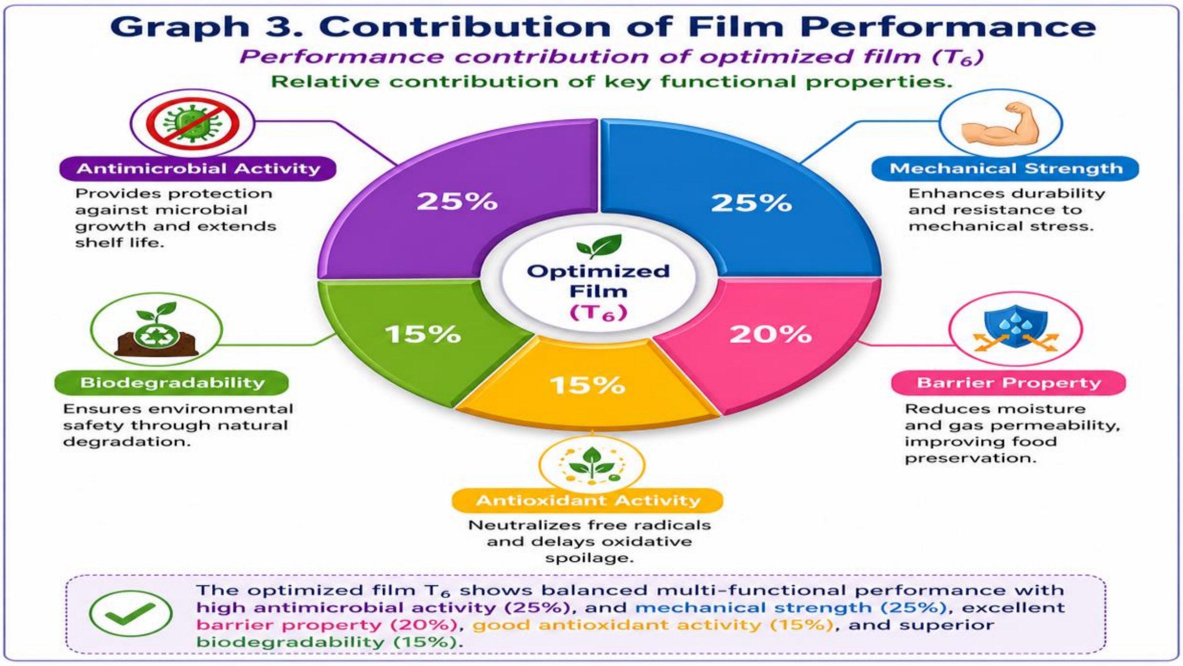

Discussion

The findings show that the mechanical strength and barrier qualities of the starch-based bioplastic films were significantly improved by nanocellulose reinforcement. Strong antibacterial and antioxidant properties were added by the use of natural plant extracts, which enhanced food preservation. With 17.3 MPa tensile strength, a 22 mm antimicrobial inhibition zone, 91% antioxidant activity, 87% biodegradation after 60 days, and an increased tomato shelf life of 14 days, T— (3% nanocellulose + clove extract) showed the best overall performance among all formulations. These results encourage the use of multipurpose plant-based bioplastics as environmentally friendly substitutes for traditional petroleum-based food packaging materials.

Conclusion

Nanocellulose and natural plant extracts were used, the resulting smart plant-based bioplastic sheets demonstrated enhanced mechanical strength, antibacterial activity, and biodegradability. By increasing the tomatoes' shelf life by up to 14 days, T— (3% nanocellulose + clove extract) demonstrated the highest overall efficacy among all treatments. These results show that the created bioplastic films offer an environmentally benign, sustainable substitute for traditional plastic food packaging.

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