

Research article

Development of Carboxymethyl Cellulose/Starch Film Composites Using Cellulose from Sugarcane Bagasse and Titanium Dioxide for Active Food Packaging Applications

Peeraches Buathongvong¹, Chanakan Phewklieng¹, Khemthat Srisujaritpanich¹, Pattara Somnuake^{1,2}, Wikoramet Teeka¹ and Sirirat Wacharawichanan^{1*}

¹Department of Chemical Engineering, Faculty of Engineering and Industrial Technology, Silpakorn University, Nakhon Pathom, 73000, Thailand

²School of Integrated Science and Innovation, Sirindhorn International Institute of Technology (SIIT), Thammasat University, Pathum Thani, 12120, Thailand

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Abstract

The development of an active food packaging film from carboxymethyl cellulose (CMC), starch, glycerol, and microcrystalline cellulose (MCC) to enhance mechanical strength and moisture resistance, which was synthesized from sugarcane bagasse (SCB), and titanium dioxide (TiO₂) was investigated. The MCC was chemically extracted from SCB via alkaline treatment, hydrogen peroxide oxidation, and acid hydrolysis, resulting in 92% cellulose purity, as confirmed by Fourier Transform Infrared (FT-IR) spectroscopy and X-ray diffraction (XRD). The biofilms were prepared using the solution casting method with 3 conditions: CMC/starch, CMC/starch/MCC, and CMC/starch/MCC/TiO₂. Incorporating MCC and TiO₂ significantly improved tensile strength (21.57 MPa to 42.79 MPa) and Young's modulus (1258 MPa to 1568 MPa). These additions decreased water solubility from 22.1% to 0.7%. FT-IR analysis of the films showed enhanced CH bonding of CMC in high content without any reaction. Biodegradability tests showed complete degradation within 7 days. Shelf-life extension tests demonstrated that bananas wrapped with CMC/starch/MCC/TiO₂ film lasted up to 12 days, compared to 5-6 days for unwrapped samples, with the addition of TiO₂ effectively scavenging ethylene without compromising film integrity. These results demonstrate the feasibility of SCB-derived MCC for sustainable, high-performance food packaging.

Keywords: carboxymethyl cellulose (CMC); microcrystalline cellulose (MCC); bio-food packaging films; polymer composites; titanium dioxide (TiO₂)

1. Introduction

The issue of plastic pollution is not only a threat to the environment but also to the health of mankind. The vast majority of traditional plastics are not readily biodegradable, resulting

*Corresponding author: E-mail: wacharawichanan_s@su.ac.th

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in their accumulation in oceans, rivers, soils, and other ecosystems (Geyer et al., 2017; Buaruk et al., 2024; Thar et al., 2025). These plastics severely affect numerous organisms, including aquatic animals and countless others in the food chain. It was estimated that over 368 tons of plastic were produced globally in 2019. Moreover, only 9% of it was recycled, while a staggering 79% of it became an environmental pollutant (Plastics Europe, 2020). Microplastics that contaminate various water sources, soil, and even food are a byproduct of the decomposition of plastic waste. The accumulation of plastic waste has very dire human and ecosystem health implications (Rochman et al., 2013; Jambeck et al., 2015). Apart from water contamination issues, plastic production exacerbates the situation by being one of the leading contributors to the emissions of greenhouse gases. The plastic industry alone is estimated to account for 3.8% of the global carbon dioxide emissions (Zheng & Suh, 2019). One way to mitigate these issues is by introducing biodegradable plastic alternatives, most notably the introduction of biodegradable films. The use of starch and carboxymethyl cellulose (CMC) in substitution for synthetic plastics can be auspicious due to their biodegradability (Siripatrawan & Harte, 2010; Shankar & Rhim, 2018).

However, the development of starch-based biofilms faces significant challenges due to the inherent brittleness and poor water resistance of the films, limiting their practical applications in packaging and other fields (Sothornvit & Krochta, 2005). Other works have strategically incorporated glycerol as a plasticizer to overcome these limitations and disrupt intermolecular polymer forces, enhancing film flexibility and processability. Glycerol, a colorless, odorless, viscous polyol compound with three hydroxyl groups ($C_3H_8O_3$), effectively penetrates between polymer chains, reducing hydrogen bonding and increasing molecular mobility, substantially improving elongation properties. However, careful optimization of glycerol concentration is essential, as excessive amounts can adversely affect moisture absorption properties and diminish tensile strength (Pereda et al., 2011; Sridach et al., 2013). Microcrystalline cellulose (MCC) derived from agricultural waste streams, particularly sugarcane bagasse (SCB), has emerged as a promising reinforcing agent that significantly improves the mechanical properties of these biofilms, simultaneously enhancing tensile strength while reducing water vapor transmission rates. SCB represents a desirable MCC source as it constitutes an abundant agricultural lignocellulosic byproduct generated in massive quantities during sugar production. It offers environmental and economic advantages through its low cost, widespread availability, and minimal environmental impact when repurposed. The structural composition of SCB, like most plant biomass, includes approximately 33% of cellulose as the primary constituent of rigid cell walls, alongside varying proportions of hemicellulose, lignin, pectin, and protein. This high cellulose content makes SCB particularly valuable for the extraction of MCC for biofilm reinforcement applications (Mzimela, 2018). Combining optimized glycerol levels with SCB-derived MCC represents a promising approach for developing high-performance, environmentally sustainable biofilms with balanced mechanical and barrier properties suitable for packaging applications (Rachtanapun & Wongchaiya, 2012).

Due to its multifunctional properties, titanium dioxide (TiO_2) is a significant additive for biodegradable films in food packaging applications. TiO_2 can be incorporated into active food packaging films in a way that adsorbs and photocatalytically degrades ethylene, slowing fruit ripening and increasing shelf life. TiO_2 nanoparticles contain reactive sites where ethylene molecules can attach and can then be oxidized into non-toxic products. At the same time, the TiO_2 composite films also provide UV-protection to food from photo-degradation, implying the delay of post-harvest loss. TiO_2 nanoparticle active food packaging is a highly effective way of utilizing the synergistic benefits of dual active packaging in improving the shelf life of food (Maneerat & Hayata, 2008; Hashimoto & Sakamoto, 2011; Maldonado et al., 2024). Beyond this active packaging function, TiO_2

provides critical UV-blocking capabilities and protects the packaging material with food products protection from degradation caused by exposure to ultraviolet radiation. Other research demonstrated that TiO₂-enhanced biofilms exhibited improved mechanical strength and barrier properties against oxygen and moisture, addressing key limitations of conventional biopolymer films (Pereda et al., 2011; Othman et al., 2014). These enhancements collectively contribute to extended shelf life for perishable foods while maintaining the environmental benefits of biodegradable packaging. Incorporating TiO₂ represents an essential advancement in sustainable food packaging technology that addresses food waste reduction and environmental concerns. TiO₂ has also been shown in several studies to improve the film's resistance to UV light and prolong its shelf life (Othman et al., 2014; Goudarzi et al., 2017; Tunma, 2018).

In addition to the formulation of materials, processing conditions also affect the final performance of bio-composite films. Heat treatment after processing has been shown to reorganize the structure, improve molecular orientation, and increase crystallinity index in composite films (Rahmadiawan et al., 2024). These achievements from the heat treatment will reduce chain mobility and voids, leading to stiffer, stronger, and improved barrier properties but less flexibility. For example, heat treatment of starch and cellulose films was found to increase tensile modulus but low break elongation when compared with unheated, because of the amplified crystallinity and densification (Ali & Dash, 2023). Nonetheless, no thorough preliminary or systematic study of heat treatment on CMC/starch films with MCC and TiO₂ as reinforcements has been conducted.

In this study, biofilms derived from CMC and starch using MCC from sugarcane bagasse, glycerol, and TiO₂ were formed using the film casting method, and their mechanical, morphological, chemical structures, water-soluble, and anti-deterioration properties were examined. Bagasse, a waste product of Thailand's sugarcane and sugar industries, was upcycled. This research can be valuable, as it can also assist in reducing the consumption of traditional plastics and plastic trash. Lastly, the product's resistance to humidity and oxidation in an ambient environment was examined for application in banana-shrunk films.

2. Materials and Methods

2.1 Materials

The materials used in this study included carboxymethyl cellulose (CMC), cassava starch, microcrystalline cellulose (MCC), titanium dioxide (TiO₂), glycerol, and various chemicals for cellulose extraction. CMC was obtained from Sigma-Aldrich, USA, with a viscosity range of 50-200 centipoise for a 4% solution at 25 °C. Cassava starch, sourced from the "Five Stars Fish" brand, served as the primary polymer matrix. MCC was either extracted from sugarcane bagasse, specifically the Suphan 50 variety, or was procured from the Ban Pong market in Ratchaburi Province. TiO₂ particles, in anatase phase with particle sizes ranging from 20-80 nm, were supplied by Sigma-Aldrich. Glycerol, acting as a plasticizer, was obtained from UNIVAR. The chemicals used for MCC extraction included sodium hydroxide (NaOH, 98% grade AR), hydrogen peroxide (H₂O₂, 30% grade AR), and hydrochloric acid (HCl, 37% grade AR), all sourced from reputable suppliers, Loba Chemie Pvt. and QREC. The MCC commercial was purchased from Sigma-Aldrich, USA.

2.2 Synthesis of MCC from sugarcane bagasse

The extraction of MCC from sugarcane bagasse involved a series of chemical treatments to isolate and purify the cellulose. Initially, the bagasse was washed thoroughly to remove surface impurities, sun-dried, and cut into small pieces. The material was soaked in a 10% (w/v) NaOH solution overnight and boiled at 80 °C for 4 h to remove lignin and hemicellulose. Subsequently, it was treated with a solution of 10% (v/v) H₂O₂ in 0.5 M NaOH at 60 °C for 2 h to purify cellulose. Acid hydrolysis was performed using 4 M HCl at 80 °C for 1 h to eliminate residual components (Thiangtham et al., 2020). After these treatments, the cellulose was washed repeatedly with distilled water until a neutral pH was achieved. The final product was dried, milled using a pulverizer at 350 rpm for 20 min, and sieved through a 42-mesh screen to obtain MCC. The MCC was then stored in a desiccator until use.

2.3 Preparation of CMC/starch, CMC/starch/MCC, and CMC/starch/MCC/TiO₂ cast films

All films were prepared using the solution casting method. For the CMC/starch film, 1 g of CMC/starch (60:40) matrix film was prepared by adding CMC to 40 mL of DI water and leaving it overnight, then stirring at 80 °C for 1 h, and adding starch to 20 mL of water and stirring at 80 °C for 30 min (Sridach et al., 2013). For the CMC/starch/MCC film, 2 wt% of MCC (relative to the CMC/starch matrix) was incorporated together with starch during film preparation (Tongdeesoontorn et al., 2011). For the CMC/starch/MCC/TiO₂ film, 2 wt% of MCC and 2 wt% of TiO₂ (relative to the CMC/starch matrix) were incorporated together during film preparation. After that, the CMC and starch were mixed and stirred at 80 °C for 1 h before 20 phr of glycerol was added and stirred at 80 °C for 30 min (Rachtanapun et al., 2007). After that, the mixture was sonicated with an ultrasonic bath for 30 min before casting onto a glass petri dish and baked in an oven at 65 °C for 12 h. The film thickness was 0.04 mm. Finally, the film was heat-treated at 135 °C for 1 h in the oven.

2.4 Characterizations

The surface morphology of MCC and composite films was observed by a field emission scanning electron microscope (FE-SEM) (MIRA3, TESCAN, Czech) at 20 kV, and the specimens were observed after gold coating. Fourier transform infrared (FT-IR) spectroscopy was applied to verify the samples' chemical structures and functional groups in a range from 600 to 4000 cm⁻¹ with a resolution of 4 cm⁻¹ and 32 scans on a BRUKER (ALPHA II). The crystallinity of MCC was investigated utilizing X-ray diffraction (XRD) (D8 Advance, Bruker, USA). The crystallinity (%X_c) was calculated according to equation 1. The universal testing machine (UTM) (EZ Test, EZ-LX/EZ-SX Series, Shimadzu, Japan) was used to test the mechanical properties of the films using ASTM D 882 at a 50 mm/min crosshead speed. The tensile test result was an average of five specimens. UV-visible light absorption was measured using a spectrophotometer (PG Instruments T92+) in the range of 200-800 nm. The UV-blocking ability of TiO₂ was evaluated by comparing the absorbance spectra of films with and without TiO₂. Solubility in water was illustrated by cutting the film into a piece of 3 cm², then the dried films were weighed, representing the initial dry weight. Next, the films were soaked and allowed to swell in RO water for 24 h. After that, they were placed in an oven at 60 °C overnight. They were then weighed again for the final dry weight. The percentage of total soluble matter (%TSM) was calculated from

equation 2, and the data analysis was calculated from 3 replicates. A biodegradation test was performed by burying the films in soil. First, the film samples were cut into pieces of 3 cm². A box containing soil was prepared under controlled conditions at a temperature of 32 °C and relative humidity of 60%, with soil moisture content of 20-25% and pH 6.5. The films were then buried in the soil box, and the samples were weighed every 24 h to represent the biodegradation model. Before weighing, loose soil particles attached to the film surface were gently brushed off to reduce errors caused by soil adhesion. Finally, the banana shelf-life extension was tested by comparing the color of bananas packed and unpacked with CMC/starch/MCC/TiO₂ films after 15 days in an area exposed to ultraviolet light at room temperature.

$$\%X_c = \frac{I_{\text{cry}}}{I_{\text{cry}} + I_{\text{amo}}} \times 100 \quad (1)$$

I_{cry} is the area of the crystalline peak.

I_{amo} is the area of the amorphous region.

$$\%TSM = \frac{\text{initial dry weight} - \text{final dry weight}}{\text{initial dry weight}} \times 100 \quad (2)$$

3. Results and Discussion

3.1 Morphology, chemical structures, and crystallinity of synthesized MCC

MCC was prepared from SCB by simple chemical treatments, including alkaline treatment, hydrogen peroxide oxidation, and acid hydrolysis, which effectively removed lignin, hemicelluloses, and other non-cellulosic compounds. The yield of MCC overall was about 28%, which was relatively reasonable compared to the weight of cellulose composition in the sugarcane bagasse. The estimated average particle size based on SEM micrographs was approximately 0.65 µm, confirming that the extraction produced fine cellulose particles suitable for reinforcement composite films. As shown in Figure 1, FT-IR confirmed cellulose with a broad peak in O-H stretching vibration at 3330 cm⁻¹ and a broad peak in C-H stretching of cellulose vibration at 2900 cm⁻¹ (Liu et al., 2006). The absence of the 1730 cm⁻¹ C=O stretching peak of hemicellulose and 1240 cm⁻¹ C-O-C stretching of lignin confirmed the removal of lignin and hemicellulose, and the peak at 1034 cm⁻¹ confirmed the pyranose ring structure of cellulose (Romruen et al., 2022; Malarat et al., 2023). The peak at 897 cm⁻¹, associated with β-glycosidic linkages with amorphous cellulose, appeared more intense in SCB-derived MCC than in commercial MCC, indicating a higher amorphous content. As shown in Figure 2, sharp diffraction peaks at 2θ of 16.2°, 22.6°, and 34.5° in XRD corresponded to the crystalline structure of cellulose I (Phan et al., 2024). The extracted MCC's %X_c was calculated to be 68.5%, slightly lower than the 74.3% observed in the commercial MCC. This difference was likely due to the remaining amorphous regions in the extracted MCC. SEM images further confirmed the successful extraction, showing the smooth fibrous structure characteristic of pure cellulose. In contrast to the rough and irregular morphology of untreated SCB, as shown in Figure 3. These results demonstrate that the MCC from bagasse exhibits high crystallinity. It has desirable chemical properties and a suitable morphology for application as a reinforcing agent in bio-composite films.

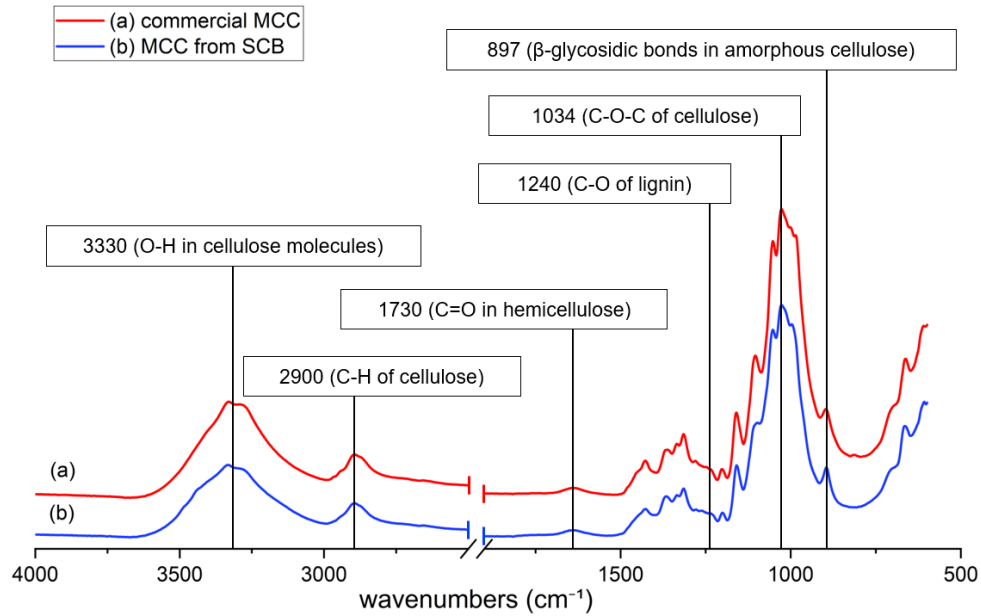


Figure 1. FT-IR spectra of (a) MCC from SCB and (b) commercial MCC

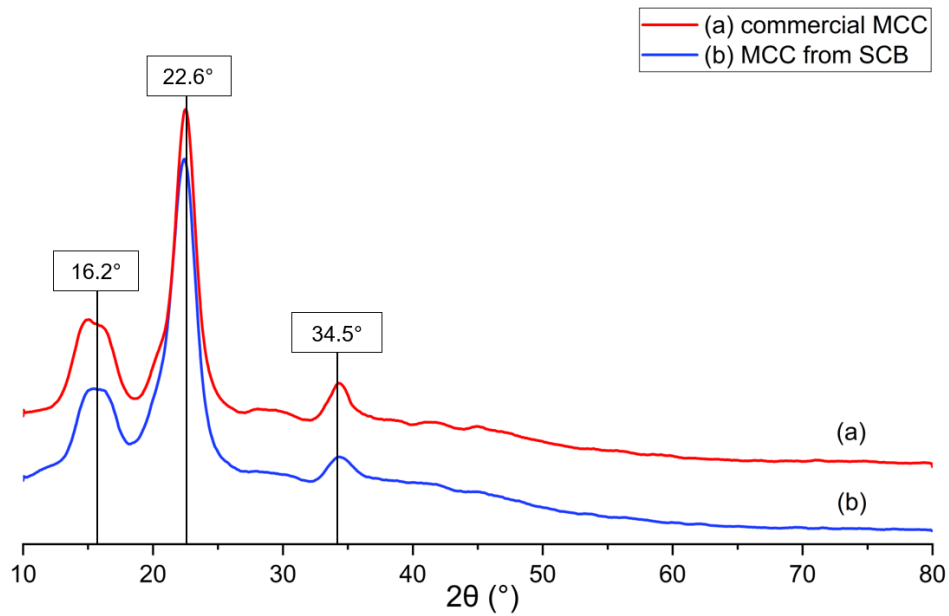


Figure 2. XRD patterns of (a) MCC from SCB and (b) commercial MCC

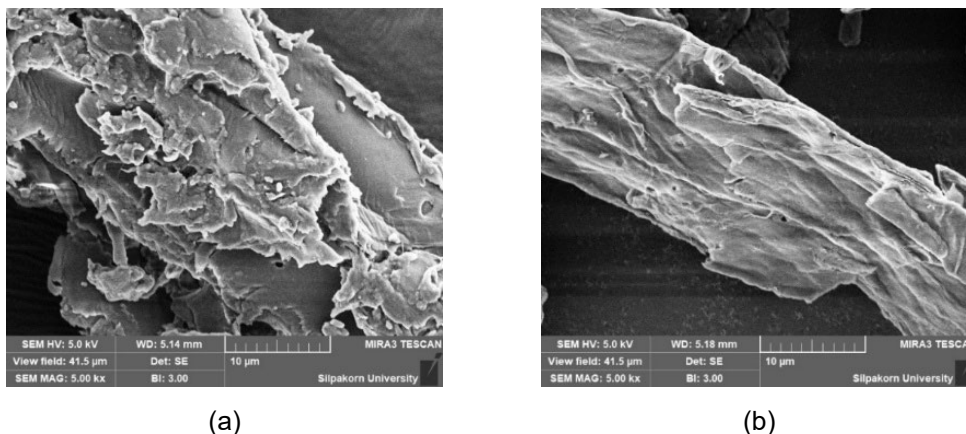


Figure 3. SEM micrographs of (a) 5000X SCB and (b) 5000X MCC from SCB

3.2 Characterization of CMC/Starch, CMC/Starch/MCC, and CMC/Starch/MCC/TiO₂ Films

3.2.1 Mechanical properties

Figure 4 summarizes the composite films' mechanical properties, highlighting the heat treatment's significant effect. A clear difference was observed for the treatments. The Young's modulus increased substantially with heat treatment for all compositions, rising from 1259 MPa for the CMC/starch film to 1556 MPa and 1568 MPa for the CMC/starch/MCC and CMC/starch/MCC/TiO₂ films, respectively. A similar trend was observed for tensile strength, and the CMC/starch/MCC/TiO₂ film achieved a maximum of 43 MPa, whereas the heat-treated CMC/starch control was at 22 MPa. The non-heated films showed low stiffness but were quite flexible. The CMC/starch film without treatment had a strain at break of 10.5%, nearly three times greater than its treated counterpart at 3.66%. The ductile characteristics are due to the high amorphous regions, which allow for greater chain mobility. Earlier research conducted with composite films also indicated that heat treatment increased the crystallinity index, which limited molecular mobility and led to a higher load-bearing capacity (Rahmadiawan et al., 2024). This structural densification and improved filler–matrix interactions account for the greater tensile strength values for heat-treated CMC/starch/MCC/TiO₂ films than non-heat-treated films. Overall, heat treatment improved toughness and tensile strength due to the increased crystallinity and densification of CMC and starch, although this comes at a cost of flexibility. In addition, MCC and TiO₂ provided additional reinforcement to the films, with the CMC/starch/MCC/TiO₂ sample showing the most significant effect, particularly when heat-treated. Overall, these results highlight the importance of post-processing in obtaining mechanical properties supportive of active food packaging applications (Rachtanapun et al., 2007; Sangeetha et al., 2016; Saeed, 2020; Van Nguyen & Lee, 2022; Teeka et al., 2024).

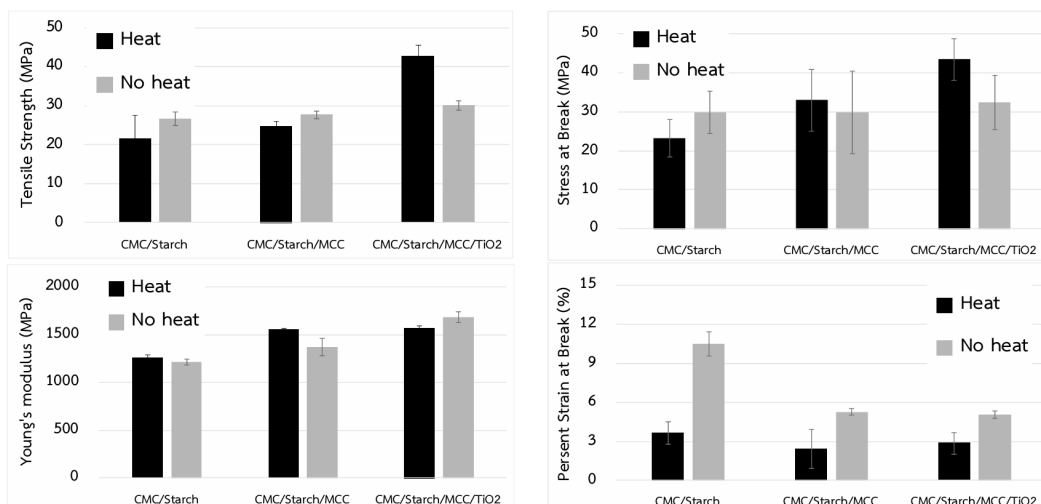


Figure 4. Mechanical properties of CMC/starch, CMC/starch/MCC, and CMC/starch/MCC/TiO₂ films with and without heat treatment

3.2.2 Chemical structures

The FT-IR spectra of all the composite film samples, as shown in Figure 5, had characteristic absorption bands corresponding to the polysaccharide and glycerol base materials. A broad strong band at about 3250 cm⁻¹ was present in all samples, indicating O-H stretching vibrations. The peak represents hydroxyl groups derived from CMC, starch, and MCC, which contain three hydroxyl groups per molecule. The intensity of this band was observed to be highest for the CMC/starch film and decreased for the CMC/starch/MCC and finally the CMC/starch/MCC/TiO₂ films. The intensity decrease indicates more hydroxyl groups from glycerol participating in hydrogen bonding with cellulose chains and TiO₂ particles, reducing the available free-OH groups and resulting in a denser film structure, indicating stronger hydrogen bonding upon filler incorporation (Tongdeesoontorn et al., 2011). The peak at 2920 cm⁻¹ represented C-H stretching vibrations of an aliphatic chain originating from polysaccharide and glycerol. This band was consistently observed in all samples, indicating that biopolymers exist in the structures. A strong peak at 1588 cm⁻¹, associated with the asymmetric stretching of carboxylate groups (COO⁻) in CMC, became more distinct with MCC and TiO₂. It indicates a stronger interaction between the carboxylate groups and the reinforcing agents, thereby increasing the cohesion of the films (Tongdeesoontorn et al., 2011). The peak at about 1413 cm⁻¹ was assigned to the CH₂ symmetric scissoring vibration, which is characteristic of cassava starches, demonstrating that the structural characteristics of the starch were lost in the film matrix (Abdullah et al., 2018). The absorption band at 1014 cm⁻¹ represents C-O-C stretching vibrations of the polysaccharide backbone and the pyranose ring structure (Chen et al., 2017; Somnuake et al., 2024). The FT-IR analysis showed a signature band for the glucopyranose ring of starch at 853 cm⁻¹, and a smaller absorption band at about 690 cm⁻¹ in the CMC/starch/MCC/ TiO₂ film (Al-Amin et al., 2016; Abd El-Ghany & Mahmoud, 2021). The 690 cm⁻¹ band corresponds to the Ti-O stretching vibration of TiO₂, confirming the presence of TiO₂ in the composite, as confirmed in Figure 6. Peaks that did not conform to CMC or starch in the composite were not identified, indicating that TiO₂ was not forming

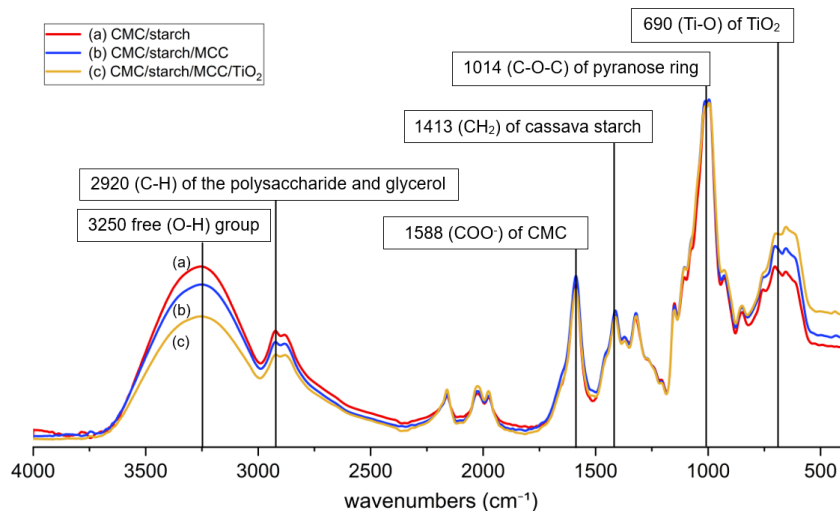


Figure 5. FT-IR spectra of (a) CMC/starch, (b) CMC/starch/MCC, and (c) CMC/starch/MCC/TiO₂ films

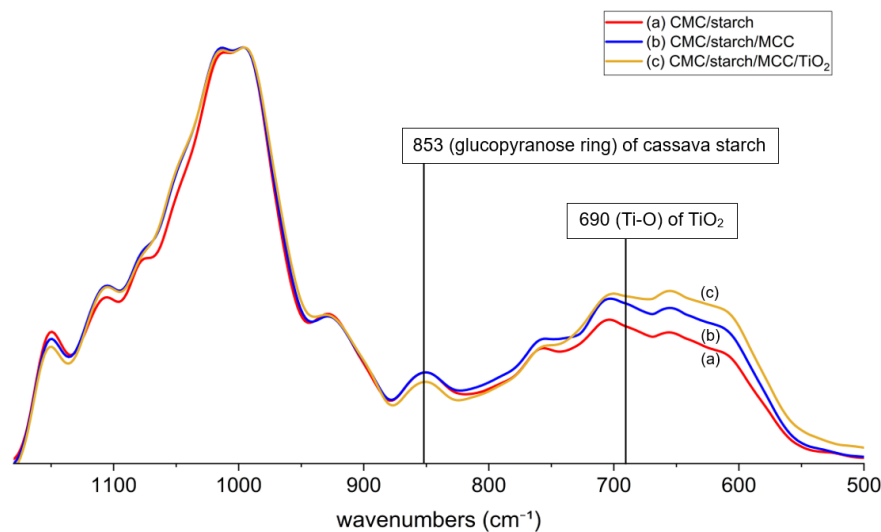


Figure 6. FT-IR spectra after baseline correction of (a) CMC/starch, (b) CMC/starch/MCC, and (c) CMC/starch/MCC/TiO₂ films

new chemical bonds with the polymer matrix. TiO₂ was likely interacting with the polymers physically by hydrogen bonding or Van der Waals forces. The excellent dispersion of TiO₂ in the polymer infrastructure, as seen in the SEM micrographs, lends credence to this hypothesis. The current study is consistent with previous published studies that reported Ti-O stretching at 680-700 cm⁻¹ in TiO₂ containing biopolymer composites (Dhandayuthapani et al., 2016).

3.2.3 Morphology

The morphology of the films revealed differences in surface characteristics among the three film types, as shown in Figure 7 (a-c). The CMC/starch film displayed a smooth and homogeneous surface, indicating good miscibility between the CMC and starch components. In contrast, the CMC/starch/MCC film showed visible dispersion of MCC particles throughout the matrix, with some irregularities or marks on the film surface caused by the incorporation of MCC. These marks may result from MCC particles protruding slightly from the matrix or uneven distribution during film preparation. For the CMC/starch/MCC/TiO₂ film, SEM characterization was illustrated in backscattered electrons (BSEs) mode to define the TiO₂. Backscattered electrons (BSEs) are energetic particles that rebound from a specimen after interaction with the primary electron beam, providing compositional contrast in microscopy. These high-energy electrons generate detailed images that reveal the spatial distribution of different elemental components within a sample, with heavier elements appearing brighter due to stronger electron backscattering. This technique allows researchers to visualize and analyze the compositional heterogeneity of materials at high resolution without destructive sample preparation (Sul, 2010; Dyukov & Nepijko, 2020). The addition of TiO₂ further enhanced the uniformity of particle dispersion, with fewer visible surface irregularities in the CMC/starch/MCC film. The improved tensile properties can be attributed to the increased crystallinity of heat treatment and the strong interfacial interactions between the fillers and the polymer matrix. The plentiful OH groups on the MCC formed hydrogen bonds to starch and CMC, respectively, which decreased the hydrophilicity and polarity. Likewise, TiO₂ nanoparticles also possess surface hydroxyl groups that could form hydrogen bonding or dipole–dipole interactions with the polymer chains. These interactions would give better dispersion and reinforcement, which contribute to the increased tensile strength of the treated films, especially the CMC/starch/MCC/TiO₂ film (Wacharawichanant et al., 2014; Wacharawichanant et al., 2018).

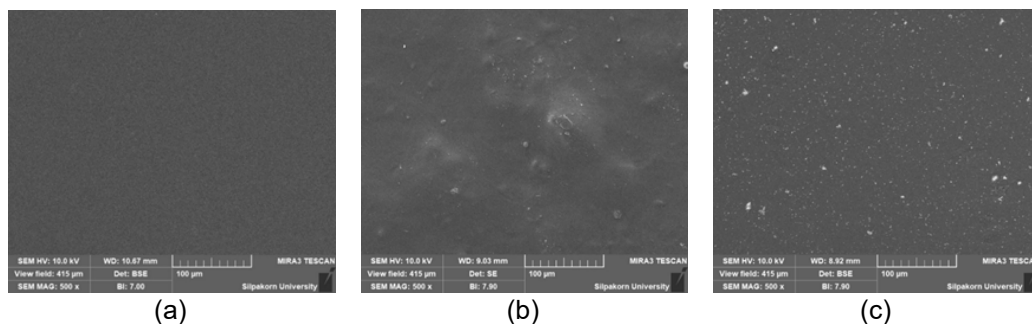


Figure 7. SEM micrographs of (a) CMC/starch, (b) CMC/starch/MCC, and (c) CMC/starch/MCC/TiO₂ films

3.2.4 UV absorption

The UV–Vis spectra in Figure 8 show significant differences in light absorption between each film. The CMC/starch and CMC/starch/MCC films exhibited high absorption in the UV region (200–300 nm) and low absorption in the visible region, providing them with some

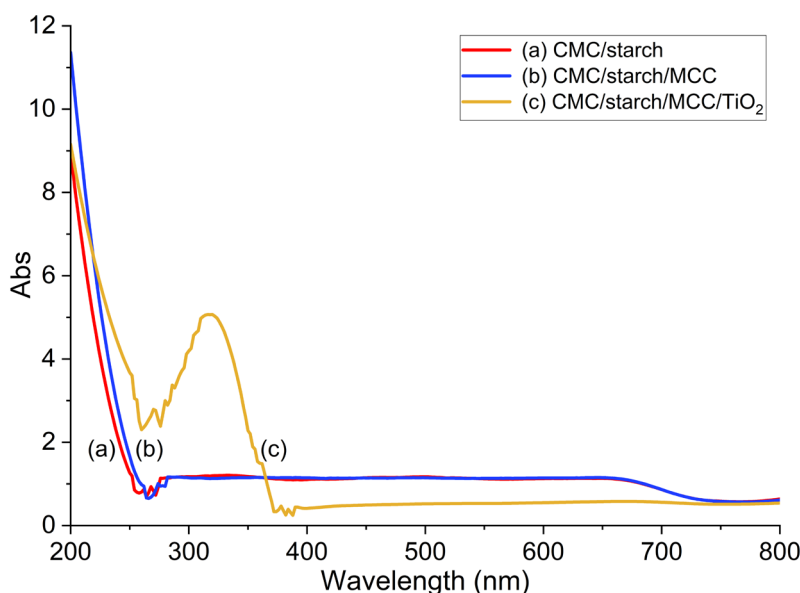


Figure 8. UV-Visible absorption spectra (a) CMC/starch, (b) CMC/starch/MCC, and (c) CMC/starch/MCC/TiO₂ films

natural UV-blocking potential. The CMC/starch/MCC/TiO₂ film, however, had a higher and wider absorbance peak also in the UV region (overall between 250-375 nm). It can be attributed to the TiO₂ nanoparticles, as TiO₂ is well known for its strong UV-blocking properties. Moreover, the result shows a peak generally within around 300-330 nm, aligning well with the radiation scattering and absorbing characteristics of TiO₂ (Hashimoto & Sakamoto, 2011). The absorbance in the visible region (>400 nm) was still relatively low, indicating that the film maintained considerable transparency. Overall, these data were interpreted to imply that incorporating the TiO₂ enhanced the films' capability to block UV radiation while maintaining visual translucent properties. This ultimately improves the functionality of the film for its intended purpose of food packaging application, which requires protection from light (Goudarzi et al., 2017).

3.2.5 Solubility in water

From Table 1, the addition of MCC and TiO₂, the film's water solubility dramatically dropped. The CMC/starch/MCC/TiO₂ film showed the lowest water solubility. The enhanced crosslinking and denser structure produced by the heat treatment were most likely the cause of the decrease in water solubility. A lower level of water absorption into the films was facilitated by the presence of MCC, which is crystalline. It is also commonly recognized that TiO₂ acts as a barrier to prevent the film from dissolving. The results of the CMC/starch films explained that their water solubility was significantly higher because of their less compact structure and absence of reinforcing ingredients. Overall, the degree of water solubility indicates that the CMC/starch/MCC/TiO₂ film displayed less water solubility, which is advantageous for applications with low water solubility (Nguyen & Lee, 2022).

Table 1. Percentage TSM of CMC/starch, CMC/starch/MCC, and CMC/starch/MCC/TiO₂ film

Sample	TSM (%)
CMC/starch	22.1±1.6
CMC/starch/MCC	8.5±0.3
CMC/starch/MCC/TiO ₂	0.7±0.1

3.2.6 Soil burial biodegradation weight loss

The biodegradation profile depicted in Figure 9 demonstrates the progressive weight loss of CMC/starch/MCC/TiO₂ biofilm during a seven-day soil burial test, clearly illustrating its complete decomposition within a week. The degradation follows a non-linear pattern, with weight loss accelerating over time and complete decomposition (100%) within a week. This rapid and complete biodegradation occurs despite incorporating MCC and TiO₂ additives, confirming that these functional components do not impede the film's environmental decomposition. The ascendancy of the natural polymer matrix (CMC/starch) in the composite structure effectively maintains the material's biodegradability while still benefiting from the improved mechanical properties, UV resistance, and ethylene scavenging capabilities that MCC and TiO₂ provide (Almasi et al., 2010; Nguyen & Lee, 2022). The soil burial biodegradation weight loss was calculated by weighing the films, which could not reveal the status of small pieces of plastic, such as micro- and nano-plastic. However, the result shows that it was a hundred percent gone, which suggests that they defoliated much more quickly than the others. Soil adhering to film surfaces could impact weights, but the samples were brushed lightly before weighing, limiting the sources of error. Thus, weight loss can be viewed as complete biodegradation. The characteristic was consistent with previous results on starch/CMC films that were said to have degraded entirely in 7 days, within soils buried (Hu et al., 2024). Moreover, the consistency of our results compared with other work confirmed that MCC and TiO₂ did not inhibit the biodegradation of the polymer matrix. For comparison, PLA films possess relatively stable properties within a soil burial environment with temperature and moisture values normal for that setting, and typically take weeks to months to lose weight visibly, and rarely undergo complete degradation within a week (Vasile et al., 2018). This stark difference underscores the advantage of the CMC/starch/MCC/TiO₂ biofilms regarding environmental sustainability when rapid biodegradability is needed. This optimal balance between functional performance and environmental safety makes these biofilms particularly suitable for sustainable food packaging applications where extended shelf life and post-consumer biodegradability are essential (Snakin et al., 1996; Suderman et al., 2016).

3.2.7 Extend the shelf-life of bananas

Based on the visual indication in Figure 10, the CMC/starch/MCC/TiO₂ film demonstrated remarkable efficacy in extending banana shelf life by approximately 2 times compared to unpackaged controls. The images clearly illustrate that unpackaged bananas progressed through ripening stages rapidly, transitioning from green to yellow with brown spots by day 6-9. In contrast, film-packaged bananas maintained a predominantly green appearance with minimal yellowing even at day 15. This preservation effect can be attributed to the synergistic properties of the composite film components. MCC enhanced mechanical strength and barrier properties, ensuring effective sealing and protection. TiO₂ functioned

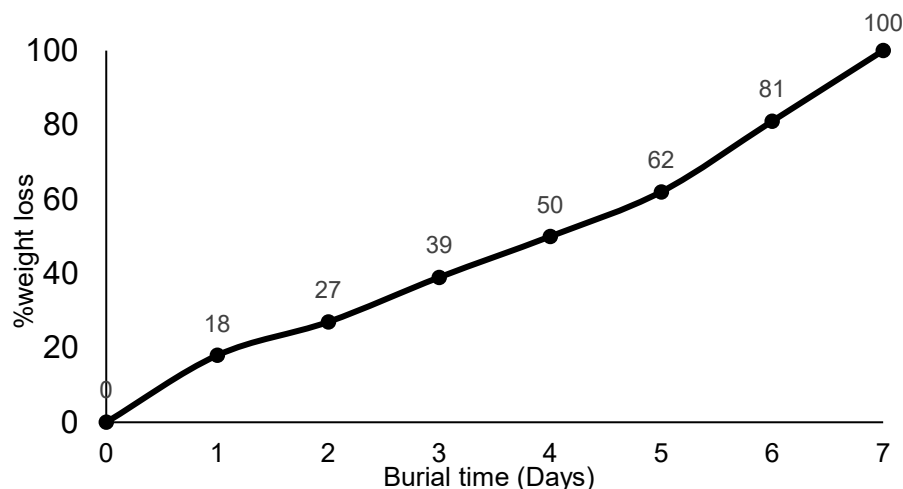


Figure 9. Weight loss (%) of CMC/starch/MCC/TiO₂ film

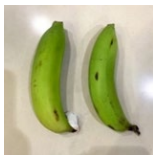
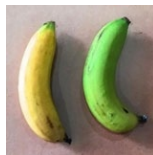
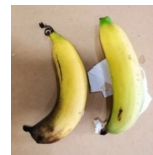
Time (Day)	3		6		9		12		15	
	Unpack	Pack	Unpack	Pack	Unpack	Pack	Unpack	Pack	Unpack	Pack
Picture										

Figure 10. Characteristics of bananas between pack and unpack with CMC/starch/MCC/TiO₂

as an ethylene scavenger to inhibit ripening, while the CMC and starch-based stimulated by heat treatment. It provided the improvement of moisture protection, stability, and structural integrity (Maneerat & Hayata, 2008; Maldonado et al., 2024). These results strongly suggest that the CMC/starch/MCC/TiO₂ composite film represents a promising active packaging solution for extending the marketable period of perishable fruits like bananas, with potential commercial applications in reducing food waste and improving product quality during distribution and merchandising display (Anindita et al., 2024; Phattarateera et al., 2025).

4. Conclusions

This study showed the effective development of biodegradable composite films for active food packaging applications utilizing CMC, starch, MCC from sugarcane bagasse, and TiO₂. Alkaline treatment, oxidative bleaching, and acid hydrolysis were used to separate the MCC from sugarcane bagasse. The product had a high cellulose purity and a crystallinity index of 68.5%, which was comparable to commercial MCC. MCC and TiO₂ were added to CMC/starch films and subsequently heat-treated, showing improved water resistance, chemical stability, and mechanical strength. SEM revealed images of a denser

and more homogeneous morphology, while FT-IR and XRD revealed strong regions of molecular interaction and crystalline structure in the films. By extending the shelf life of bananas by 12 days and facilitating ethylene scavenging, the addition of TiO₂ highlighted the active packaging properties. Under soil burial conditions, all types of composite films containing TiO₂ maintained complete biodegradability within 7 days. This suggests that composites made from MCC from agricultural waste with functional nanoparticles like TiO₂ can produce high-performance and sustainable biopolymer films appropriate for food packaging applications to help reduce plastic pollution and increase participation in a circular bioeconomy. Future studies should cover the film preparation's scale-up and assess their potential for industrial-scale production. Comprehensive cost analyses and market feasibility assessments should be conducted to determine the cost-effectiveness of these films compared to conventional plastic packaging. Furthermore, life cycle assessment (LCA) studies would complement this research by evaluating the environmental benefits of switching to these polymeric biofilms. These assessments would help bridge the gap between laboratory-scale breakthrough innovations and commercial deployment.

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6. Authors' Contributions

P.B. and C.P. conceptualized, experimented, and analyzed the data. K.S. wrote the first draft paper and rearranged images and tables. P.S. analyzed the data, reviewed, edited, and contributed to the final draft. W.T. arranged image. S.W. conceptualized, supervised all experiments, reviewed, and edited.

ORCID

Pattara Somnuake  <https://orcid.org/0009-0001-7915-5843>

Sirirat Wacharawichanant  <https://orcid.org/0000-0002-2726-0756>

7. Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

8. AI Declaration

The preparation of this manuscript by Chat GPT and Claude AI in order to check facts and research some ideas has been reviewed and edited as needed by P.S. and S.W. The authors take full responsibility for the content of the publication.

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