

Physico-mechanical and ethylene scavenging properties of active packaging from Bambusa fibers modified with TiO_2/Cu_2O composite

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ABSTRACT: The physico-mechanical and ethylene scavenging properties of active packaging consisting of paper prepared from bamboo (*Bambusa vulgaris*) fibers loaded with varying concentrations of nano titanium dioxide/cuprous oxide (TiO_2/Cu_2O) composite was investigated for its ability to delay ripening of Philippine climacteric fruits. Tests of paper containing 1% to 5% TiO_2/Cu_2O showed no or limited negative impact on its physical, optical, and mechanical properties. Images from a field emission scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (FESEM-EDS) showed dispersion and agglomeration of TiO_2/Cu_2O nanoparticles on the paper surface. The percent weight of titanium and copper increased with increasing metal oxide composite concentration used in this study. Attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy indicated small shifts in band intensity at 3330 cm^{-1} and 1100 cm^{-1} in the hydroxyl (O-H) and C-O regions, respectively, suggesting possible chemical or physical interactions between the metal oxide and paper. Contact angle measurement suggested that TiO_2/Cu_2O nanoparticles may have imparted paper hydrophobicity at 3%–5% concentration, possibly through increased microscale roughness.

The ethylene scavenging experiment indicated that there was a significant delay in the ripening process of mango and tomato when packed in paper doped with 3% and 5% TiO_2/Cu_2O . The fruits were greener with a firmer texture compared with untreated control after three days of storage under natural light and ambient condition. The preliminary results suggested that 3%–5% TiO_2/Cu_2O active packaging modification can remove ethylene from the fruit's storage environment, extending shelf life and maintain quality for three days. This simple technique could have potential economic benefits for the fruit industry by directly reducing post-harvest waste, and the delayed ripening could provide flexibility in supply chain management.

Application: This study provides insights into the development of bamboo fiber-based active packaging enhanced with TiO_2/Cu_2O composites for ethylene scavenging, which offers a practical solution to extend the shelf life of climacteric fruits such as mangoes and tomatoes. The findings may serve as a reference for future research on sustainable packaging technologies aimed at reducing postharvest losses.

The Philippines is a major exporter of fresh tropical fruits. Its favorable climate and fertile soils make it an ideal location for tropical fruit production. In 2024, the Philippines exported \$473M worth of tropical fruits to South Korea, Japan, China, Hong Kong, Taiwan, Singapore, and the Middle East [1]. The country exports several economically important fruits, such as banana, pineapple, mango, papaya, and calamondin. Unfortunately, most tropical fruits are climacteric, i.e., they continue to ripen after harvest. Climacteric fruits undergo a dramatic surge in cellular respiration and ethylene production after reaching ripening peaks [2,3]. Ethylene is a natural plant hormone that regulates growth and development. Consequently, the fruit ripens rapidly and develops flavor and aroma. However, increased ethylene production results in biochemical changes causing overripening and spoilage during storage and transportation [4]. Postharvest losses (as

high as 30%–50%) of climacteric fruits from spoilage are relatively high, often disrupting the fruits' supply chain [5]. In recent years, ozone treatment [6], 1-methylcyclopropene [7], low temperature and modified atmosphere [8,9], and edible films and coatings [10], among others, have been studied to control ripening of climacteric fruits. An alternative strategy is to use ethylene scavengers in active packaging to control ethylene accumulation [11].

An ethylene scavenger is a material that adsorbs ethylene molecules or chemically breaks it down to less harmful compounds [11,12]. Removal of ethylene from the storage atmosphere extends the shelf life and maintains quality of climacteric fruits. Recent reports indicated that titanium dioxide (TiO_2) can be used as ethylene scavenger of climacteric fruits and vegetables [13,14]. Unlike traditional scavengers like activated carbon, which adsorbs ethylene, or potassium permanganate ($KMnO_4$), which chemically

oxidizes it, TiO_2 uses photocatalytic oxidation (PCO) to break down ethylene. When exposed to ultraviolet (UV) light, TiO_2 generates reactive oxygen species (ROS) and hydroxyl radicals on the surface that break down ethylene molecules into harmless end products, primarily carbon dioxide and water [15,16]. Unfortunately, the main limitation of TiO_2 photocatalysis is its requirement for UV light [13,17]. To overcome these limitations, various treatment strategies have been developed to enhance the photocatalytic activity of TiO_2 . [18]. An effective technique to improve photocatalytic efficiency is to combine the *n*-type TiO_2 with a *p*-type semiconductor to form a *p-n* heterojunction [19,20]. The formation of this new interface significantly boosts photocatalytic efficiency, mainly by extending light absorption and promoting charges separation between the two materials [21]. In recent years, cuprous oxide (Cu_2O), a *p*-type, non-toxic, and naturally abundant semiconductor, has been investigated to improve the range of absorptive capability of TiO_2 to visible light [22,23]. Studies showed that photocatalytic activity of $\text{TiO}_2/\text{Cu}_2\text{O}$ can be used in a wider range of applications than pure TiO_2 . Applications such as low-cost hydrogen production using solar energy and decomposition of organic pollutants, among others, were reported [19,22]. However, no or limited studies have been reported in the literature on the use of $\text{TiO}_2/\text{Cu}_2\text{O}$ as an ethylene scavenger to delay the ripening process of climacteric fruits. Incorporation of such material in active packaging could help extend the shelf life of fresh fruits and vegetables with significant economic benefit, primarily due to their major role in the country's agriculture and trade.

The present paper reports on the use of a $\text{TiO}_2/\text{Cu}_2\text{O}$ composite as ethylene scavenger in active packaging made from bamboo (*Bambusa vulgaris*) fibers and its effect on the physical and mechanical properties of the resulting paper. Bamboo fibers were selected because they are eco-friendly and sustainable, allow gas exchange to limit spoilage, and have a natural antimicrobial property [24]. The use of environmentally friendly packaging material doped with an active $\text{TiO}_2/\text{Cu}_2\text{O}$ could help manage the high perishability of fresh climacteric fruits. This simple technique could potentially minimize postharvest losses and maximize export potential of fresh fruits and vegetables.

MATERIALS AND METHODS

Raw materials

Bamboo (*Bambusa vulgaris* Schrad ex. Wendl) culms (10-cm diameter, 3–5 years old) were harvested from the Bambusetum of Department of Environment Natural Resources — Ecosystems Research and Development Bureau (DENR-ERDB) in Laguna, Philippines, and transported to the laboratory. The *B. vulgaris* is a common and widely distributed species of bamboo in the Philippines and Southeast Asia, known for its fast growth and versatility. The culms were split, outer skin removed, chipped (25 mm), and air dried for two weeks prior to pulping. Nano-titanium (IV) oxide (TiO_2 ,

21 nm, >99.5% purity, 35–65 m^2/g) and Cu_2O were purchased from Sigma-Aldrich (St. Louis, MO, USA). Pre-harvest tomatoes and mangoes (*Mangifera indica* L), Carabao cultivar, were sourced from a local orchard in Los Banos, Laguna, and used for the testing of active packaging material.

Preparation of $\text{TiO}_2/\text{Cu}_2\text{O}$ composite

The $\text{TiO}_2/\text{Cu}_2\text{O}$ (1:7.5) was prepared following the ethanol reduction protocol used by Riahi et al. [13]. First, 0.15 g of Cu_2O was added into an 80-mL ethanol suspension containing 2.0 g nano TiO_2 . The suspension was uniformly stirred for 2 h at 25°C, then immersed in a hot water bath at 80°C to partially evaporate the solvent. Once the ethanol was separated, the remaining mixture was left in the oven overnight at 60°C to completely evaporate the ethanol. Finally, the dried $\text{TiO}_2/\text{Cu}_2\text{O}$ composite was calcined at 400°C for 2 h.

Soda pulping

Bamboo chips were disintegrated via soda pulping using sodium hydroxide (NaOH) with 5:1 liquid-to-fiber ratio. A total of 500 g (oven-dry weight) of chips were processed in a laboratory rotary digester (RDB-D15L, Sumet-Messtechnik; Peiting, Germany) using 100 g of NaOH (18% solids content). The cooking process involved heating to maximum temperature for 100 min, followed by cooking the chips at 170°C for 120 min. After pulping, the bamboo fiber slurry was washed with water (10 min) and screened to remove the black liquor and any impurities. Screen yield was calculated based on the ratio of initial chip and fiber weight.

Handsheet preparation and addition of $\text{TiO}_2/\text{Cu}_2\text{O}$

Bamboo pulp stock was disintegrated (10 min) to uniformly separate the fibers. The $\text{TiO}_2/\text{Cu}_2\text{O}$ composite (0%, 1.0%, 3.0%, and 5.0% based on dry weight of fiber) was introduced during the disintegration process. The *B. vulgaris* fibers were formed into handsheets following TAPPI T 205 “Forming handsheets for physical tests of pulp,” with a target grammage of 90–100 g. Using the TAPPI sheet former, 10 handsheets were prepared for each concentration of $\text{TiO}_2/\text{Cu}_2\text{O}$ used in this study. After couching, metal plates were placed on the wet sheets and were pressed via a hydraulic press for 7 min at 50 psi. After pressing, the handsheets were placed in drying rings and air dried for two days. The dried handsheets were conditioned in a conditioning room maintained at 23°C and 50% RH (TAPPI T 402 “Standard conditioning and testing atmospheres for paper, board, pulp handsheets and related products”) for at least 4 h prior to testing.

Physical, optical, and mechanical tests

The TAPPI and ISO Standard Test Methods (Table I) were followed to determine physical, optical, and mechanical properties of paper from bamboo fiber containing varying concentrations of $\text{TiO}_2/\text{Cu}_2\text{O}$. Three replications were used for each test. Data for physical and mechanical tests were

Standard Test Method	Description
TAPPI T 205	"Forming handsheets for physical tests of pulp"
TAPPI T 220	"Physical testing of pulp handsheets"
ISO 2470	"Paper, board, and pulps — Measurement of diffuse blue reflectance factor"
ISO 2471	"Determination of opacity (paper backing)"
TAPPI T 403	"Bursting strength of paper"
TAPPI T 494	"Tensile breaking properties of paper and paperboard"
TAPPI T 414	"Internal tearing resistance of paper"

I. Standard test methods used to determine physical, optical, and mechanical properties of paper from bamboo fiber modified with titanium dioxide/cuprous oxide (TiO₂/Cu₂O).

evaluated by analysis of variance (ANOVA) using Statgraphics (Plains, VA, USA) Centurion 16.1 software. Means were separated by Tukey's Honest Significance Difference (HSD) test ($\alpha = 0.05$).

Contact angle measurement

Contact angle measurement was performed to determine wettability and water resistance of bamboo fiber-based paper modified with TiO₂/Cu₂O (ASTM D724-99 "Standard test method for surface wettability of paper (angle-of-contact method).") A static sessile drop method using one droplet (5 μ L) of distilled water was deposited on the surface of each specimen using a micro syringe at ambient temperature. A high-resolution digital camera was used to capture the droplet profile after it had established equilibrium. Three measurements were made at random points on the surface of each specimen. Contact angles were measured directly by drawing a tangent line from the droplet profile to the paper surface using open-source ImageJ processing and analysis software running on Dropsnake v2.0 drop analysis plugin.

Fourier transform spectroscopy

Attenuated total reflectance (ATR)—Fourier transform infrared (FTIR) spectroscopy (ATR-FTIR) was carried out using a Shimadzu IR Prestige 21 (Shimadzu; Kyoto) spectrometer to investigate chemical changes, if any, on paper containing various concentrations of TiO₂/Cu₂O. Scans were made using a diamond crystal (45° incidence angle, single bounce) from 400–4000 cm⁻¹ wavelength with 10 scans for each sample at a resolution of 4 cm⁻¹.

Scanning electron microscopy

Field emission scanning electron microscopy (FESEM) was used to observe the morphology and dispersion of TiO₂/Cu₂O nanoparticles on a paper surface. Random surface area of treated and untreated papers was examined using FESEM at 3.0 kV and 8.15 pA equipped with an energy dispersive X-ray

spectrometer (EDS) at 15 kV and 2.81 nA (JEOL JSM-IT800 SHL, Jeol; Tokyo). The EDS was carried out to determine elemental composition and distribution TiO₂/Cu₂O on the specimen surface. Each specimen was sputter coated with platinum to improve conductivity prior to observation. The FESEM images and EDS spectra were obtained using Aztec software (Oxford Instruments; Abingdon, UK).

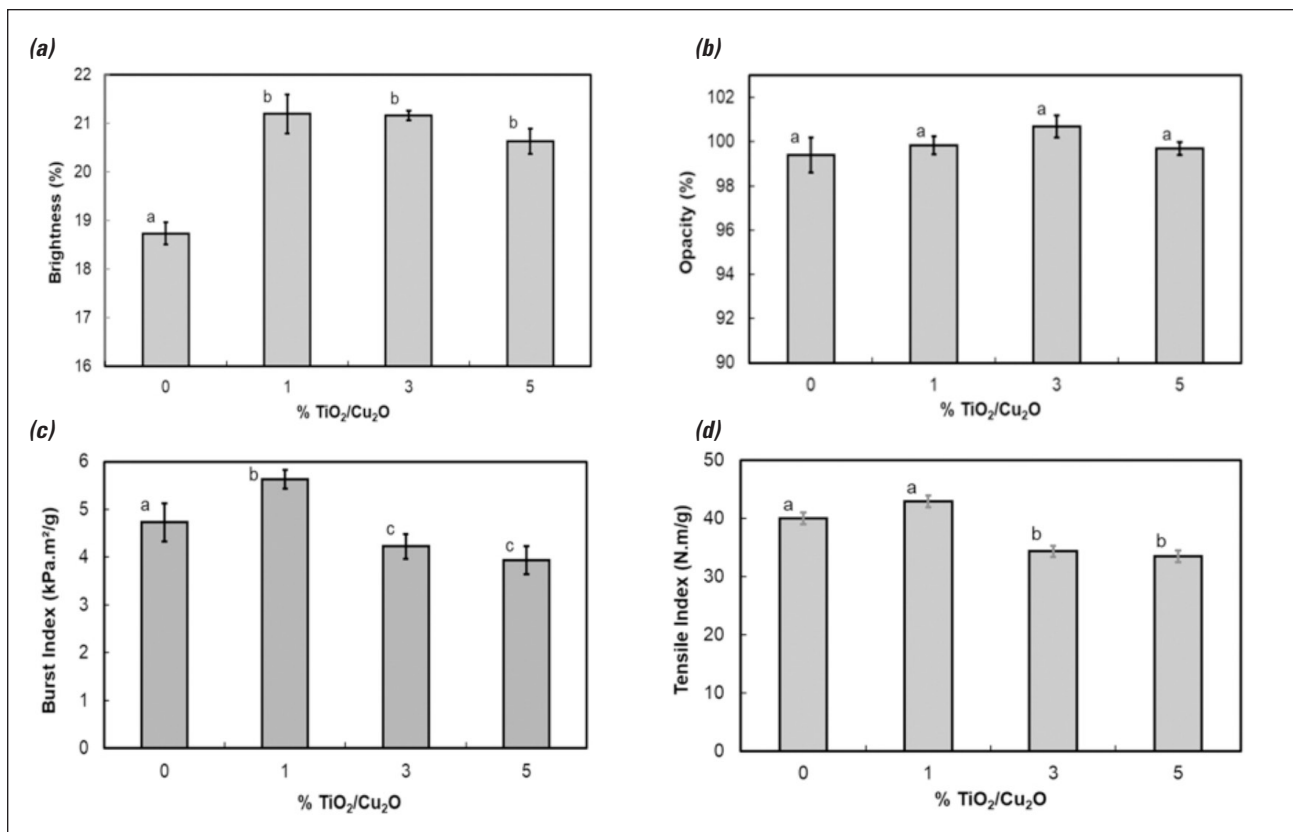
Ethylene scavenger evaluation

Healthy, defect-free mangoes and tomatoes of about similar size, weight, and appearance were selected, washed with distilled water, and then dried for the experiment. Initial weight, color, and softness (firmness) of the fruits were determined. The fruits were then placed in polyethylene terephthalate (PET) containers (one mango or three tomatoes) covered with TiO₂/Cu₂O active packaging. The containers were kept at ambient conditions (28°C and 65% RH) under indirect natural light for three days. To assess ripening and rate of development, fruit softness was evaluated based on thumb pressure using a scale of 1 to 5 where 1 is very hard and 5 is over ripe, both before and after the storage period. Peel color was assessed using a rating scale of 1 to 5 where 1 is fully green and 5 is fully yellow, similar to that reported by Anwar et al. [25]. The evaluations of the degree of ripening and fruit softness were performed by five individuals to minimize bias, and the average was reported.

RESULTS AND DISCUSSION

Physical, optical, and mechanical properties

Physical, optical and mechanical properties of paper from *B. vulgaris* fibers modified with various concentrations of TiO₂/Cu₂O were tested following TAPPI and ISO Standard Test Methods (Table I). Paper brightness increased significantly (10%–14%) with increasing concentration of TiO₂/Cu₂O (p -value <0.001) compared with untreated control (**Fig. 1a**). The increase in brightness of modified paper was likely due to the high light-scattering ability TiO₂, a premium quality filler commonly used in the paper industry



1. (a) Brightness, (b) opacity, (c) burst, and (d) tensile indices of paper made from *B. vulgaris* fibers modified with titanium dioxide/cuprous oxide (TiO₂/Cu₂O). Each value is the mean and standard error of three replicates. Bars followed by the same letter between different TiO₂/Cu₂O concentrations were not significantly different (Tukey's Honest Significance Difference (HSD) test, $\alpha = 0.05$).

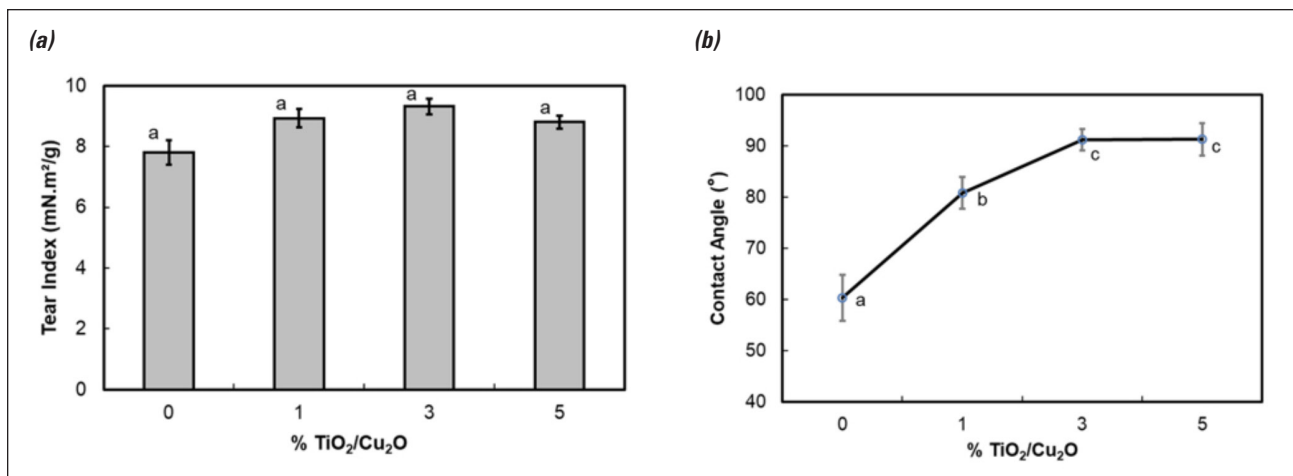
to produce high-quality white paper. Further addition of TiO₂/Cu₂O over 1% resulted in no significant change in brightness. This could be due to the paper reaching an optimal TiO₂/Cu₂O concentration level where the benefit of adding more TiO₂/Cu₂O is canceled out by the negative effects of light shielding, surface saturation, and particle agglomeration [26]. In addition, the reduced accessible surface area at higher TiO₂/Cu₂O concentration may have offset any benefit of adding more additive, causing the photocatalytic reaction rate to level off.

Similarly, the incorporation of TiO₂/Cu₂O nanoparticles resulted in an initial increase in burst (16%) and tensile (7%) indices, followed by both indices decreasing at 3% and 5% TiO₂/Cu₂O compared to untreated control (Fig. 1c and Fig. 1d). This is a common trend for nanocomposites, i.e., initially increasing to an optimum point and then decreasing with further increase in nanoparticle concentration [27]. At low concentration, the TiO₂/Cu₂O nanoparticles were well-dispersed and act as a reinforcing filler throughout the cellulose fiber matrix. Their high surface area and stiffness allowed them to effectively transfer load between fibers, helping distribute the applied stress over a larger area [28]. However, at higher concentration, nanoparticle agglomeration blocks the critical fiber-to-fiber contact necessary for high cohesive strength [29].

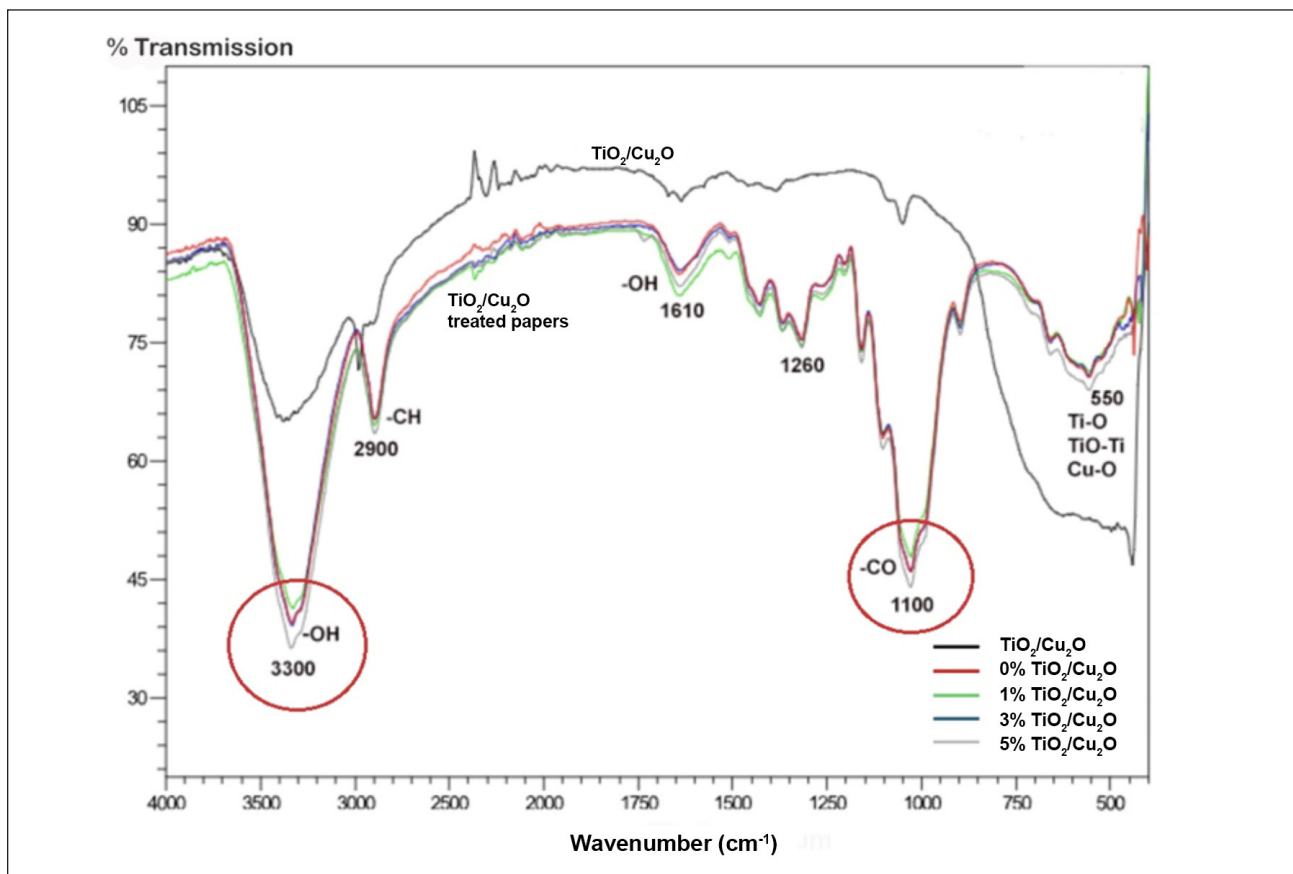
The addition of TiO₂/Cu₂O had no significant effect on paper opacity (Fig. 1b). This is contrary to some reports that TiO₂/Cu₂O enhances light absorption contributing to increased opacity by reducing light transmission [30]. Apparently, concentrations used in this study were not high enough to produce said effect. Tear index was unaffected by the presence of TiO₂/Cu₂O. No significant reduction in tear strength was also observed with increasing concentration of TiO₂/Cu₂O (p -value >0.05) (Fig. 2a). The reason for this observation was unclear. However, previous studies indicated extremely fine particles (nanofillers) or specific shapes might integrate better, resulting in no or negligible impact on paper strength [31].

Surface characterization

The FTIR spectra of paper prepared from *B. vulgaris* fibers modified with varying concentrations of TiO₂/Cu₂O are shown in Fig. 3. The results showed combination of the characteristic signals from the lignocellulosic fibers, TiO₂ and Cu₂O. A broad band in the 3330 cm⁻¹ region was observed, indicating stretching vibrations of hydroxyl (OH) groups from adsorbed water on the cellulose fibers and TiO₂ surface. The presence of -OH groups is common due to the high surface area of cellulose and TiO₂ and their tendency to adsorb moisture from the surrounding air. A bend-



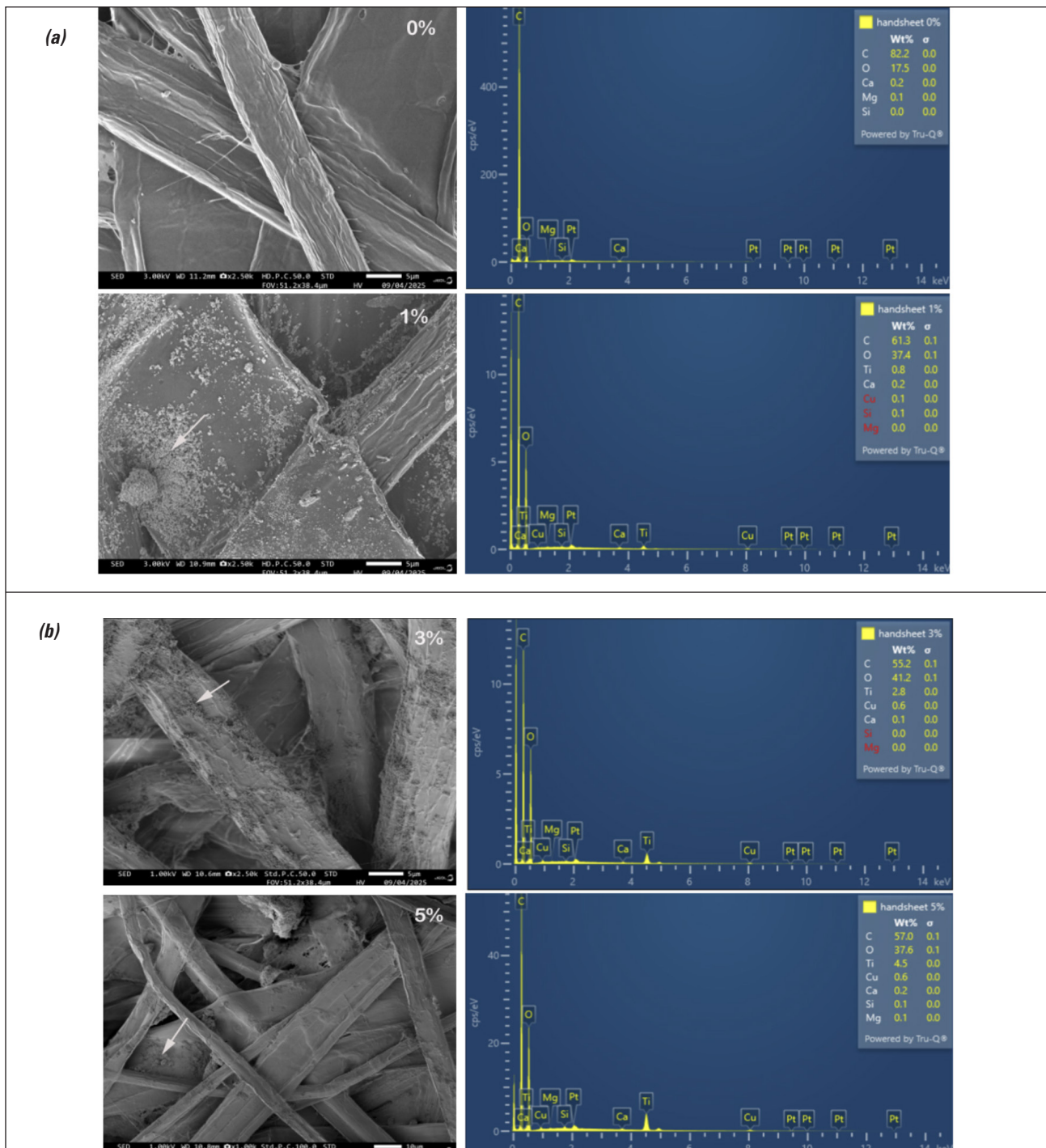
2. (a) Tear index and (b) contact angle of paper made from *B. vulgaris* fibers modified with TiO₂/Cu₂O. Each value is the mean and standard error of three replicates. Bars followed by the same letter between different TiO₂/Cu₂O concentrations were not significantly different (Tukey's HSD test, $\alpha = 0.05$).



3. Attenuated total reflection Fourier transform infrared (ATR-FTIR) spectra of papers prepared from *B. vulgaris* fibers modified with TiO₂/Cu₂O.

ing vibration of adsorbed water molecules on the cellulose and TiO₂ surface was also evident around 1610 cm⁻¹. Broad and strong bands at around 1010 cm⁻¹ indicate C-O stretching from the cellulose matrix. A broad band about 550 cm⁻¹ was prominent, likely from the stretching vibrations of Ti-O and Ti-O-Ti bonds or Cu-O bond in Cu₂O. The spectra of

treated papers confirmed the presence of TiO₂ and Cu₂O by the stretching bands of the metal and oxygen about 550 cm⁻¹. Similar bands for TiO₂/Cu₂O were reported in the literature at around 450–550 cm⁻¹ [32–34]. Possible interactions between the metal oxide and paper were observed at 3330 cm⁻¹ and 1100 cm⁻¹ in the hydroxyl (O-H) and C-O



4. (a) Field emission scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (FESEM-EDS) images and elemental analyses of papers prepared from *B. vulgaris* fibers modified with varying concentration of $\text{TiO}_2/\text{Cu}_2\text{O}$ showing agglomeration of $\text{TiO}_2/\text{Cu}_2\text{O}$ nanoparticles (pointed by arrows). (b) FESEM images and elemental analyses of papers prepared from *B. vulgaris* fibers modified with varying concentration of $\text{TiO}_2/\text{Cu}_2\text{O}$.

regions, respectively (Fig. 3). These interactions were evident in the spectra of pure $\text{TiO}_2/\text{Cu}_2\text{O}$ and treated paper with increasing concentration of metal oxide. Small shifts or changes in intensity at 3300 cm^{-1} band suggested the formation of new or stronger hydrogen bonds with the -OH groups from the surface of TiO_2 and Cu_2O and the cellulose

polymer [35]. Shifts at the 1100 cm^{-1} band related to C-O-C and C-O stretching may indicate slight modifications in the crystalline or amorphous structure of the cellulose due to the presence of the nanoparticles [35]. These spectral changes confirmed the chemical or physical interaction between paper and the $\text{TiO}_2/\text{Cu}_2\text{O}$ composite, rather than just

Element	% TiO ₂ /Cu ₂ O			
	0%	1%	3%	5%
Carbon (C)	82.16	61.33	55.19	57.04
Oxygen (O)	17.52	37.44	41.18	37.81
Magnesium (Mg)	0.07	0.05	0.04	0.05
Silicon (Si)	0.04	0.05	0.05	0.13
Calcium (Ca)	0.21	0.19	0.15	0.15
Titanium (Ti)	–	0.83	2.80	4.45
Copper (Cu)	–	0.10	0.60	0.57

II. Percent weight of elements detected using FESEM-EDS on papers from *B. vulgaris* fibers modified with TiO₂/Cu₂O.

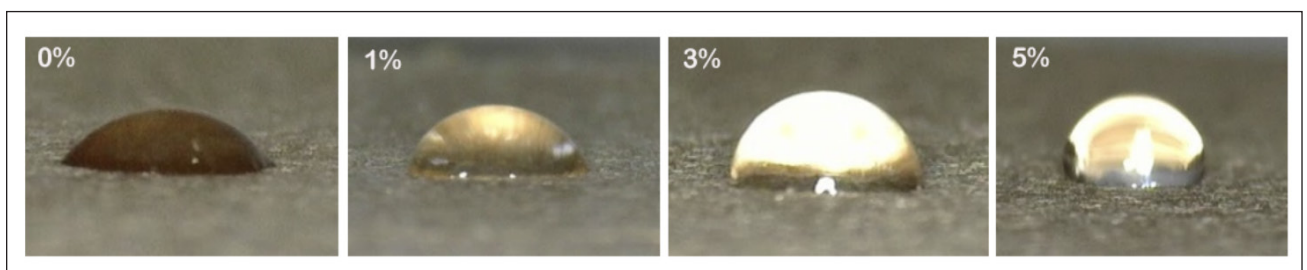
a simple mixture of two materials.

The FESEM images of paper surface modified with TiO₂/Cu₂O particles and their corresponding EDS spectra are shown in **Fig. 4a–4b**. Untreated specimen (0%) showed bamboo fibers and vessel elements with pristine surface, free of any deposit. However, treated specimens showed agglomeration of TiO₂/Cu₂O particles of varying dispersion on the paper surface. The higher the concentration of the additive used, the more nanoparticles are evident, forming aggregates on the fiber surface (Fig. 4a–4b). The distribution of TiO₂/Cu₂O nanoparticles appeared to be nonuniform but likely contributed to surface microroughness, affecting paper wettability, hydrophobicity, and moisture resistance. Elemental analyses showed that the percentage weight of titanium and copper on paper surface was consistent with increasing concentration TiO₂/Cu₂O used in this study (**Table II**). Considering that TiO₂/Cu₂O nanoparticles have a relatively large surface area, they are likely bound to the lignocellulosic network by Van der Waals interactions [36,37]. This observation agreed with the results of the previously-discussed FTIR analyses, indicating the presence of a chemical or physical interaction between the metal oxide and the paper matrix.

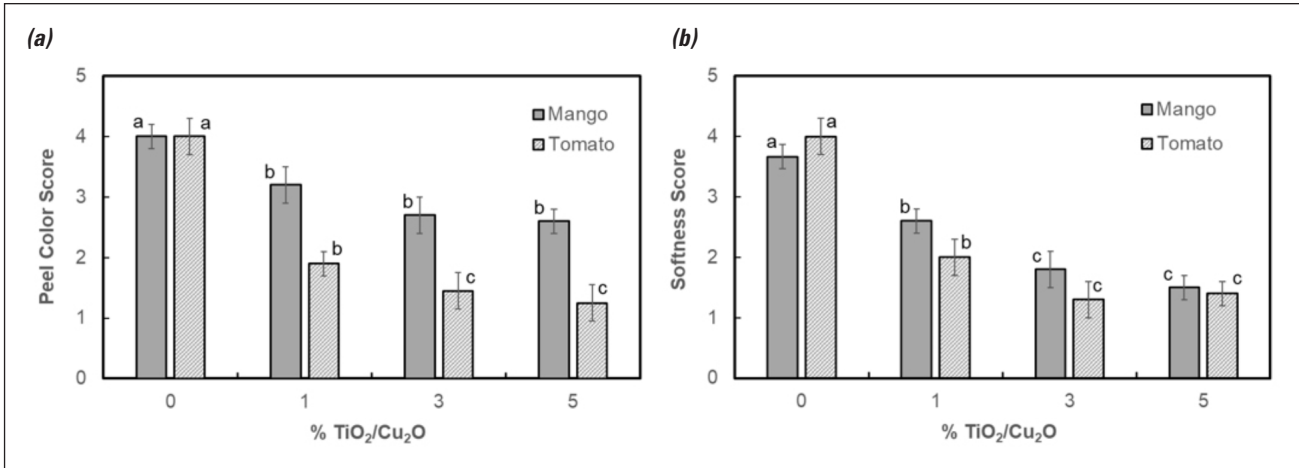
Contact angle

Contact angles of water droplets on papers modified with varying concentrations of TiO₂/Cu₂O are shown in Fig. 2b.

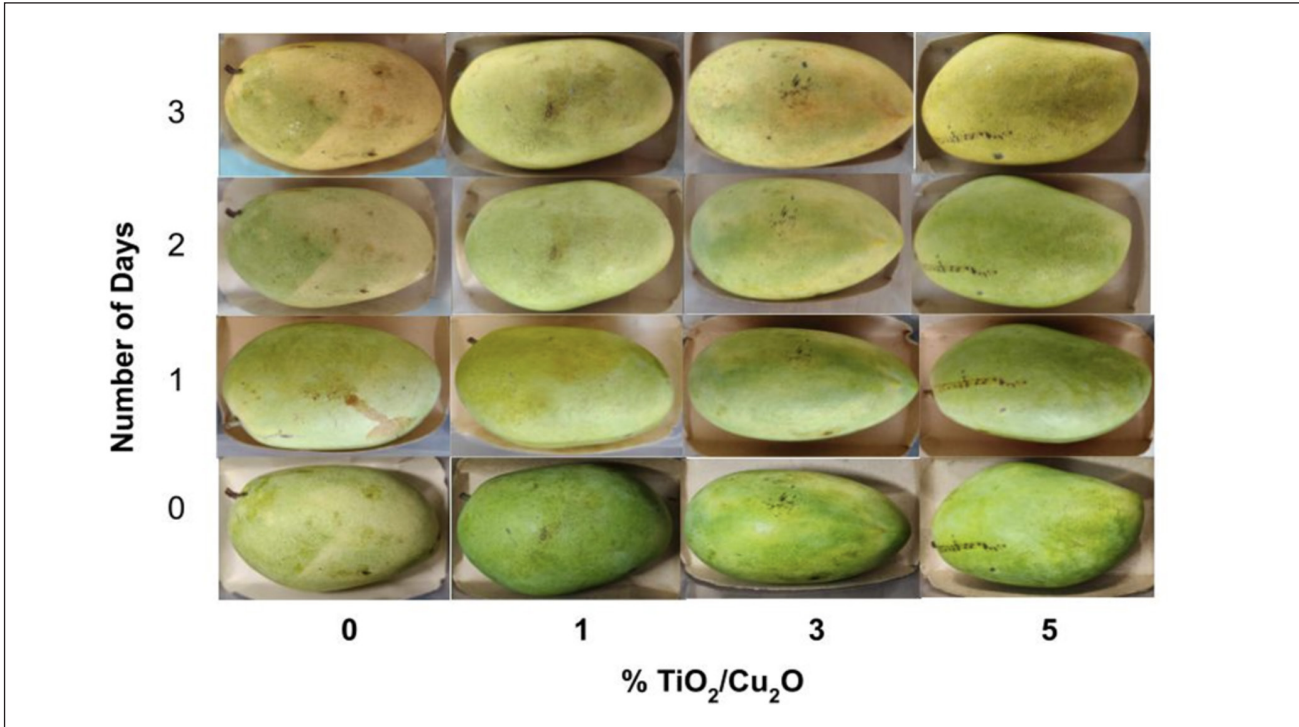
Contact angles greater than 90° are considered hydrophobic, and those less than 90° are hydrophilic [38]. Because of the hydrophilic nature of bamboo fibers, water droplets spread rapidly into the surface of untreated paper (0%), resulting in contact angles <60°. The natural hydrophilicity of untreated paper is due to accessible hydroxyls of the cellulose chain, hemicellulose, or lignin. The low contact angles at 0% to 1% TiO₂/Cu₂O were more consistent with homogenous wetting (Wenzell model), where the liquid water penetrated and conformed to the pores and crevices of the rough paper surface, displacing all the air between the liquid and the solid [39]. However, TiO₂/Cu₂O doped specimens (3% and 5%) formed high contact angle droplets and exhibited improved water repellency with hydrophobic angles of about 89°–93° (**Fig. 5**). The agglomeration of TiO₂/Cu₂O nanoparticles on the surface of treated paper, as confirmed by FESEM images and EDS analyses, may have contributed to increased microscale roughness to impart hydrophobicity at 3%–5% concentration. The results were more consistent with heterogeneous wetting (Cassie-Baxter model) where the water droplet rests on top of the TiO₂/Cu₂O nanoparticles, trapping air pockets within the pores and cavities of the paper and reducing the contact area between the liquid and the solid [41,42]. Similar results of the creation of hydrophobic surfaces using metal oxide nanoparticles on paper matrices were reported in the literature [39,40].



5. Water droplets formed on paper surface made from *B. vulgaris* fibers modified with TiO₂/Cu₂O.



6. (a) Peel color and (b) softness scores of mangoes and tomatoes covered in active packaging consisting of *B. vulgaris* fibers modified with $\text{TiO}_2/\text{Cu}_2\text{O}$ after three days of storage. Bars followed by the same letter between different $\text{TiO}_2/\text{Cu}_2\text{O}$ concentrations were not significantly different (Tukey's HSD test, $\alpha = 0.05$).

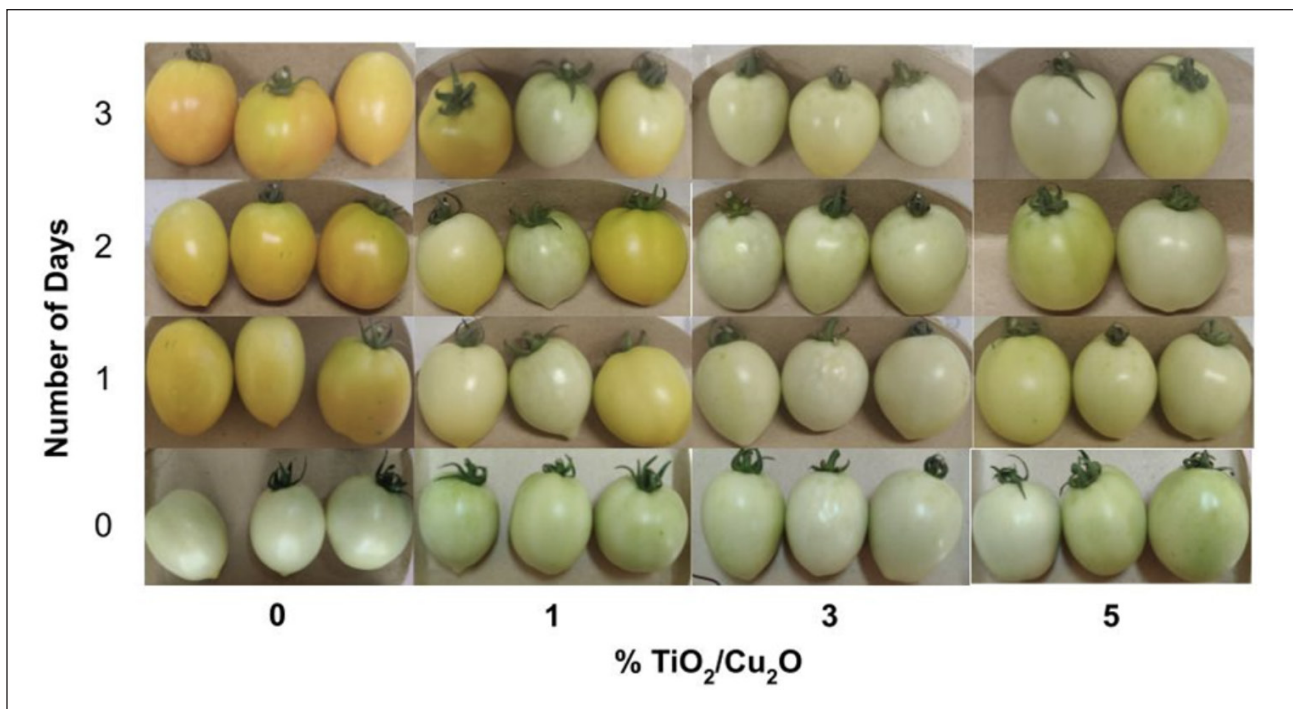


7. Development peel color in mango covered with active packaging consisting of *B. vulgaris* fibers modified with $\text{TiO}_2/\text{Cu}_2\text{O}$ after three days of storage.

Ethylene scavenger evaluation

Results of the ripening development of mango and tomato in active packaging with bamboo fibers modified with $\text{TiO}_2/\text{Cu}_2\text{O}$ are shown in **Figs. 6–Fig. 8**. Results indicated that there was significant delay (p -value < 0.001) in ripening rate of mango when packed under paper modified with 3% and 5% $\text{TiO}_2/\text{Cu}_2\text{O}$. The fruit appeared to be greener with a firmer texture (peel color: 2.70 and softness score: 1.80, and peel color: 2.60 and softness score: 1.50, respectively) compared with untreated control (peel color: 4.0 and soft-

ness score: 3.67) after three days of storage (Fig. 6 and Fig. 7). This would suggest ethylene removal from the surrounding fruit atmosphere, delaying the ripening process. Similarly, tomato peel color and softness were observed to be significantly different under $\text{TiO}_2/\text{Cu}_2\text{O}$ modified packaging used in this study. Tomato color and softness under 3% and 5% $\text{TiO}_2/\text{Cu}_2\text{O}$ active packaging were markedly greener and firmer compared to untreated control (peel color: 1.45 and softness score: 1.30, and peel color: 1.25 and softness score: 1.40, respectively) (Fig. 6 and Fig. 8). Paper pack-



8. Development of peel color in tomatoes covered with active packaging consisting of *B. vulgaris* fibers modified with $\text{TiO}_2/\text{Cu}_2\text{O}$ after three days of storage.

aging with 1% $\text{TiO}_2/\text{Cu}_2\text{O}$ modification showed moderate delay in ripening for both mango and tomato as indicated by peel color and softness. These observations are consistent with reports that $\text{TiO}_2/\text{Cu}_2\text{O}$ absorbs a broader spectrum of visible light, enhancing contact and reaction rate with ethylene molecules [22,23]. By actively removing ethylene from the storage environment, the $\text{TiO}_2/\text{Cu}_2\text{O}$ delayed the ripening process and maintained the quality of the fruits for a longer period of time. Copper nanoparticles, particularly Cu_2O , are known to release copper ions (Cu^{2+}) in packaging material, imparting a strong antimicrobial property to the paper [42]. In addition, the moisture resistance of paper packaging (i.e., high contact angles, Fig. 5), could have acted as water vapor barrier, preventing wilting and weight loss while maintaining turgor and freshness [43]. The combined effects of ethylene scavenging, antimicrobial action, and moisture control may provide the mechanism by which the $\text{TiO}_2/\text{Cu}_2\text{O}$ additive prevented softening, discoloration (yellowing), and loss of quality of mangoes and tomatoes used in this study.

CONCLUSIONS

In general, this study showed that active packaging prepared from *B. vulgaris* fibers modified with varying concentrations of $\text{TiO}_2/\text{Cu}_2\text{O}$ nanoparticles was able to delay the ripening process of Philippine mango and tomato over a three-day period. Tests of papers made from *Bambusa* fibers loaded with 1% to 5% $\text{TiO}_2/\text{Cu}_2\text{O}$ had no or limited negative impact on physical, optical, and mechanical properties of paper. Paper brightness increased significantly

(10%–14%), but burst and tensile indices decreased (10%–16%) with increased $\text{TiO}_2/\text{Cu}_2\text{O}$ concentration. The $\text{TiO}_2/\text{Cu}_2\text{O}$, however, had no effect on tear index and paper opacity. The FESEM-EDS images showed dispersion and agglomeration of $\text{TiO}_2/\text{Cu}_2\text{O}$ nanoparticles on the paper surface with percentage weight of titanium and copper consistent with increasing metal oxide concentration used in this study. The ATR-FTIR spectra indicated possible chemical or physical interactions between the $\text{TiO}_2/\text{Cu}_2\text{O}$ and paper and not a simple mixture of two material. Contact angle measurements showed that $\text{TiO}_2/\text{Cu}_2\text{O}$ nanoparticles have imparted hydrophobicity to paper at 3%–5% concentration. The ethylene scavenging experiment indicated that there was significant delay in the ripening process of mango and tomato when packed under paper modified with 3% and 5% $\text{TiO}_2/\text{Cu}_2\text{O}$. The fruit appeared to be greener with a firmer texture compared with untreated control. The synergistic effects of ethylene scavenging, antimicrobial action, and moisture barrier may have contributed to this result, maintaining the quality of the tomatoes and mangoes for a longer period of time. Although the research is preliminary, the technique reported in the present paper could have potential economic benefits for the fruit industry by reducing postharvest waste and providing flexibility in supply chain management. **TJ**

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We chose to study this topic to address the significant postharvest losses of tropical fruits like mangoes and tomatoes caused by ethylene buildup during storage and transport. It was aimed to develop an eco-friendly active packaging material using locally available bamboo fibers and $\text{TiO}_2/\text{Cu}_2\text{O}$ nanocomposites to extend fruit shelf life and promote sustainable agriculture. This research supports previous studies on ethylene scavengers and photocatalytic materials by applying $\text{TiO}_2/\text{Cu}_2\text{O}$ composites to an eco-friendly bamboo fiber-based packaging system. It differs from earlier works by combining sustainable local materials with visible-light-active photocatalysts, offering a more practical and environmentally-friendly approach to extending the shelf life of tropical fruits.

The most difficult aspect of this research was achieving uniform dispersion of $\text{TiO}_2/\text{Cu}_2\text{O}$ nanoparticles within the bamboo fiber matrix. This was addressed by optimizing the mixing process and using controlled stirring and calcination to ensure even particle distribution and consistent paper quality.

We discovered that combining bamboo fibers with $\text{TiO}_2/\text{Cu}_2\text{O}$ composites can effectively delay fruit ripening while maintaining paper quality. This finding highlights the potential of sustainable, nanomaterial-based packaging to reduce postharvest losses and support eco-friendly agricultural practices. The most interesting finding was that paper containing 3%–5% $\text{TiO}_2/\text{Cu}_2\text{O}$ significantly delayed the ripening of mangoes and tomatoes under natural light. It was surprising that this visible-light-active composite effectively worked without UV exposure, making it more practical for real-world fruit packaging applications.



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Mills can use the information presented here to develop new paper products with ethylene scavenging properties, giving them a competitive edge in the growing market for smart and sustainable packaging. By utilizing abundant bamboo fibers and $\text{TiO}_2/\text{Cu}_2\text{O}$ technology, they can reduce production costs while promoting environmentally responsible innovation.

Our next step in this research is to improve the formulation and processing of the $\text{TiO}_2/\text{Cu}_2\text{O}$ bamboo composite to enhance its strength and long-term effectiveness. Future research can also focus on testing other fruit varieties and integrating the material into commercial packaging systems.

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