

Effect of starch concentration in PBAT–nanoclay biodegradable films on shelf-life extension of fresh produce under ambient storage

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Abstract: Purpose: This study aimed to develop and evaluate PBAT-based biodegradable composite films incorporating modified potato starch (MPS) and nanoclay for improving the shelf life of fresh produce under ambient storage conditions. Biodegradable films were prepared using poly (butylene adipate-co-terephthalate) (PBAT), MPS, glycerol, and nanoclay through extrusion followed by blown film processing. Four formulations were developed: T₀ (pure PBAT as control) and T₁–T₃ containing varying levels of MPS (5%–15%) along with constant nanoclay (3%) and glycerol (30%). The films were evaluated for preservation of green chili, tomato, and banana by analyzing weight loss, color, texture, and aroma over storage periods of 14 to 25 days under ambient conditions. The results demonstrated that on day 25, weight loss of green chili was 39.41%, 43.14%, 44.66%, and 48.89% for T₀, T₁, T₂, and T₃, respectively, compared with 74.40% under open-atmosphere conditions. Thus, all biodegradable film treatments reduced weight loss compared with the open-atmosphere condition. Among all formulations, T₃ (85:15 PBAT: MPS) showed the best performance, reducing weight loss by 33%–56% and effectively maintaining color, texture, and aroma of the produce. The improved performance is attributed to the combined effect of starch and nanoclay in enhancing moisture retention and delaying deterioration. The developed PBAT–starch–nanoclay composite films offer a sustainable and effective alternative to conventional plastic packaging for short-to medium-term storage of fresh produce. The study highlights the advantage of using a single biodegradable film system across multiple commodities, demonstrating its practical applicability in postharvest preservation.

Keywords: green chili, weight loss, postharvest preservation, sustainable packaging, biodegradable films, and nanoclay

Citation: Adsare, A. D., R. N. Shukla, and G. Immanuel. 2026. Effect of Starch Concentration in PBAT – Nanoclay Biodegradable Films on Shelf-Life Extension of Fresh Produce under Ambient Storage. *Agricultural Engineering International: CIGR Journal*, 28(3): 235-244.

1 Introduction

The sustainability of the environment is seriously threatened by the quick buildup of non-biodegradable plastic trash, especially from single use packaging. Because of their advantageous mechanical and barrier qualities, traditional petroleum-based polymers like

polyethylene (PE) and polypropylene (PP) are frequently employed in food packaging (Moshood et al., 2022). Their inability to decompose and recycling difficulties, however, greatly increase pollution on land and in the ocean. Eco-friendly, biodegradable packaging options that can provide both practical and environmental advantages are therefore becoming

Received date: 2025-08-18 **Accepted date:** 2026-04-03

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more and more popular (Ncube et al., 2020).

A flexible, biodegradable copolyester, poly (butylene adipate-co-terephthalate) (PBAT) has become a viable option for environmentally friendly packaging because of its superior mechanical qualities and biodegradability (Burford et al., 2023). However, by combining it with natural polymers like thermoplastic starch (TPS), which is made from renewable agricultural sources like potato starch, its high cost and limited barrier qualities can be overcome. Although TPS is inexpensive, biodegradable and compatible with other polymers, its hydrophilic nature necessitates the use of plasticizers, such as glycerol, to improve flexibility and processability (Bulatović et al., 2021; Othman et al., 2024).

A lot of research has been done on nanofillers such as nanoclay to further enhance film performance. When evenly distributed throughout a polymer matrix, nanoclays layered silicates significantly improve mechanical, thermal and barrier qualities. They prolong the shelf life of packaged fresh products by forming a convoluted pathway that prevents the transport of gases and moisture (Dharini et al., 2022). Food preservation is improved when nanoclay is added to starch or biopolymer-based films because it lowers microbiological activity and reduces the rate at which water vapor is transmitted (Ahari et al., 2021; Jamróz et al., 2019).

This study is innovative because it thoroughly evaluates PBAT/starch films with nanoclay for a variety of horticulture products with the goal of creating an affordable, environmentally friendly packaging option that can be used to store perishable fruits and vegetables for short to medium term periods of time (Basavegowda and Baek, 2021; Venkatesan et al., 2024).

Despite significant progress in the development of biodegradable polymer blends and nanocomposite films for food packaging, most previous studies have primarily focused on material characterization, such as mechanical, thermal, and barrier properties, under controlled laboratory conditions. Limited research has

been conducted on the real-time application of such films for postharvest storage of fresh produce under ambient conditions, particularly across multiple commodity types. In addition, many studies evaluate packaging performance on a single fruit or vegetable, which restricts the broader applicability of the developed materials.

Furthermore, although nanoclay and starch have been individually reported to improve the functional properties of polymeric films, there is a lack of systematic studies investigating the combined effect of modified potato starch and nanoclay in PBAT-based films, especially in terms of their practical performance in reducing weight loss and preserving sensory attributes during storage.

Therefore, the present study aims to address these gaps by developing PBAT-based biodegradable composite films incorporating modified potato starch and nanoclay, and evaluating their effectiveness in extending the shelf life of multiple fresh produce types (banana, tomato, and green chili) under ambient storage conditions.

The novelty of this work lies in the evaluation of a single biodegradable composite film system across different categories of fresh produce under real storage conditions, demonstrating its practical applicability as a sustainable alternative to conventional plastic packaging. Unlike previous studies that focus mainly on material properties, this research emphasizes functional performance in terms of weight loss reduction and retention of quality attributes, providing a more application-oriented approach to biodegradable packaging development.

2 Materials and methods

The supplier of poly (butylene adipate-co-terephthalate) (PBAT) was TGP Chemical Industry Pvt. Ltd., located in Satara, Maharashtra, India. Loba Chemie Pvt. Ltd., located in Mumbai, India, provided the analytical grade glycerol (purity 99%), nanoclay, and modified potato starch (MPS).

2.1 Preparation of biodegradable composite blends

A co-rotating twin screw extruder (Make: RKP

Drives India Pvt. Ltd. Model: 16.5/7.5/1.0) was used to create blends of biodegradable film quality. Modified potato starch (MPS) served as the bio-filler, nanoclay as the nano-reinforcement, glycerol as the plasticizer, and PBAT as the base polymer. Different PBAT: MPS weight ratios were used to prepare four formulations: T₀ (100:0), T₁ (95:5), T₂ (90:10), and T₃ (85:15). T₀ served as the control sample consisting of neat PBAT without glycerol, starch, or nanoclay, whereas T₁– T₃ were composite films containing modified potato starch (5%–15%), nanoclay (3%), and glycerol (30%). Glycerol was used as a plasticizer and nanoclay as a nano-reinforcement in the composite formulations (T₁– T₃). To ensure the uniform mixing and dispersion of all ingredients, the extruders barrel temperature was progressively raised during melt blending from 70°C in the feed zone to 150°C at the die zone. The screw speed was kept constant at 240 rpm. After being extruded, the strands were cooled, pelletized (Make: KBM Extrusion Pvt. Ltd. Model: SKJ2-350B) and kept for later use in airtight, sealed containers.

2.2 Film fabrication

A blown film extruder (Make: Rashions International FZE, Model: NE GIAR) operating on a laboratory scale was used to convert the composite pellets into thin films. To guarantee even melting and consistent film creation, the temperature was adjusted between 130°C and 160°C in each of the extruder barrels four heating zones. For further testing and characterization, the blown films were gathered, let to come to room temperature, and then placed in desiccators.

2.3 Experimental design

The study was designed to evaluate the effect of biodegradable film formulations on the shelf life of selected fresh produce under ambient storage conditions. Three types of horticultural produce, namely banana, tomato, and green chili, were selected based on their perishability and commercial relevance. For each treatment (Open atmosphere, LDPE, T₀, T₁, T₂, and T₃), uniform and defect-free samples were selected and divided into groups. Each treatment

consisted of three independent replicates, with each replicate containing a fixed number of samples (e.g., 5–10 fruits per replicate).

The packaged samples were stored under ambient conditions (temperature: ~25°C–30°C; relative humidity: 60%–70%) and evaluated periodically for changes in weight, color, texture, and aroma over storage durations of 14 days (banana), 18 days (tomato), and 25 days (green chili).

2.4 Weight loss percentage

Weight loss was calculated by weighing samples on a regular basis. A and D Company Ltd.'s digital balance (model FZ-300i, San Jose, CA, USA) was used to measure the weight (Sanad Alsbu et al., 2023). The weight loss percentage was calculated by Equation (1).

$$\text{Weight Loss (\%)} = [(\text{Initial Weight} - \text{Final Weight}) / \text{Initial Weight}] \times 100 \quad (1)$$

2.5 Colour

The visual examination of stored fruits and vegetables under natural daylight at 3- to 5-day intervals was used to assess color changes. A trained panel of five people evaluated discoloration, reddening or browning and recorded visual variations across treatments (Bodaghi, 2024).

2.6 Texture

Firmness was determined by evaluating texture using finger pressure and hand feel. Firm (unaltered), Moderately Soft, and Very Soft/Decayed were the three categories used to describe texture deterioration (Pramudya and Seo, 2019). Even though these qualitative judgments are subjective, they are appropriate for packaging assessments conducted in ambient storage.

2.7 Aroma

An organoleptic assessment of aroma was conducted by a five-member trained sensory panel. Odors such as a rotting, sour or fermented smell were signs of senescence or microbiological spoiling. The samples were divided into three categories: mild off-odor, strong off-odor and no odor change (Roidoung et al., 2025).

2.8 Statistical analysis

All experiments were conducted in triplicate, and the results are expressed as mean values. Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test to determine significant differences among treatments. Differences between mean values were considered statistically significant at $p < 0.05$. The analysis was carried out using JASP software (version 0.95.4).

3 Results and discussion

In order to evaluate the quality retention and shelf-life extension of bananas, tomatoes and green chilies, the impact of various packaging films on their physical characteristics such as weight loss, color, texture and odor was assessed during storage.

3.1 Banana weight loss percentage

The substantial differences in the weight loss percentage of bananas throughout a 14-day storage period between the treatments is displayed in Table 1. With a weight loss of 23.05% by Day 14, bananas kept in an open atmosphere showed the greatest rate of degradation and moisture loss. Likewise, significant weight reductions of 17.25% and 17.36% were observed in the LDPE and T₀ (neat PBAT) treatments, respectively. On the other hand, the weight loss of the nanoclay incorporated biodegradable films (T₁, T₂ and T₃) was significantly less; T₃ had the greatest performance (12.45%), followed by T₂ (13.72%) and T₁ (15.13%).

The improved barrier qualities of the nanoclay filled films, which reduce water vapor permeability and improve in retaining interior moisture, are responsible for this decrease in weight loss. It is well known that the tortuous path effect created by nanoclay layers and the hydrophilic interaction of starch restrict mass transfer and delay transpiration and respiration losses (Ahari et al., 2021). Nath et al. (2022) found similar results that by lowering the moisture and gas exchange rates in packaged products, nanoclay based films greatly extend shelf life. Furthermore, using biopolymer blends with nanofillers efficiently slows down weight loss and improves fruit preservation during storage, according to Basavegowda and Baek (2021), and Perera et al. (2023).

These findings are consistent with previous studies reporting that PBAT-based nanocomposite films reduce moisture loss and delay ripening in climacteric fruits under ambient storage conditions (Nath et al., 2022; Perera et al., 2023).

Statistical analysis (ANOVA) revealed that the differences in weight loss among treatments were significant ($p < 0.05$). The T₃ treatment showed significantly lower weight loss compared to T₀, LDPE, and open atmosphere, indicating superior preservation performance. The progressive reduction in weight loss from T₁ to T₃ also confirms the positive effect of increasing starch content in the presence of nanoclay.

Table 1 Banana weight loss in various packaging films over 14 days

Days	Banana weight loss (%)					
	Open Atmosphere	LDPE	T ₀	T ₁	T ₂	T ₃
3	5.27	2.83	2.16	1.90	1.50	1.11
6	11.42	6.09	6.94	4.72	3.39	2.46
9	17.60	8.92	11.89	7.95	6.16	5.35
12	21.01	14.81	15.56	13.47	11.17	10.81
14	23.05	17.25	17.36	15.13	13.72	12.45

3.2 Physical characteristics of bananas at different treatments during storage

The notable changes in the visual, olfactory and textural qualities of bananas kept in various packaging conditions over a period of 14 days are illustrated in Figure 1. Bananas in LDPE and open atmosphere

treatments ripened and spoiled quickly; by Day 14, they had completely blackened, had a strong fermented odor and had a dissolving texture. Similar to T₀ (neat PBAT film), which showed evidence of fungal growth and significant weakening, it provided only a limited level of protection.

The other hand, T_3 (PBAT/starch/nanoclay composite film) preserved the bananas color integrity throughout storage, exhibiting little browning and no foul odor. Despite being structurally intact, the texture remained soft, suggesting that the use of nanoclay successfully postponed senescence. In addition, T_3 treated bananas maintained a subtle banana scent, in contrast to the sour or fermented smells of the other treatments.

The improved barrier qualities that nanoclay in the polymer matrix provides, which restrict the transmission of oxygen and moisture essential in regulating ethylene activity and microbial spoiling are responsible for this improved preservation. Davis and Clark (2024) found similar results, stating that nanocomposite films dramatically slow down fruit ripening and respiration rates. The findings support the effectiveness of nanoclay reinforced biodegradable coatings in prolonging bananas postharvest shelf life.

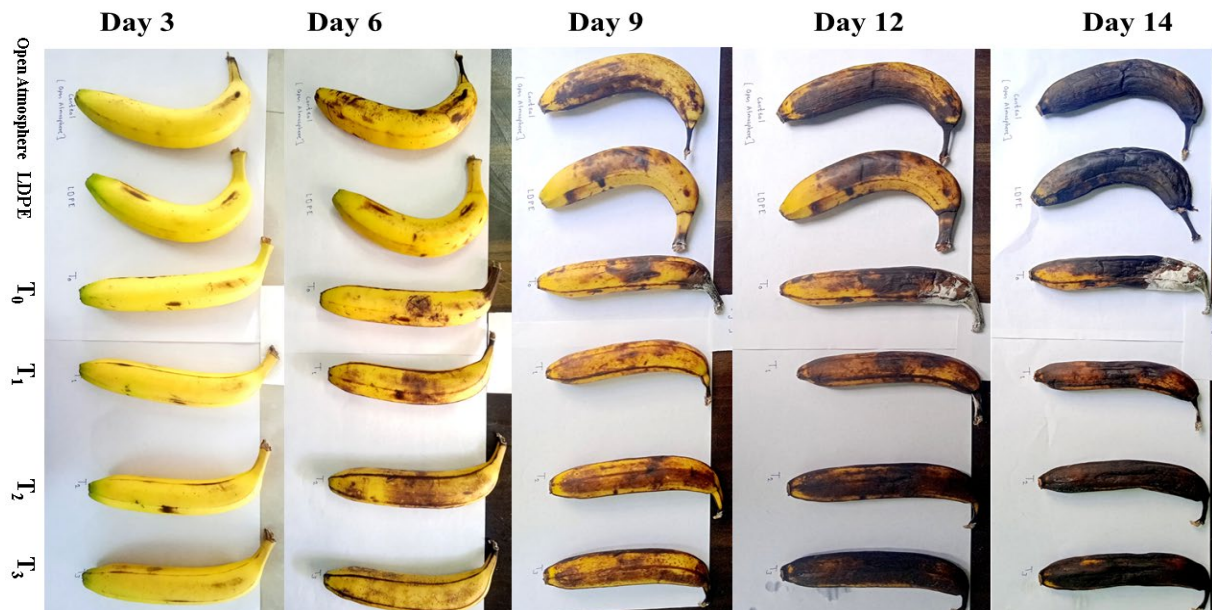


Figure 1 Packaging effects on banana appearance after 14 days of storage

3.3 Tomato weight loss percentage

The weight loss percentage of tomatoes packed under various film treatments over an 18-day period varied significantly, according to the storage research, as shown in Table 2. The tomatoes that were kept in an open atmosphere lost the most weight 24.94% by Day 18. The tomatoes packaged in LDPE and T_0 (pure PBAT) films showed weight losses of 14.79% and 14.08%, respectively, indicating comparatively lower moisture loss during storage. On the other hand, weight loss was successfully reduced by the biodegradable films featuring nanoclay and starch (T_1 , T_2 and T_3). T_3 had the lowest result at 11.26%, followed by T_2 (12.68%) and T_1 (13.47%).

This steady improvement from T_0 to T_3 illustrates how the films barrier qualities are improved by a higher starch and nanoclay content. While nanoclay layers reduce transpiration and respiration losses by creating a convoluted pathway for vapor and gas

transport, starch helps regulate moisture absorption. These results are in line with earlier studies that found that fresh produces moisture loss was considerably decreased by bio nanocomposite sheets. According to Pires et al. (2021), nanoclay enhanced biopolymer films increase the oxygen and water vapor barriers, prolonging the shelf life of perishable goods. Additionally, Karnwal et al. (2025) verified that starch-based films with nanofillers improve turgor and freshness during storage by lowering water permeability.

Similar improvements in shelf life and moisture retention of tomatoes using nanocomposite biodegradable films have been reported by Bodaghi (2024) and Popović et al. (2018), supporting the effectiveness of such materials in postharvest applications.

The differences in weight loss among treatments were found to be statistically significant ($p < 0.05$).

Among the composite films, T₃ exhibited significantly lower weight loss than T₁ and T₂, while all composite

films performed significantly better than T₀ and control conditions.

Table 2 Tomato weight loss under different packaging films over 18 days

Days	Tomato weight loss (%)					
	Open Atmosphere	LDPE	T ₀	T ₁	T ₂	T ₃
3	2.86	1.50	2.01	1.37	0.84	0.74
6	5.62	3.39	3.69	2.94	2.70	1.97
9	9.74	5.35	5.90	5.00	4.30	3.07
12	12.61	7.52	7.52	6.98	5.96	5.42
15	18.05	10.19	10.39	9.75	8.70	8.60
18	24.94	14.79	14.08	13.47	12.68	11.26

3.4 Physical characteristics of tomatoes at different treatments during storage

The physical attributes of cherry tomatoes kept in different packaging circumstances over an 18-day period showed notable variations in quality preservation shown in Figure 2. By Day 18, tomatoes that were kept in LDPE films with an open atmosphere degraded more quickly, turning dark red, smelling fermented and becoming incredibly mushy and shriveled. On the other hand, samples kept in PBAT/starch films with nanoclay added, specifically T₂ and T₃, showed slower ripening, retaining their red but smooth appearance, mild ripe aroma and moderately soft texture, all of which were signs of excellent preservation.

The enhanced gas barrier and moisture retention qualities of the films, which are attributed to nanoclays capacity to generate a convoluted pathway that restricts oxygen transfer and water vapor loss, are probably the cause of the T₂ and T₃ treatments better performance.

This is consistent with earlier research that demonstrated that nanocomposite films might postpone ripening and increase the shelf life of fresh fruit, including strawberries and tomatoes (Bodaghi, 2024; Popović et al., 2018). In addition to preserving firmness and minimizing odor development, the presence of starch and glycerol in combination with nanoclay was important for preserving sensory acceptability throughout storage.

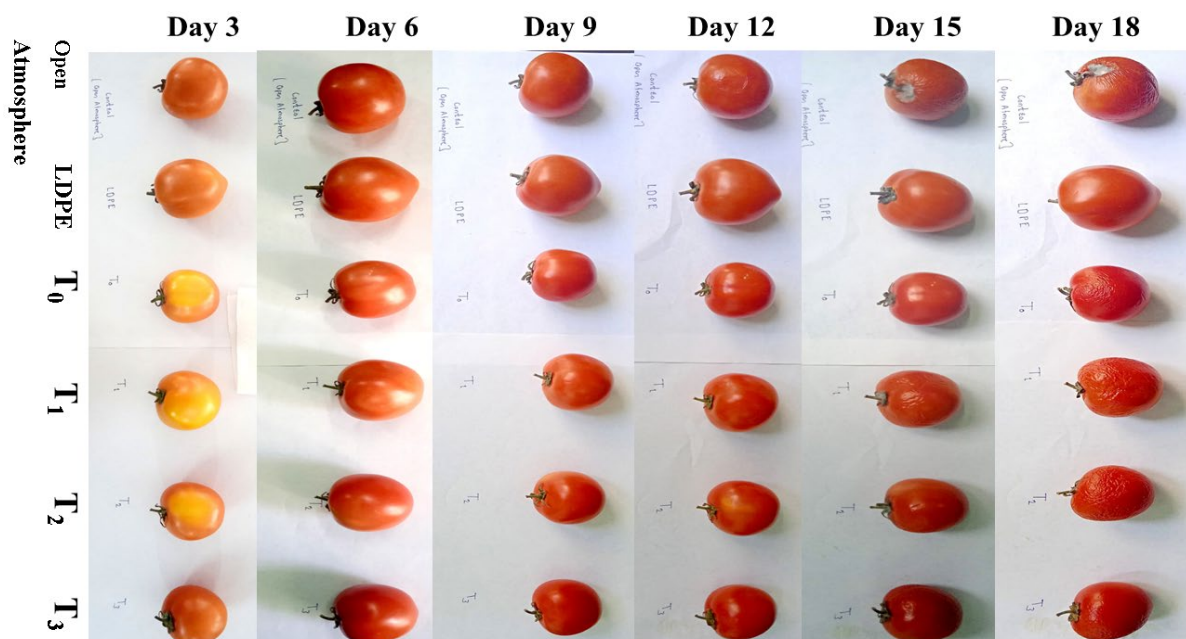


Figure 2 Packaging effects on tomato appearance and quality during 18 days of storage

3.5 Green chilies weight loss percentage

The weight loss of green chilies after a 25-day

storage period varied significantly depending on the packaging procedure, as indicated in Table 3.

Significant moisture evaporation and freshness loss were indicated by the open atmosphere groups quick and steady weight loss, which reached 74.40% by day 25. Comparatively, LDPE packaging decreased this loss to 30.80%, demonstrating its capacity to regulate water vapor permeability to some extent. Nevertheless, depending on their composition, the biodegradable films (T_0 to T_3) showed different effects on the weight loss of fresh green chilies during storage. As presented in Table 3, the weight loss increased progressively with storage duration in all treatments. On day 25, T_0 showed the lowest weight loss among the biodegradable film treatments (39.41%), followed by T_1 (43.14%), T_2 (44.66%), and T_3 (48.89%). Thus, T_0 demonstrated the highest moisture-retention ability among the biodegradable film treatments, whereas T_3 showed the highest weight loss. However, all biodegradable film treatments resulted in lower weight loss than the open-atmosphere treatment (74.40%), indicating that the films reduced moisture loss during storage.

The results suggest that the incorporation of starch and nanoclay into the PBAT matrix influenced the barrier properties of the films; however, the higher starch content in T_3 did not result in improved moisture retention under the conditions of the present study. Therefore, the conclusion regarding the relative moisture-retention performance of T_0 – T_3 should be interpreted based on the observed weight-loss values.

Table 3 Percentage weight loss of green chili stored in different packaging films over 25 days

Days	Chili weight loss (%)					
	Open Atmosphere	LDPE	T_0	T_1	T_2	T_3
3	13.08	1.14	5.47	5.92	6.10	6.35
5	23.52	2.61	10.39	11.65	13.61	15.96
10	44.10	11.61	24.54	26.24	29.14	30.60
15	58.11	17.12	30.07	31.85	36.69	38.61
20	62.30	23.11	34.38	39.52	41.25	44.64
25	74.40	30.80	39.41	43.14	44.66	48.89

3.6 Comparative performance across commodities

The variation in preservation performance across banana, tomato, and green chili can be attributed to

The initial rapid weight loss in an open atmosphere (13.08% on day three and 23.52% by day five) was brought on by direct air exposure and a large moisture gradient. The weight loss was limited to 6.35% by day three for the nanocomposite films, which, in contrast, maintained modest initial loss. According to earlier studies, bio-nanocomposite films lower water vapor transfer rate (WVTR) because of the tortuous path mechanism given by nanoclay platelets. This suggests a controlled microenvironment surrounding the product (Long et al., 2023).

The results of this study are corroborated by Venkatesan et al. (2024) and Othman et al. (2024) that starch-based films containing nano-additives enhance moisture barrier qualities and maintain fresh produces firmness. T_3 and other developed films assist produce sustainable packaging choices while extending shelf life for high-respiring crops like green chili.

However, the comparatively higher weight loss observed in green chili aligns with earlier reports indicating that high-respiring vegetables are more difficult to preserve due to rapid moisture loss and metabolic activity (Venkatesan et al., 2024).

Statistical analysis indicated significant differences ($p < 0.05$) in weight loss among all treatments. Although all biodegradable films improved performance compared to open atmosphere, the differences among T_1 , T_2 , and T_3 were less pronounced due to the high respiration rate and moisture loss characteristics of green chili.

their inherent physiological and structural differences. Bananas and tomatoes are climacteric fruits with relatively higher moisture content but slower

transpiration rates compared to green chili, allowing better retention of moisture under packaging conditions. In contrast, green chili exhibits a higher surface area-to-volume ratio, thin skin, and higher respiration rate, leading to rapid moisture loss even under controlled packaging.

Additionally, the effectiveness of biodegradable films depends on the interaction between film barrier properties and commodity-specific characteristics such as respiration rate, cuticle thickness, and water activity. Therefore, although T_3 showed improved performance across all commodities, the magnitude of weight loss reduction was more pronounced in banana and tomato compared to green chili.

3.7 Physical characteristics of green chilies at different treatments during storage

The green chilies kept in various packaging conditions for 25 days were visually analyzed, and the results showed notable variations in physical quality criteria as color, texture and odor (Figure 3). With noticeable shriveling, staining (brownish red) and a strong rotten stench by Day 15, the open atmosphere (control) samples deteriorated the fastest and were no longer fit for consumption by Day 20. By Day 20, the LDPE packed chilies had moderate softening and odor

changes, but they were slightly firmer and discolored more slowly than the open condition.

The biodegradable PBAT/starch-based films (T_0 to T_3) showed improved preservation as the amount of nanoclay and starch increased. By Day 20, there were indications of softening and a slight off-odor, but T_0 and T_1 displayed intermediate retention of quality parameters. Up to Day 20, T_2 packaging successfully maintained its firm structure and green tint with little odor buildup. Over the course of the 25-day period, T_3 remarkably demonstrated the finest preservation, retaining its firm texture, light fresh odor and vivid green to reddish hue.

These results confirm earlier findings that biodegradable films enhanced with plasticizers and nanoclay offer better mechanical and barrier qualities, lowering oxidation, moisture loss and microbial activity while being stored (Bangar et al., 2025). Water vapor and gas barrier qualities are improved by adding starch and nanoclay, which delays ripening and spoiling (Mafe et al., 2025; Roidoung et al., 2025). As a result, the T_3 formulation works very well to extend the green chilies shelf life when stored at room temperature.

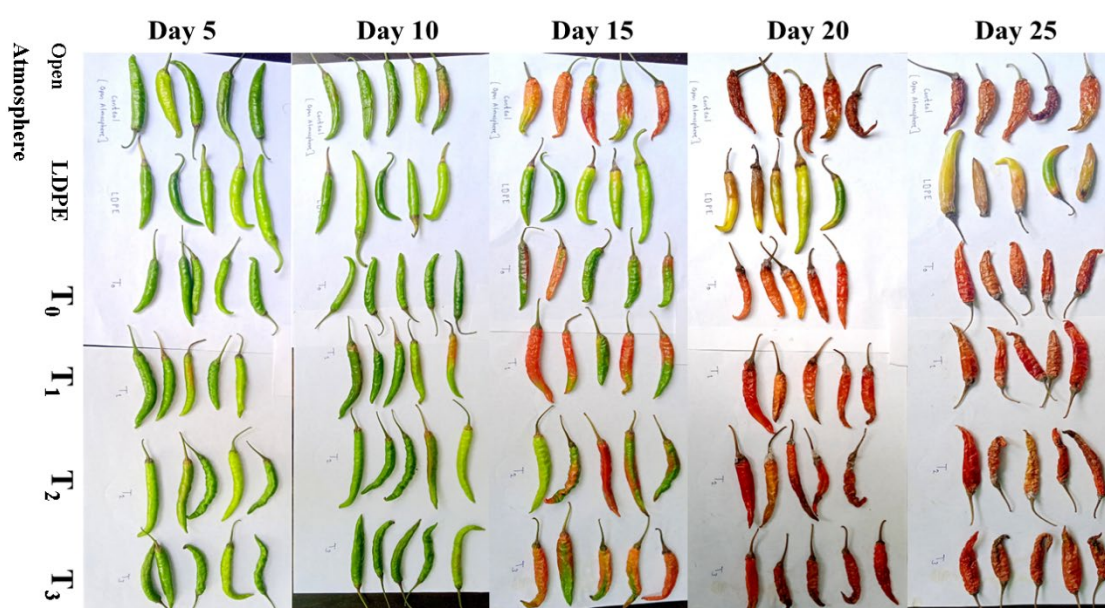


Figure 3 Packaging effects on visual quality of green chilies during 25-day storage

4 Conclusion

The present study demonstrated the successful development and evaluation of PBAT/starch-based

biodegradable composite films incorporating nanoclay for the packaging of perishable fruits and vegetables, including tomato, green chili, and banana. Among the formulations, T_3 (PBAT with 15% modified potato

starch, 3% nanoclay, and 30% glycerol) exhibited the best performance in maintaining physicochemical quality under ambient storage conditions. Compared to open atmosphere storage, T₃ significantly reduced weight loss across all commodities, recording 12.45% for banana (14 days), 11.26% for tomato (18 days), and 48.89% for green chili (25 days), along with improved retention of color, texture, and aroma, indicating delayed senescence and reduced spoilage.

From an industrial perspective, the developed PBAT–starch–nanoclay composite films show strong potential as sustainable alternatives to conventional plastic packaging such as LDPE for fresh produce. The films can be applied in postharvest handling, transportation, and short- to medium-term storage of fruits and vegetables, particularly under ambient conditions prevalent in developing countries. Their biodegradability, combined with effective moisture retention and quality preservation, makes them suitable for reducing postharvest losses and supporting environmentally friendly packaging solutions in the agri-food sector.

The developed PBAT–starch–nanoclay films have potential as sustainable alternatives to LDPE for postharvest handling, transportation, and storage of fresh produce. Their biodegradability and ability to reduce quality deterioration may help minimize postharvest losses. Future research should focus on scaling up the film production process for industrial applications and evaluating cost-effectiveness and process feasibility. Further studies may also explore the incorporation of natural antimicrobial or antioxidant agents to enhance active packaging functionality, as well as detailed analysis of mechanical, barrier, and biodegradation properties under real supply chain conditions.

Funding

“This research was supported by the Chhatrapati Shahu Maharaj National Research Fellowship (CSMNRF) 2023, awarded by the SARTHI Fellowship, Maharashtra Government. The authors

acknowledge the financial assistance provided for conducting this study.”

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