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Innovation in Eco-Friendly, Sustainable Bio-Material for Food Packaging: Characterization of PLA/Banana Fiber/Tulsi Essential Oil Composite Films, A Preliminary Evaluation for Strawberry Preservation

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ABSTRACT

In this work, poly (lactic acid) (PLA)-based composite pellets were first prepared by varying loading rates (5, 10, and 15 wt.%) of banana fibers (BF) by the twin extrusion method. These PLA-based pellets were subsequently used to fabricate composite films via the solution casting route, incorporating 2 wt.% Tulsi essential oil (TEO) as a natural bioactive agent. According to the Fourier Transform Infrared Spectroscopy (FTIR) results, the composite films interactions among the PLA matrix and the additives (BF and TEO) were indeed physical in nature. Particularly, the PLA-based films that were incorporated with 2 wt.% TEO and 10 wt.% BF (PLA/2TEO/10BF) exhibited an increase in tensile strength from 22.1 ± 1.03 to 36.3 ± 0.64 MPa (64.25%) and a corresponding increment in water contact angle (WCA) from 81° to 90° when contrasted with the virgin PLA films. In addition, the PLA/2TEO/10BF composite films demonstrated exceptional flexibility, with an elongation at break of 8.74%, and superior oxygen and water vapor barrier characteristics in comparison with neat PLA films. Compact morphology and uniform distribution of BF were observed in the PLA/2TEO/10BF films through Field Emission Scanning Electron Microscopy (FESEM) analysis. Furthermore, these composites exhibited exceptional inhibiting action against *Staphylococcus aureus* (*S. aureus*) and *Escherichia coli* (*E. coli*). In a preliminary proof-of-concept strawberry storage study, the PLA/2TEO/10BF film exhibited the lowest physiological weight loss (3.27%, 8.85%, and 11.89% at 5, 10, and 15 days, respectively) indicating its promising potential for strawberry preservation.

1 | Introduction

Human diets significantly depend on fruits and vegetables as vital elements, which supply not only calories but also critical nutrients necessary for daily requirements. Even after harvesting, perishable items undergo biological changes such

as transpiration and respiration, which significantly reduce their quality during transit [1]. As per Food and Agriculture Organization of the United Nations reports, more than 40%–50% of global fruits and vegetables deteriorate or become infected prior to consumer purchase [2]. The critical problem underscores the necessity for innovative methods to enhance

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Summary

- Banana fiber and Tulsi essential oil were used to create PLA-based bioactive composite films.
- PLA/2TEO/10BF films demonstrated exceptional flexibility (8.74%) and tensile strength of (36.3 MPa).
- Improved water vapor barrier, oxygen, and hydrophobicity qualities were attained.
- Strong antibacterial activity against *E. coli* and *S. aureus* was noted.
- Strawberries kept for up to 10 days when wrapped with PLA/2TEO/10BF films.

the durability of these items. Microbial infection and lipid deterioration are the primary factors contributing to food degradation, posing significant challenges for the food industry [3]. Enhancing the functionality of food packaging also requires constant improvements in the characteristics of polymer materials. In order to increase food shelf life while ensuring human health safety, efforts are concentrated on improving properties such as printability, mechanical, and barrier features of packaging materials. Industries aim to manufacture very thin films in order to decrease material and manufacturing costs, alongside minimizing the environmental effects caused by packaging disposal [4]. Current research is increasingly concentrating on the advancement of active packaging materials to prevent food spoilage problems like rancidity, nutrient loss, dehydration, microbial growth, and the formation of odors or senescence [5]. Simultaneously, thermoplastic polymers have a vital function in numerous sectors, such as aerospace and medicine. The benefits of plastics compared with their metal equivalents include versatility, mass production capabilities, affordability, flexibility, longevity, and the ability to resist water damage [6]. Most food packaging polymers are made from non-biodegradable materials that resist natural decomposition processes. The breakdown of plastic waste in landfills and the environment results in plastic pollution, which harms ecosystems and wildlife, and also contributes to microplastics tiny plastic fragments that increase environmental and potential health risks [7]. The usage of bio-based polymers has several environmental benefits, including a decrease in dependence on fossil fuels, the ability to break down naturally, a lower carbon impact, the efficient use of sustainable resources, and the potential to participate in a circular economy.

Among the different biopolymers, PLA has attracted a lot of interest because it is biodegradable, compostable, and derived from renewable agricultural resources like corn, rice, wheat, and sugarcane [8]. The manufacture of PLA presents multiple benefits, such as substantial energy conservation, the capacity for recycling into lactic acid, compatibility with degradable hybrid paper-plastic packaging, diminished landfill waste, and potential enhancements to the agricultural economy [9]. Moreover, PLA's physical characteristics may be customized by material modifications, facilitating its use across many sectors. PLA demonstrates beneficial properties, such as excellent transparency, exceptional tensile strength, stiffness, and

a glossy surface, making it a promising material for food packaging applications [10]. However, it also exhibits drawbacks including low thermal distortion temperature, decreased melt viscosity, and brittleness, which can limit its use in some applications [11]. In food packaging, attributes including antibacterial efficacy, as well as barrier and mechanical improvements, are especially significant. Recent developments have shown that the characteristics of PLA may be substantially enhanced and tailored for specific purposes by the integration of appropriate fillers and the optimization of processing parameters [12]. In order to resolve these concerns, researchers have explored the incorporation of PLA with other additives, such as nanoparticles, natural substances, agricultural by-products, and other bio-based polymers [13–15]. The potential for nanotechnology to enhance the quality and safety of food, while simultaneously reducing the generation of packaging waste and the consumption of basic materials, has emerged as a promising approach in food packaging. This modification has demonstrated substantial improvements in the structural, mechanical, and functional characteristics of PLA composites, making them promising for food packaging applications [16]. Developments in PLA-based composites not only address food spoilage challenges but also align with the growing customer and industrial need for ecologically conscious solution for packaging [17]. This study examines the possibility of PLA-based biodegradable composites in food packaging, highlighting their capacity to prolong shelf life, mitigate environmental effect, and tackle the two-pronged problem of food deterioration and waste management for plastics. This research also examines the emergence of antimicrobial packaging films for food packaging applications. Agriculture is a primary occupation in the Indian subcontinent, and incorporating agricultural products into the antibacterial flexible packaging market offers mutual benefits for both farmers and the packaging industry [18]. Farmers can contribute to sustainable packaging solutions while gaining economic opportunities, and packaging industries can leverage natural resources to create eco-friendly products. Recent studies have demonstrated that the incorporation of natural fibers and plant-derived essential oils can significantly enhance the performance of biodegradable packaging materials [19]. Srivastava et al. (2024) developed starch-based biocomposite films reinforced with rice husk fiber (10–50 wt.%) and peppermint essential oil (PEO, 1–6 wt.%). The film containing 10 wt.% rice husk fiber and 1 wt.% PEO exhibited the highest tensile strength (2.25 MPa) and elastic modulus (57.4 MPa). Furthermore, the developed films effectively extended the shelf life of bread by suppressing the growth of food-borne microorganisms, demonstrating their potential for active food packaging applications [20]. In another study, Srivastava et al. (2024) fabricated starch-based active biocomposite films reinforced with sugarcane bagasse fiber (SBF) and menthol-encapsulated powder (MEP) for fresh-cut food packaging. The formulation containing 20 wt.% SBF and 1 wt.% MEP exhibited the optimum combination of mechanical, physical, barrier, and thermal properties. These studies highlight the synergistic role of natural fibers and bio-active compounds in improving the functional performance of biodegradable packaging materials and underscore the potential of developing sustainable active packaging systems using renewable resources [21]. This work specifically explores Tulsi (*Ocimum sanctum*) essential oil, recognized for its

TABLE 1 | Comparison of recently reported biopolymer based natural fiber/essential oil composite films for active food packaging applications.

Polymer matrix	Natural fiber or fillers	Essential oil/ active agent	Fabrication method	Key findings	Food packaging application	References
PBAT	Graphitic carbon nitride/ multiwalled carbon nanotubes	—	Solution casting	The optimal film extended shelf life from 1 to 18 days, reduced weight loss, and improved vitamin C retention.	Green Grapes	[22]
PLA/PBAT	SiO ₂ /TiO ₂ and ZnO	Cardanol oil	Film casting method	Incorporation of 1 wt.% ZnO, TiO ₂ , and SiO ₂ with 5 wt.% cardanol oil enhanced the tensile strength and elongation of the composite films.	Not evaluated	[23]
Poly (3-hydroxybutyrate) (PHB)	MgO nanoparticles	Grapeseed oil	Sonication-assisted solution casting technique	The developed films proved beneficial effects in terms of extending the shelf-life of white button mushrooms up to 6 days at ambient room conditions	White button mushrooms	[24]
Poly (3-hydroxybutyrate)	—	Grapeseed oil (GS), bergamot oil (BG), and ginger oil (GG)	Solution casting technique	PHB/essential oil composites demonstrated good UV-blocking properties without affecting its transparency	Not evaluated	[25]
Corn starch	Rice husk fiber	Peppermint essential oil	Solution casting	Improved tensile strength; extended bread shelf life	Bread packaging	[20]

(Continues)

TABLE 1 | (CONTINUED)

Polymer matrix	Natural fiber or fillers	Essential oil/ active agent	Fabrication method	Key findings	Food packaging application	References
Corn starch	Sugarcane bagasse fiber	Menthol encapsulated powder	Solution casting	Improved mechanical, barrier, and thermal properties	Fresh-cut apples	[21]
PLA	Curcumin	Fenugreek essential oil	Solution casting	Better antibacterial and anti-oxidant properties	Strawberry	[26]

potent antimicrobial activity, as a bioactive constituent in the development of active packaging materials [19]. Recently reported studies on essential oil-based biopolymer systems are summarized in Table 1.

Strawberries (*Fragaria × ananassa*) are highly nutritious fruits, known for their rich level of fiber, vitamins (particularly vitamin C), minerals, antioxidants, and bioactive compounds including polyphenols and flavonoids. These attributes make strawberries a popular choice among consumers for their health benefits and appealing taste. Nevertheless, their short shelf life of 3–7 days under ambient conditions greatly restricts their economic viability [27]. This limitation is a result of their high respiratory rate, sensitivity to microbial contamination, and quick degradation, which includes changes in color and stiffness. Because of these difficulties, strawberries were chosen in order to assess the effectiveness of the active food packaging material that was developed. Studies were conducted to determine the shelf life of fruits at ambient temperatures, with an emphasis on their quality preservation over time. These results give light on the potential use of biodegradable packaging for prolonging the storage life of foods with a short shelf life, like strawberries.

The objective of this work was to develop PLA-based composite active packaging films using varying weight percentages of BF (5, 10, and 15 wt.%) and 2 wt.% of Tulsi essential oil (TEO) through the use of melt blending and solution casting methods. The prepared films were characterized using FESEM and FTIR. Additionally, tensile, antimicrobial, barrier properties, and food quality tests were conducted.

2 | Materials and Methods

2.1 | Materials

PLA pellets, labeled as PLA 4032D, with a density of 1.24 g/cm³, were obtained from Nature Works LLC (United States). Chloroform and Luria Bertani were procured from Hi-Media Laboratories Pvt. Ltd., India. TEO was acquired from All Naturals Ltd., India. All chemicals were utilized as received.

Raw BF were obtained from a fiber source in Chennai, Tamil Nadu, India. The strawberries of similar maturity and size, with no visible defects, were acquired from the regional market in Chennai, India.

2.2 | Pre-Treatment of BF

Initially, the BF strands were sliced into small pieces, typically ranging in length from 250 to 500 μm. These BFs were then soaked in water for 24 h to remove most of impurities, including pith, followed by drying at room temperature for another 24 h to eliminate residual moisture and volatile substances. After being dried in an oven at 90°C for 6 h, the fibers were screened through sieves with a mesh number of 60.

To enhance the surface properties of BF, an alkaline (NaOH) treatment, also known as mercerization, was carried out [28]. For mercerization, 150 g of BF were incubated in the 1000 mL of 5% NaOH solution and allowed to stand for 1 h. The treated fibers were thoroughly rinsed with running tap water and dried at room temperature for 24 h, followed by further drying in a hot air oven at 90°C for 6 h. Finally, the treated BF were stored in a desiccator containing a drying agent to prevent moisture absorption until further use.

2.3 | Preparation of PLA/BF Composite Pellets

The PLA pellets and alkali-treated BF, varying in weight percentages of 5, 10, and 15 wt.%, were introduced into the hopper of a twin screw extruder. The optimized screw speed was set at 100 rpm, while the thermal profile was adjusted from 150°C in the feeding zone to 190°C (TP1) and 210°C (TP2) at the die, respectively. The bio-composite wire was obtained in the process called extrusion injection molding [29]. The bio-composite strands underwent cooling by passing through water. Subsequently, the material was transformed into pellets utilizing a pelletizer, achieving a size range of 3–5 mm. The schematic illustrating the preparation of PLA/BF composite pellets is presented in Figure 1.

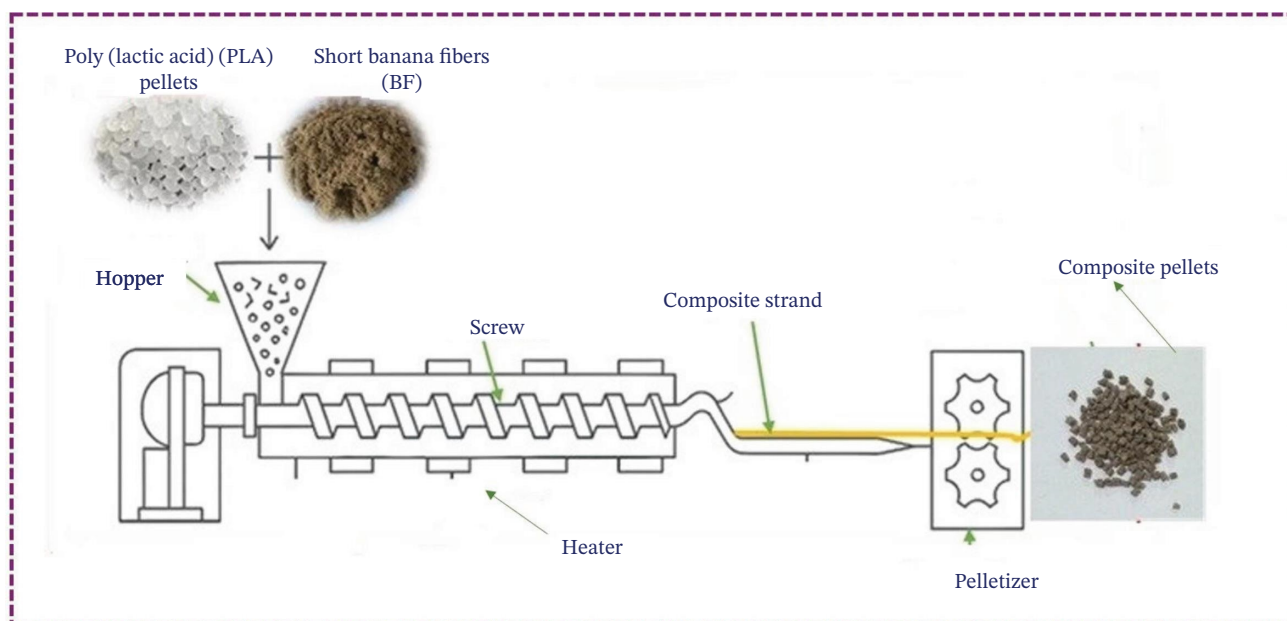


FIGURE 1 | Schematic showing the preparation of PLA/BF composite pellets.

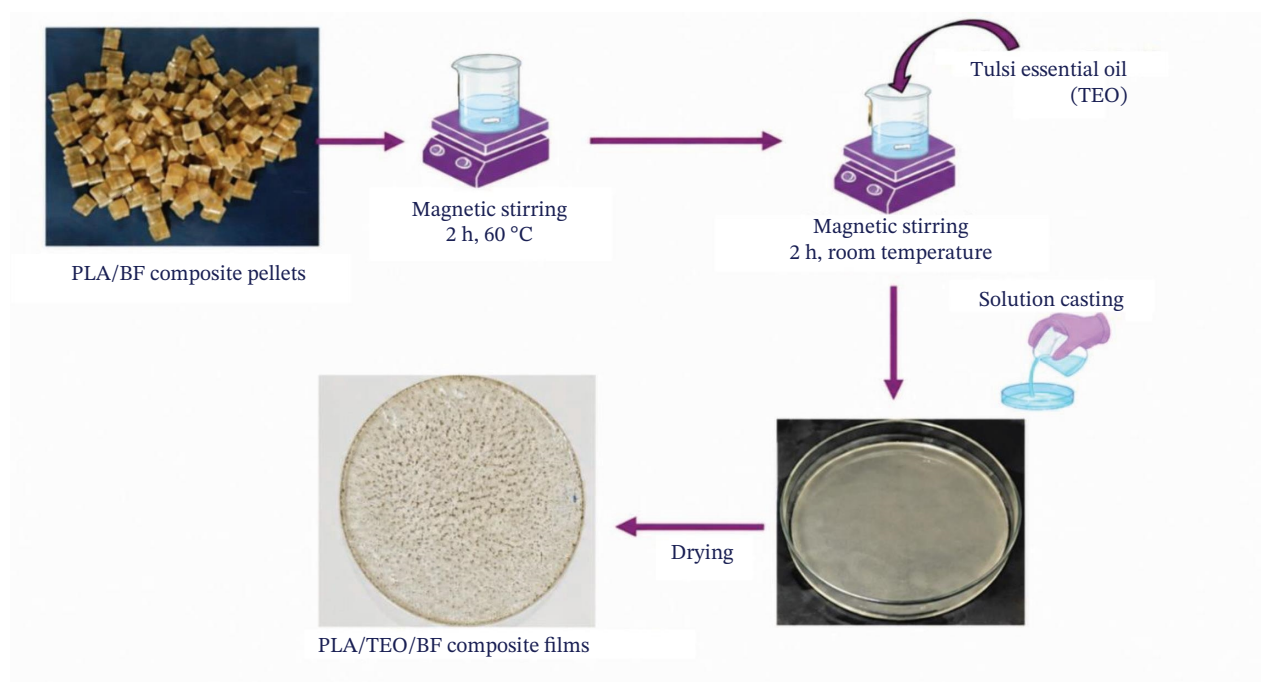


FIGURE 2 | Schematic showing the preparation of PLA/TEO/BF composite films.

2.4 | Development of PLA/TEO/BF Composite Films

The PLA-based composite films with 2wt.% of TEO and 5, 10, and 15wt.% of BF were fabricated via the solution casting method (Figure 2). In the present study, the TEO content was fixed at 2wt.% in all formulations to provide antimicrobial functionality. Initially, 2g of PLA/BF composite pellets was dissolved in 20mL of chloroform through constant stirring for 2h at 60°C under reflux conditions. After that, precisely measured TEO was added to the PLA/BF mixture and then agitated at 300rpm for 2h at ambient temperature. The next step was to pour the mixture onto petri dishes made of glass

and to let it sit undisturbed so that the solvent might evaporate. PLA films prepared without essential oil and BF were utilized as a control in this study, and indicated as neat PLA. The composition details of each type of PLA-based film prepared in this study are summarized in Table 2. The prepared PLA-based films were stored in air-tight bags for characterization. Each formulation of the composite films was prepared in a single casting batch. All specimens used for characterization were obtained from the same batch to minimize batch-to-batch variability. The thickness of each film was measured using a digital micrometer at five different locations on each specimen, and the average value was calculated. All films exhibited a

TABLE 2 | Composition of PLA-based films developed in this study.

S. no	Sample code	PLA (wt.%)	TEO (wt.%)	BF (wt.%)
1	PLA	100	—	—
2	PLA/2TEO/5BF	93	2	5
3	PLA/2TEO/10BF	88	2	10
4	PLA/2TEO/15BF	83	2	15

uniform thickness of approximately 0.40 ± 0.02 mm, ensuring consistency for subsequent mechanical and barrier property measurements.

2.5 | Characterization of PLA-Based Films

2.5.1 | Tensile Properties

Tensile testing was conducted on both virgin and composite PLA films according to ASTM D882-12 standard, utilizing an Electromechanical Universal Testing Machine (Zwick Roell, Z005TN, United States). Thickness of films was measured using digital micrometer. The dimensions of the samples utilized in this examination are 80 mm in length, 50 mm in gauge length, and 5 mm in width. The crosshead speed for the measurement was set at 5 mm/min.

2.5.2 | Water Contact Angle

The WCA measurement for various PLA-based films was conducted using a goniometer (Kyowa contact angle meter, DME-211 series, Japan). The water droplet size and image capturing time were fixed as $4\mu\text{L}$ and capture time 40 s, for all the samples. The measurements were conducted on three samples per composition, and the resulting mean values with standard deviations (SDs) were presented.

2.5.3 | Barrier Properties

The oxygen transmission rate (OTR) of virgin and composite (PLA/TEO/BF) films was assessed using Noselab (Make: ATS, Model: PERME OTR 201, Country: Italy) at 23°C as per ASTM D-3985 standard. The water vapor transmission rate (WVTR) of the PLA/TEO/BF composite film was determined using the Lissy L80-5000 water vapor transmission tester (Make: Lyssy, Model: L80-5000, Country: Switzerland). The WVTR tests were carried out following the ASTM F1249-90 standard. Barrier property analysis was conducted on five samples per composition, and the resulting mean values with SDs were presented.

2.5.4 | Physicochemical Properties

Using a FESEM (Zeiss, Sigma 300, Germany), the surface morphology of different PLA-based films was examined. In

order to ensure conductivity, the samples were first coated with a small coating of gold and mounted on stainless steel stubs before imaging.

FTIR was utilized to ascertain the functional groups in the virgin and composite films of PLA, employing a Shimadzu IR Affinity-1 spectrometer from Japan. The FTIR spectra were obtained within the range of $400\text{--}4000\text{ cm}^{-1}$ at a resolution of 4 cm^{-1} , averaging 30 consecutive scans to enhance signal quality.

2.5.5 | Antimicrobial Assay

The antibacterial effectiveness of various PLA-based films made in this study was tested using the zone-of-inhibition method (Adapted from ISO 20645:2004) against Gram-positive bacteria (*Staphylococcus aureus*) and Gram-negative bacteria (*Escherichia coli*) [30]. Film samples were put on agar plates that had been inoculated with the appropriate bacterial strains in order to measure the antibacterial activity. The antibacterial activity of each film sample was assessed by measuring the zone of inhibition, or the width of the clear zone, following a 48-h incubation period at 37°C .

2.6 | Shelf-Life Study of Strawberries

The application potential of PLA/2TEO/10BF composite films was assessed for the packaging and storage of strawberries under ambient room conditions. After being cleaned with tap water, fresh strawberries were wiped clean using a sterile muslin cloth. The fruits were separated into three groups and put in different glass beakers after being thoroughly cleaned. For the shelf-life study, five strawberries were used for each treatment group. Each strawberry was individually packaged using the respective film and stored at $25^\circ\text{C} \pm 2^\circ\text{C}$ under laboratory conditions throughout the storage period. Each set contained four sample groups: (i) unwrapped and exposed to the open environment (control), (ii) wrapped with commercial low-density polyethylene (LDPE) films, (iii) wrapped with virgin PLA films, and (iv) wrapped with PLA/2TEO/10BF composite films. Strawberries were checked for visible spoilage on the first, fifth, ninth, and 12th days of storage. Factors including microbial growth, surface discoloration, as well as physical deterioration (softness or collapse) were monitored to estimate the potential of each type of packaging to maintain the fruit quality and prolong the shelf-life duration.

2.6.1 | Physiological Loss in Weight (PLW, %)

To determine the PLW, strawberry samples from each replication were weighed before storage using a precision electronic balance. The samples were subsequently weighed at 5-day intervals throughout the storage period. The PLW was calculated from the difference between the initial and final fruit weights using the following equation:

$$PLW(\%) = \frac{W_i - W_f}{W_i} \times 100 \quad (1)$$

where W_i is the initial weight of the fruit (g) and W_f is the fruit weight (g) at the respective storage interval.

2.7 | Statistical Analysis

The experimental data were obtained from three technical replicate measurements ($n=3$) from the same casting batch and presented as the mean $\pm$ SD. Statistical analyses were performed using GraphPad Prism version 11.0.2 (92) (GraphPad Prism Software, San Diego, CA, United States). Differences among the

experimental groups were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's multiple comparisons test for pairwise comparisons. A value of $p < 0.05$ was considered statistically significant.

3 | Results and Discussion

3.1 | FESEM Analysis

The morphology of solution-cast polymer composites including essential oils and BF is affected by several factors. These include the physicochemical characteristics of the essential oils, the dimension, structure, and the amount of the BF, the dispersion of these additives throughout the polymer matrix, and the rate of solvent evaporation at the time of drying [31]. Furthermore, the microstructure of these composite films has a direct influence on their optical, barrier, mechanical, and structural properties. The surface morphology of virgin PLA films appeared relatively smooth and uniform, with no visible aggregates, suggesting well-integrated polymer chains, as shown in Figure 3a. The microstructures of the PLA/2TEO/5BF and PLA/2TEO/10BF composite films exhibited compact and uniform surfaces, comparable with that of virgin PLA, with no visible voids or

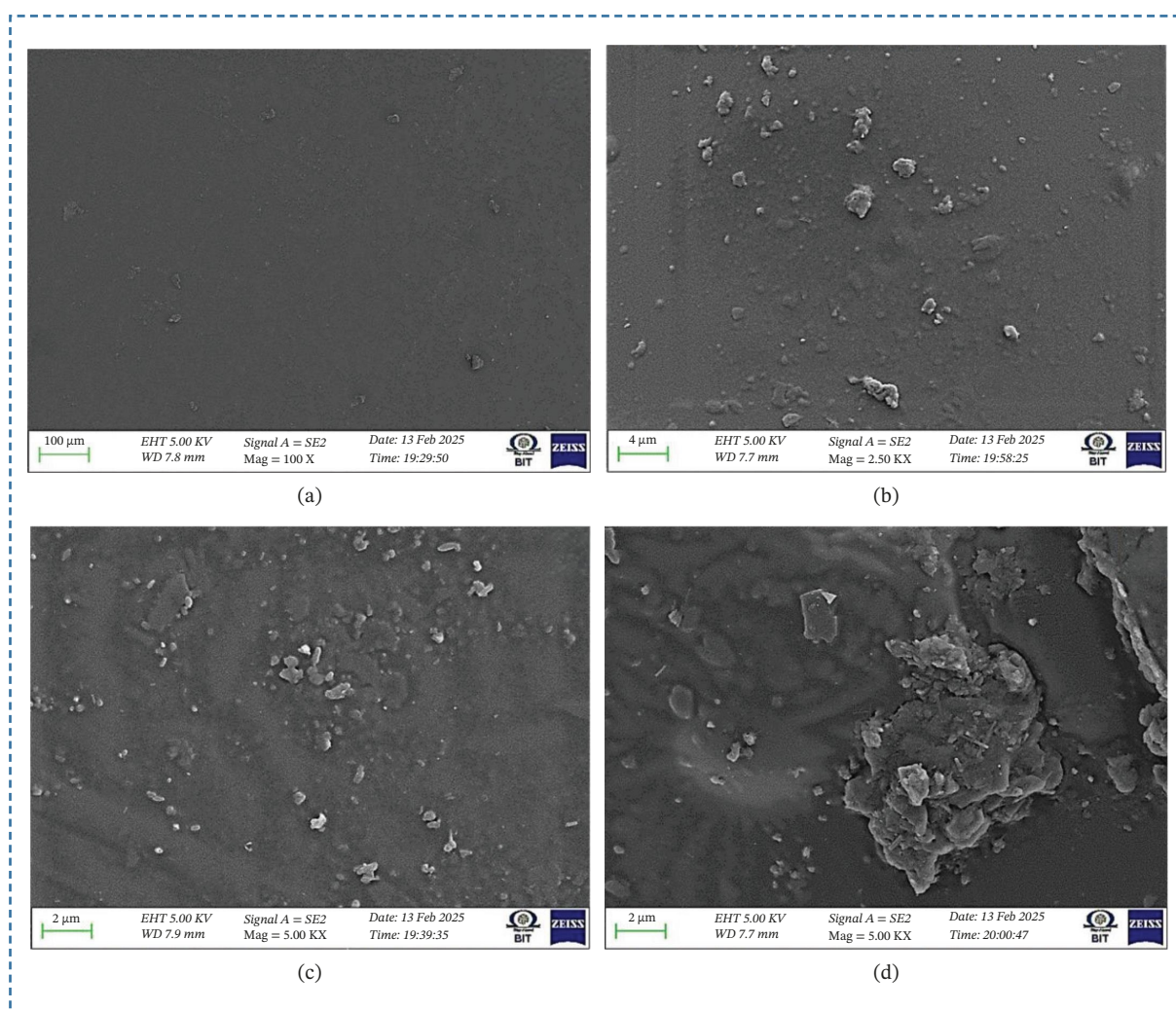


FIGURE 3 | FESEM images of (a) PLA, (b) PLA/2TEO/5BF, (c) PLA/2TEO/10BF, and (d) PLA/2TEO/15BF composite films.

phase separation. This suggests good interfacial compatibility among BF, PLA, and TEO, as shown in Figure 3b,c. In contrast, the FESEM image of the PLA/2TEO/15BF composite film (Figure 3d) revealed noticeable agglomeration of BF, attributed to the overcrowding effect that arises when the filler content exceeds the optimal threshold.

3.2 | Tensile Properties

The tensile properties, such as tensile strength and elongation at break of virgin and composite films of PLA, were presented in Figure 4. The virgin PLA films exhibited a tensile strength of 22.1 ± 1 MPa and lower flexibility with an elongation at break of $2.14\% \pm 0.3\%$. Upon incorporation of 2wt.% TEO and 5wt.% BF, the tensile strength of the composite (PLA/2TEO/5BF) films increased to 27 MPa, indicating efficient interfacial interaction among the PLA matrix and the BF, which contributed to enhanced stress transfer. Moreover, the elongation at break increased to $11.6\% \pm 0.41\%$, which can be attributed to the plasticizing effect of TEO, resulting in increased polymer chain mobility. The tensile strength of the PLA-based composite films reached its maximum value for the PLA/2TEO/10BF samples, recording 36.3 ± 0.64 MPa. One-way ANOVA followed by Tukey's multiple-comparisons test revealed a statistically significant difference among the formulations ($p < 0.0001$). The simultaneous improvement in tensile strength and elongation at break seen in the PLA/2TEO/10BF composite suggests a synergistic reinforcement mechanism. Alkali treatment eliminates surface contaminants, hemicellulose, and a portion of the lignin from banana fibers, enhancing interfacial adhesion to the PLA matrix and enabling efficient stress transmission, which increases tensile strength. Furthermore, the presence of 2wt.% TEO may boost polymer chain mobility while decreasing localized stress concentrations, allowing the composite to

undergo greater deformation before fracture. The homogeneous dispersion of fibers and strong fiber–matrix interfacial bonding further delay crack start and propagation, contributing to an increase in both strength and ductility. The moderate reduction in elongation at break ($8.74\% \pm 0.71\%$) remained within acceptable limits, indicating a good balance between flexibility and tensile strength. However, further enhancing the BF concentration to 15wt.% (PLA/2TEO/15BF) resulted in a decline in tensile strength of PLA-based films to 31.6 ± 1.42 MPa, which could be attributed to fiber agglomeration and potential stress concentration points that act as defects within the matrix. In addition, the elongation at break of these films reduced to $7.52\% \pm 0.9\%$. In general, composite materials that exhibit moderate elongation at break and high tensile strength are appropriate for use in food packaging [32]. The findings of the present study demonstrated that the PLA/2TEO/10BF composite films provide the ideal combination of tensile strength and elongation at break, providing them a viable option for sustainable, biodegradable food packaging applications.

3.3 | Water Contact Angle

WCA analysis was employed to assess the wettability of the PLA and PLA/TEO/BF composite films, as illustrated in Figure 5. In general, a WCA greater than 90° shows a hydrophobic nature of the material, while a WCA less than 90° displays a hydrophilic nature [33]. Figure 5 reveals that the virgin PLA displays a WCA of 81.4° , signifying a moderately hydrophilic surface owing to polar ester functional groups present in PLA. The composite film samples PLA/2TEO/5BF, PLA/2TEO/10BF, and PLA/2TEO/15BF exhibited WCA of 87.8° , 90.1° , and 93.5° , respectively. One-way ANOVA followed by Tukey's multiple-comparisons test indicated significant differences among the formulations ($p < 0.0001$). The

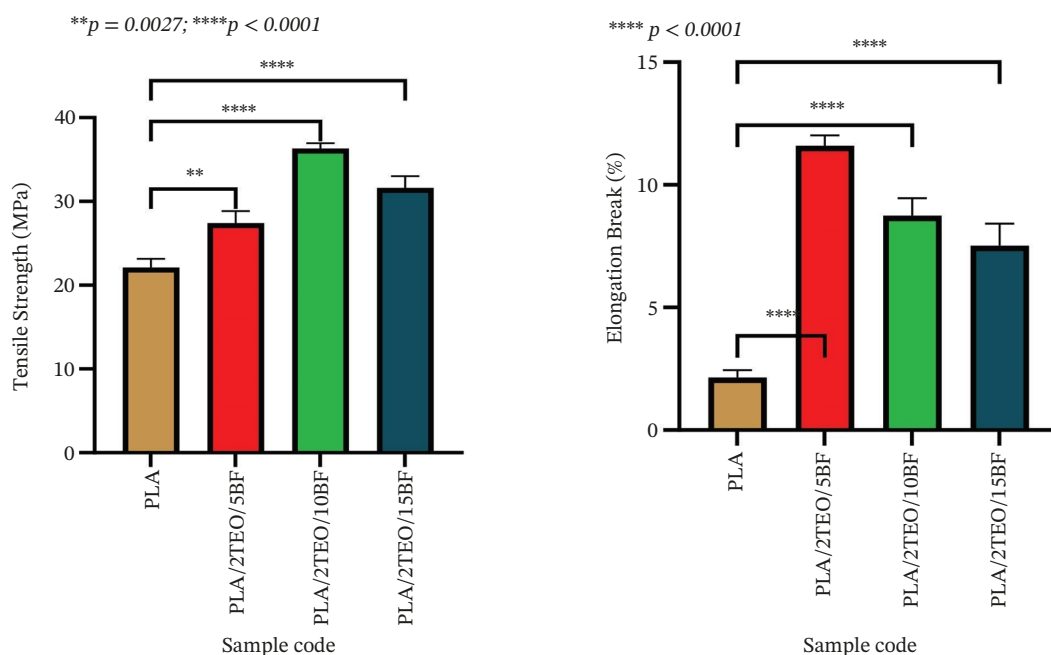


FIGURE 4 | Tensile properties of PLA and PLA/TEO/BF composite films (statistical analysis was performed using one-way ANOVA followed by Tukey's multiple comparisons test. **** indicates $p < 0.0001$ compared with PLA).

enhancement in the WCA of the composite films compared with virgin PLA may be attributed to the incorporation of TEO, which has been reported to contain hydrophobic constituents, such as eugenol and methyl eugenol, depending on its source and composition. These hydrophobic constituents may preferentially migrate toward the film surface during film formation, thereby increasing the surface hydrophobicity [34]. The

use of BF enhances surface roughness, which might entrap air and diminish the solid–liquid surface area, hence increasing the WCA [35]. The PLA/2TEO/10BF and PLA/2TEO/15BF composite films exhibited a WCA above 90°, hence affirming their hydrophobic characteristics. The increase in surface hydrophobicity is advantageous for food packaging applications, since it inhibits moisture intrusion, thereby enhancing food shelf life.

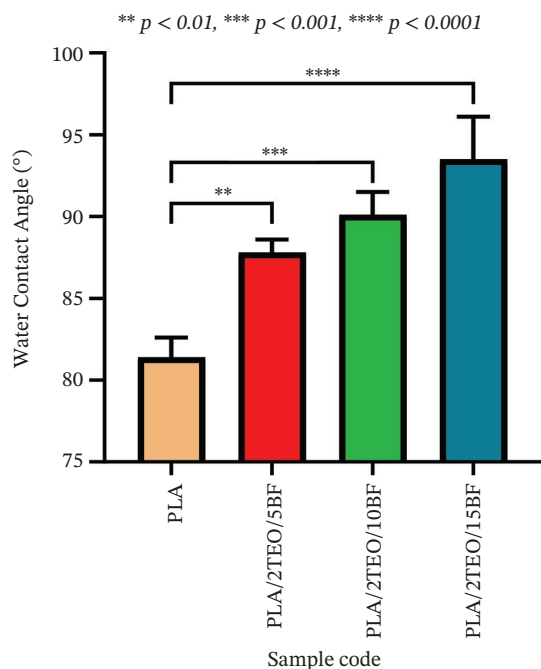


FIGURE 5 | Water contact angle results of PLA and PLA/TEO/BF composite films (statistical analysis was performed using one-way ANOVA followed by Tukey's multiple comparisons test. **** indicates $p < 0.0001$ compared with PLA).

3.4 | Gas Barrier Properties

One essential feature of food packaging materials is the oxygen and water vapor barrier, which keeps moisture and oxygen from the surroundings from getting into the food within. Ideally, food packaging should have minimum permeability to oxygen and water vapor in order to better retain food quality and safety [36]. The OTR and WVTR values of PLA and PLA/TEO/BF composite films were depicted in Figure 6. The PLA films exhibited OTR and WVTR values of $1024 \pm 1.5 \text{ cc/m}^2 \text{ day atm}$ and $113 \pm 2.2 \text{ g/m}^2 \text{ day}$, respectively. Upon incorporating TEO and increasing concentrations of BF, the OTR as well as WVTR values of the PLA-based composite films decreased significantly. The PLA/2TEO/15BF composite films showed the lowest values: $624 \pm 2.5 \text{ cc/m}^2 \text{ day atm}$ (OTR) and $58.1 \pm 2.8 \text{ g/m}^2 \text{ day}$ (WVTR), corresponding to a reduction of approximately 39% and 49%, respectively, compared with neat PLA. One-way ANOVA followed by Tukey's multiple comparisons test indicated statistically significant differences between the PLA control and all BF-containing formulations ($p < 0.0001$). The decrease in WVTR noted in the composite films can be primarily ascribed to the inherent hydrophobic nature of added TEO. The TEO decreases the overall hydrophilicity of the film matrix, thereby restricting the diffusion and permeation of water molecules through the films.

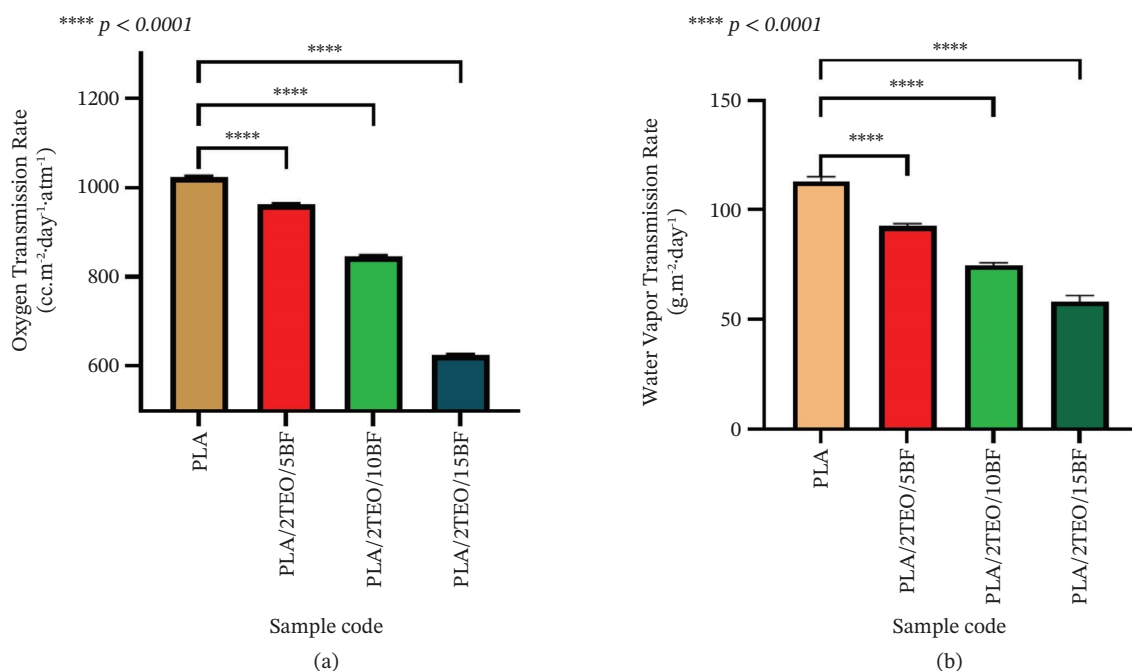


FIGURE 6 | (a) OTR and (b) WVTR results of PLA and PLA/TEO/BF composite films (statistical analysis was performed using one-way ANOVA followed by Tukey's multiple comparisons test. **** indicates $p < 0.0001$ compared with PLA).

Additionally, the incorporation of BF contributes to enhanced barrier performance by introducing a tortuous pathway within the polymer matrix. This increased path length and complexity obstruct the direct permeation of gas molecules, effectively lowering the OTR and WVTR by increasing diffusion resistance [37]. The OTR and WVTR findings from this study have been compared with those of other PLA composites documented in the literature. It is noteworthy to highlight that the PLA-based composite films developed in this study exhibited superior oxygen and water vapor barrier properties compared with the PLA/mesoporous silica/nisin composites [38], PLA/thyme, PLA/rosemary, PLA/myrtle essential oil composites [39], and PLA/oregano essential oil composites [40] that have been reported in the literature.

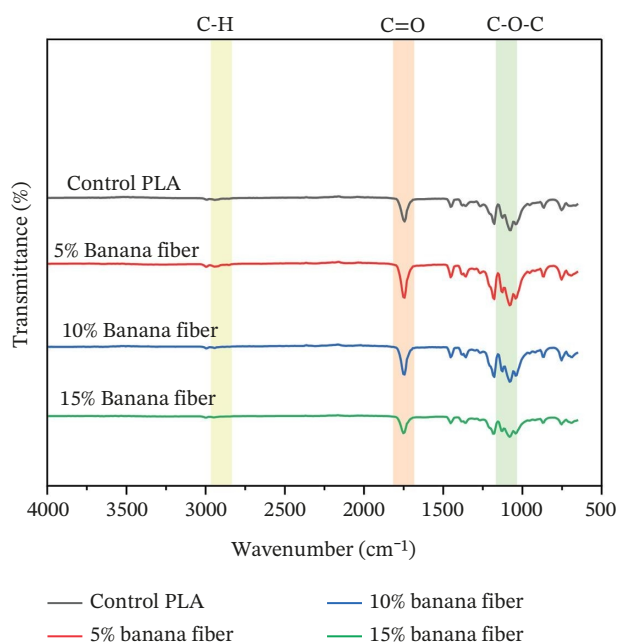


FIGURE 7 | FTIR spectra of PLA and PLA/TEO/BF composite films.

3.5 | FTIR Analysis

The FTIR spectra of PLA and PLA/TEO/BF composite films are presented in Figure 7. PLA exhibited characteristic transmittance peaks at 2925, 1725, and 1050–1290 cm^{-1} , which are indicative of the C–H, C=O, and C–O–C groups, respectively [41]. In addition, the appearance of transmittance peaks at 748 and 877 cm^{-1} demonstrated the presence of both crystalline and amorphous phases in PLA [41]. The PLA/TEO/BF films displayed all transmission peaks corresponding to those of PLA, without any modification or shift, suggesting that the chemical backbone structure of PLA is not affected by the loading of additives. Moreover, no additional peaks of additives (TEO and BF) were seen in the FTIR spectra of the composite films, which could be attributed to their lower loading rates. Comparable results from FTIR analysis have been documented in the literature for PLA/natural fiber [42], and PLA/bamboo/kenaf fiber [43] composites.

3.6 | Antimicrobial Activity

The development of antimicrobial food packaging is critical for increasing food shelf life, maintaining quality, and keeping its sensory qualities. Figure 8 shows the results of an evaluation of the antimicrobial characteristics of PLA and PLA/TEO/BF composite films using the zone-of-inhibition method. The organisms tested were against *S. aureus* and *E. coli*. The corresponding zone-of-inhibition values (mm) were presented in Table 3 and Tukey's multiple comparisons test in Table 4. Virgin PLA films showed zone-of-inhibition values of 3.1 mm for *S. aureus* and 2.5 mm for *E. coli*, indicating its limited inherent antimicrobial potential. The small inhibition zone observed for the neat PLA film should be interpreted with caution, as PLA is generally considered an inert polymer with negligible intrinsic antimicrobial activity. Although the films were thoroughly dried before testing, residual solvent analysis was not performed, and therefore the possible contribution of trace residual chloroform cannot be completely excluded. However, the incorporation of TEO

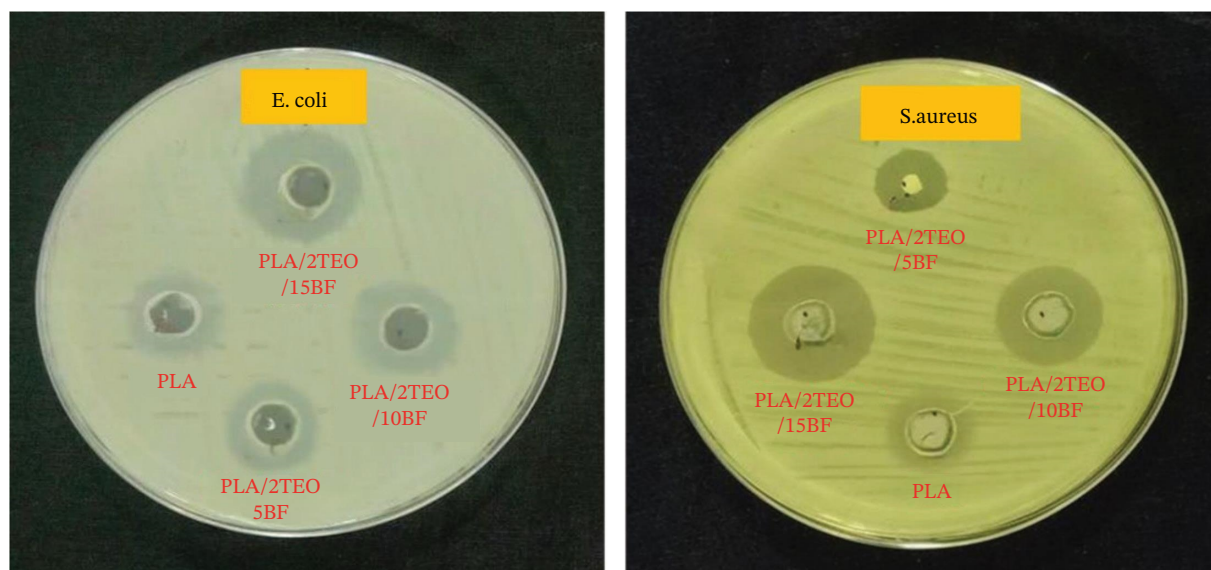


FIGURE 8 | Antimicrobial properties of PLA and PLA/TEO/BF composite films.

TABLE 3 | Antimicrobial activity of PLA and PLA/TEO/BF composite films against *S. aureus* and *E. coli*, expressed as zone of inhibition (mm).

Strain	PLA	PLA/2TEO/5BF	PLA/2TEO/10BF	PLA/2TEO/15BF
<i>S. aureus</i>	3.10 ± 0.25	9.30 ± 0.41	11.60 ± 0.50	13.60 ± 0.60
<i>E. coli</i>	2.50 ± 0.38	6.40 ± 0.47	9.30 ± 0.51	11.40 ± 0.58

TABLE 4 | Tukey's multiple comparisons test for the antimicrobial activity of PLA and PLA/TEO/BF composite films.

Strain	Comparison	Mean difference (mm)	95% CI	Adjusted <i>p</i> value	Significance
<i>S. aureus</i>	PLA vs. PLA/2TEO/5BF	−6.20	−7.405 to −4.995	< 0.0001	****
<i>S. aureus</i>	PLA vs. PLA/2TEO/10BF	−8.50	−9.705 to −7.295	< 0.0001	****
<i>S. aureus</i>	PLA vs. PLA/2TEO/15BF	−10.50	−11.705 to −9.295	< 0.0001	****
<i>E. coli</i>	PLA vs. PLA/2TEO/5BF	−3.90	−5.175 to −2.625	< 0.0001	****
<i>E. coli</i>	PLA vs. PLA/2TEO/10BF	−6.80	−8.075 to −5.525	< 0.0001	****
<i>E. coli</i>	PLA vs. PLA/2TEO/15BF	−8.90	−10.175 to −7.625	< 0.0001	****

Note: Statistical analysis was performed using one-way ANOVA followed by Tukey's multiple comparisons test. Comparisons were made against PLA as the control.

****Indicates $p < 0.0001$.

and BF considerably increased the antibacterial performance of the composite films. The antimicrobial activity of PLA/TEO/BF films may be attributed to the diffusion of bioactive TEO constituents from the polymer matrix, which can interact with bacterial cell membranes and disrupt their integrity. The incorporation of BF may modify the film microstructure and diffusion pathways, potentially enhancing the availability of TEO constituents at the film and bacteria interface. An increase in the zone-of-inhibition values was observed with increasing BF content. Against *S. aureus*, the zone-of-inhibition values increased from 9.3 ± 0.41 mm (PLA/2TEO/5BF) to 11.60 ± 0.50 mm (PLA/2TEO/10BF), reaching a maximum of 13.60 ± 0.60 mm for PLA/2TEO/15BF. Likewise, for *E. coli*, the zone-of-inhibition values increased from 6.40 ± 0.47 for PLA/2TEO/5BF to 11.40 ± 0.58 mm for PLA/2TEO/10BF. One-way ANOVA revealed a significant difference among the formulations for both *S. aureus* [$F(3, 8) = 292.89$, $p < 0.0001$] and *E. coli* [$F(3, 8) = 187.79$, $p < 0.0001$]. Tukey's multiple comparisons test further confirmed that all PLA/TEO/BF composite formulations exhibited significantly higher inhibition zones than the PLA control ($p < 0.0001$). Interestingly, the antibacterial property of the various PLA-based films was prominent against *S. aureus* than *E. coli*, due to the difference in their cell wall frameworks. Gram-negative bacteria like *E. coli* possess an outer membrane that serves as a barrier to many antimicrobial agents, making them inherently more resistant than Gram-positive bacteria [44]. From the results of this test, it can be inferred that the developed PLA-based composite films could be well-suited for active food packaging applications where microbial contamination prevention is essential.

Values are expressed as mean ± SD, $n = 3$.

3.7 | Shelf-Life Studies of Strawberries

Consumers are increasingly preferring fresh, visually appealing, and nutritious fruits that are free from artificial preservatives or chemical pretreatments. However, two major factors

contribute to the spoilage and wastage of fresh produce. One is the influence of environmental and storage conditions, viz., exposure to bacteria, moisture, light, and air that can significantly accelerate their degradation process. The other relates to maturity; once fruits and vegetables reach an advanced stage of ripening, they begin to lose firmness, develop wrinkles, and change color, making them less appealing to consumers. As a result, such produce is often discarded, even if it is safe to consume [44]. Herein, in this work, the visual appearance of strawberries stored without packaging, wrapped with LDPE film, PLA film, and PLA/2TEO/10BF, as can be seen in Figure 9. Moreover, from the Figure 9, it can be observed that unpacked strawberries are more susceptible to bacterial contamination and weight loss due to direct exposure to the environment. LDPE and PLA offered minimal protection against bacterial contamination and weight loss. On the other hand, the strawberries wrapped with PLA/2TEO/10BF showed minimal weight loss, remained visually appealing, and were free from fungal growth after 10 days of storage, making them a potential choice for strawberry storage. As per the findings of Raja et al. (2024), incorporating gallic acid as a cross-linker in PBAT-cellulose blend films significantly enhanced their antibacterial efficacy against food-borne pathogens such as *S. aureus* and *E. coli*, while also extending the shelf life of strawberries stored in contact with these films [45]. PLW was evaluated as a quantitative indicator of strawberries during storage. As shown in Table 5, the weight loss increased progressively with storage duration for all packaging conditions.

Strawberries stored under open-air conditions exhibited the highest weight loss, increasing from 14.23% at 5 days to 36.70% at 15 days. Commercial PE reduced the weight loss to 6.39%, 12.61%, and 20.05% at 5, 10, and 15 days, respectively. The PLA-packaged strawberries showed further reduction in weight loss, with values of 4.47%, 10.57%, and 14.45%, respectively. Notably, the PLA/2TEO/10BF packaging exhibited the lowest physiological weight loss, with values of 3.27%, 8.85%, and 11.89% at 5, 10, and 15 days, respectively. Compared with the open-air control, the PLA/2TEO/10BF packaging reduced

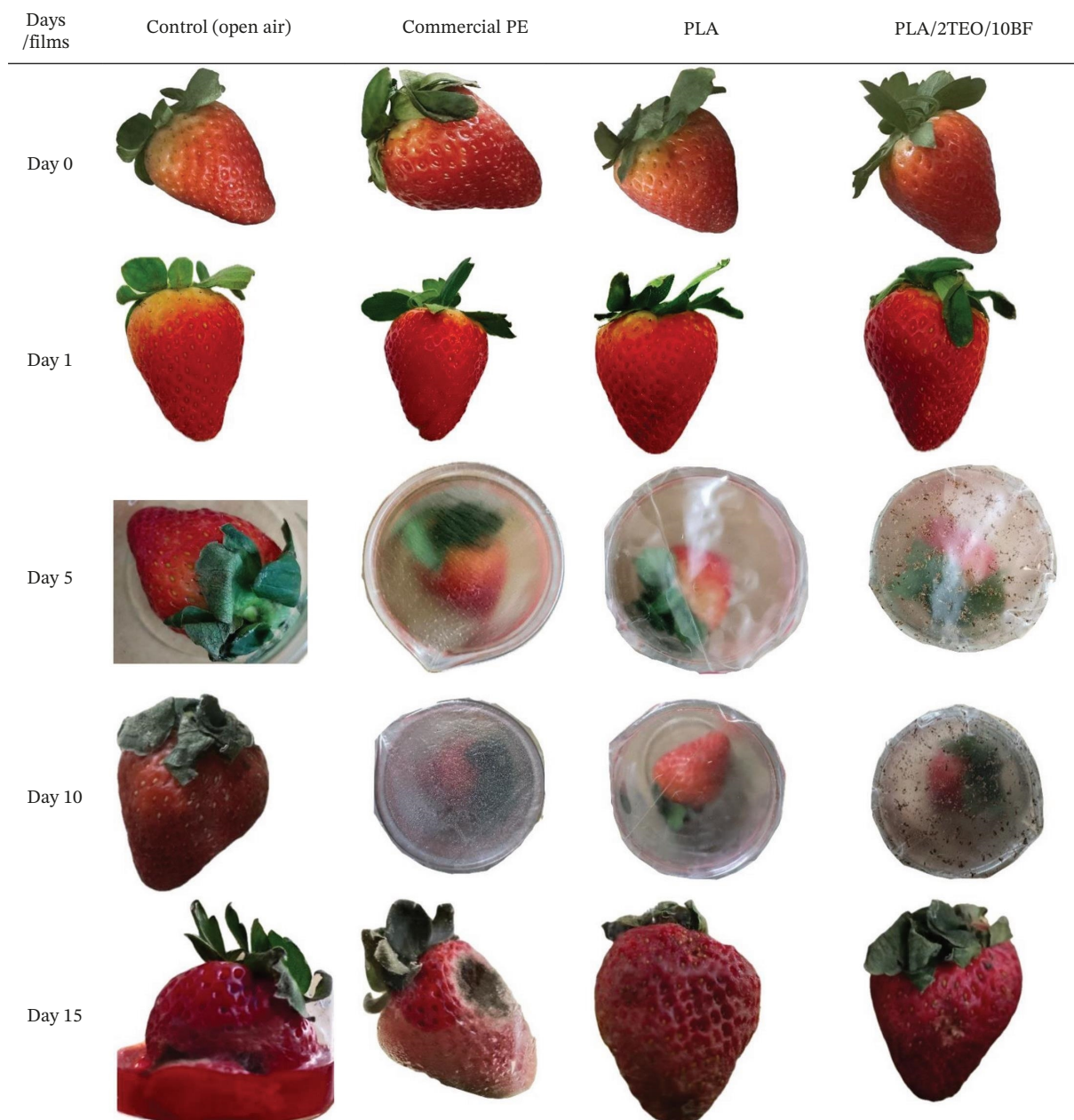


FIGURE 9 | Visual appearance of strawberries under various storage conditions.

weight loss by approximately 77.0%, 61.6%, and 67.6% at 5, 10, and 15 days, respectively. The lower weight loss observed with PLA/2TEO/10BF may be associated with the improved barrier characteristics of the composite packaging, which can reduce moisture transfer between the strawberry and the surrounding environment. The shelf-life assessment given in this study was based on visual observations and weight loss therefore it serves as a preliminary demonstration of the developed composite films for active food-packaging applications. Although the observed reduction in visual deterioration indicates superior preservation performance, quantitative evaluations such as hardness, pH, total soluble solids (TSS), color measures, and microbiological analysis are required to fully assess shelf-life extension. These investigations will be the focus of future efforts.

3.8 | Limitations and Regulatory Considerations

A limitation of this study is that each film formulation was prepared from a single casting batch; therefore, the triplicate measurements represent technical rather than independent replicates. Future studies should use multiple independent batches to assess batch-to-batch variability and strengthen statistical validation. Despite the produced PLA/banana fiber/TEO composite films showed promising physicochemical, antibacterial, and food preservation capabilities, chloroform was used as a solvent during laboratory-scale film manufacturing. The films were properly dried to aid in solvent evaporation, although residual chloroform was not detected in the current investigation. As a result, compliance with food-contact rules, such as the

TABLE 5 | Physiological loss in weight of strawberries stored in different packaging materials.

Packing materials	Physiological loss in weight (%)		
	5 days	10 days	15 days
Open air (control)	14.23	23.07	36.70
Commercial PE	6.39	12.61	20.05
PLA	4.47	10.57	14.45
PLA/2TEO/10BF	3.27	8.85	11.89

standards of the US FDA and Regulation (EU) No. 10/2011 for plastic materials intended to come into contact with food, cannot be certified. Prior to practical or commercial food-packaging applications, residual solvent analysis, overall and particular migration tests, and full safety evaluations should be performed to verify compliance with applicable food-contact regulatory standards.

4 | Conclusions

In this study, active and environment-friendly PLA-based composite films loaded with TEO and BF were successfully developed using melt blending followed by solution casting techniques. The prepared films were systematically characterized to evaluate their morphological, gas barrier, tensile, wettability, antimicrobial, and food preservation properties. The incorporation of 2wt.% TEO and varying concentrations of BF significantly enhanced the WCA, oxygen, and water vapor barrier characteristics of PLA-based films. Particularly, the PLA/2TEO/10BF and PLA/2TEO/15BF films exhibited a WCA of $>90^\circ$, demonstrating their hydrophobic nature. FESEM analysis revealed a uniform distribution of BF in PLA/2TEO/10BF films, while aggregation of BF was noticed in PLA/2TEO/15BF films. Consequently, the tensile strength of the PLA/2TEO/10BF films was significantly greater than that of the neat PLA films, increasing by about 1.6 times. The active composite films that were made also showed great antibacterial properties against *S. aureus* and *E. coli*. These findings, supported by the lower PLW observed for the PLA/2TEO/10BF packaging, provide preliminary proof-of-concept evidence of its preservation potential. However, further systematic studies are required to validate its effectiveness for extending the shelf life of highly perishable fruits. The developed composite films show promising mechanical, barrier, and antimicrobial properties, further studies on scalable manufacturing, essential oil migration safety, long-term storage stability, economic feasibility, and compliance with food-contact regulations are required before commercial implementation in food-packaging applications.

Author Contributions

Soundhar Arumugam: writing – original draft, writing – review and editing, conceptualization, methodology, investigation, data curation, visualization, validation, supervision. **J. Anita Jessie:** interpretation of results, writing – review and editing. **Murugan Rajesh:** investigation,

data interpretation. **Jissy Jacob:** writing – review and editing, investigation, visualization. **M. Lavanya:** investigation, data curation, formal analysis. **Ravikumar Rajarathinam:** methodology, conceptualization, validation. **Ashwath Pazhani:** conceptualization, methodology, supervision. **Andre Batako:** data curation, visualization, validation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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