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Cellulosic sol barrier coating for nonclimacteric star apple (*Chrysophyllum cainito* L.) preservation

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This study demonstrated the great performance of a surfactant free cellulose-based sol barrier coating for extending the shelf life of a non-climacteric fruit – star apple (*Chrysophyllum cainito* L.). Microfibrillated cellulose (MFC) produced from a bleached kraft hardwood pulp and carboxymethyl cellulose (CMC) were mixed to form an aqueous sol for barrier coating. Dip coated star apples were evaluated for weight loss, external visual appearance of the pericarp and internal pulp quality in terms of dryness and color, pericarp firmness, and fruit pulp total dissolved solids. The results indicated that coating with CMC substitution for MFC improved fruit freshness and shelf life by at least 12 days. No respiration-limit induced star apple spoilage was observed even at 40% CMC substitution. The coating also significantly decreased fruit weight loss by up to 40% over two weeks of storage. Respiration measurements indicated that star apples, though non-climacteric, exhibited a postharvest ethylene surge associated with the decay of the fruit rather than ripening observed in climacteric fruits. Barrier coatings especially with high CMC substitution substantially delayed and decreased ethylene production and extended shelf life.

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Sustainability spotlight

This study developed a renewable plant cellulose-based formulation consisting of microfibrillated cellulose (MFC) and carboxymethyl cellulose (CMC) for barrier coating to extend the shelf-life of a tropical non-climacteric fruit – star apple. By decreasing post-harvest fruit spoilage, the barrier coating facilitates meeting the United Nations sustainability goal (SDG) 12.3. Compared with commercial refrigeration fruit preservation, the MFC/CMC barrier coating saves electricity to decrease environmental impact. Compared with literature methods using petroleum derived surfactants and/or nanoscale cellulose materials through extensive chemical and mechanical processing, the MFC/CMC formulation is more sustainable due to its low energy input for fibrillation and free of petroleum chemicals and chemical processing (SDG 13, Climate Actions).

1 Introduction

Caimito (*Chrysophyllum cainito* L., Sapotaceae), commonly called star apple, is a non-climacteric pantropical fruit valued for its sweet, jelly-like pulp and nutritional quality. It is grown across the Caribbean, Central and South America, and parts of Asia and is now cultivated in South Florida, USA.^{1–4} Star apples have a typical diameter of 5–10 cm and weight of 28–229 g^{4,5} in green or purple peel types with 47–57% edible pulp.^{2,3,6} The pulp is a good source of dietary fiber, minerals, vitamin C, and phenolic antioxidants, with total dissolved solids (TSS) of 10.3–27.7 °Brix and a titratable acidity of ~0.31% (citric acid).^{5,7,8} As a non-climacteric fruit, star apples are harvested at the fully

mature state. The fruit is mainly consumed fresh. However, star apples typically have a very short shelf-life of only a few days and are especially prone to post-harvest spoilage. Extending the shelf-life of star apples is therefore critically important to the economic bottom lines of growers and grocers. It is also important from food safety and sustainability points of view. The United Nations Sustainable Development Goal 12.3 sets the target of a 50% decrease in global food loss and waste in the production and supply chain by 2030 (<https://champions123.org/>, last accessed 05/18/2026). Currently, star apples are often stored at 3–6 °C and ~90% relative humidity (RH) for post-harvest preservation; however, refrigeration and humidity control increase energy costs as well as negative environmental impact associated with electricity production – another factor that decreases the sustainability of fruit production and distribution.

Among the various shelf-life extension methods for fruits and vegetables such as novel cellulose based composite films for packaging,⁹ barrier coating has attracted great interest for its effectiveness in preventing water loss, decreasing gas

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respiration (particularly important to delay the ripening process for climacteric fruits), and post-harvest disease and microbial load^{10–12} to result in extending fruit shelf life.^{13–15} Shellac, a lipid-based edible coating, has been commercially applied to fruits such as apples.¹⁶ Unfortunately, recent concern over the potential presence of residue pesticide in shellac and the difficulty in removing them through normal water washing¹⁷ resulted in some major retailers in Australia ceasing to sell shellac coated apples.¹⁶ Cellulose, the most abundant renewable natural polymer on Earth, can be sustainably produced and is a potential alternative for barrier coatings of fruits due to its great film forming capabilities through tight hydrogen bonding^{18,19} as we recently demonstrated using microfibrillated cellulose (MFC).^{20,21} Furthermore, cellulose is inherently benign to humans and safe for ingestion based on animal dietary²² and *in vitro* gastrointestinal digestion studies.²³ Therefore, cellulose migration through the coating layer should not be a health and safety concern. Furthermore, the U.S. Food and Drug Administration recently approved MFC for commercial barrier coating of bananas whose peels are not consumed.²⁴

Earlier studies on cellulose based coatings used chemically derived cellulose nanomaterials (CNM) and cellulose derivatives such as carboxymethyl cellulose (CMC) to make composite formulations with the application of petroleum derived surfactants.^{25–28} Producing CNM such as nanocrystals (CNC) and fibrils (CNF) often requires expensive chemical and mechanical processing with substantial energy consumption.²⁹ Therefore, using CNM and surfactants in existing studies represents a lack of sustainability. Fortunately, MFC is a sustainable alternative to CNM by directly fibrillating commercial wood fibers without additional chemical processing at microscales rather than nanoscales to significantly decrease fibrillation energy input. A relative comparative life cycle assessment (LCA) study indicated that direct fibrillating wood fibers to produce CNF without any pretreatment has lower environmental impact than using either enzymatic or chemical (TEMPO-mediated oxidation) treatments.³⁰ This conclusion was further reinforced by a recent quantitative study that reported numerical values of different environmental impact measures.³¹ Using MFC with significantly low mechanical energy input for fibrillation, for example with a specific fibrillation energy of only 13.0 MJ kg^{−1} in the present work (Table S1), lower than the 72 MJ kg^{−1} (20.0 kWh kg^{−1})³⁰ and 81.7 MJ kg^{−1} (22.7 kWh kg^{−1})³¹ used in these two reported LCA studies, will have much less environmental impact. Yet, satisfactory results were achieved in preventing gas permeation and extending fruit shelf life using MFC for barrier coating of bananas.²⁰ Directly adding CMC into MFC without surfactant and emulsification can further decrease the porosity of the film layer for proper fruit respiration and delaying browning of bananas.²¹

Most reported studies on barrier coating preservation were focused on climacteric fruits such as bananas,^{21,27} apples,^{32,33} mangos,^{34,35} and avocados.¹³ These fruits are harvested before ripening to extend shelf life and decrease post-harvest losses during transportation and storage.³⁶ Therefore, climacteric fruits experience a post-harvest ripening process signaled by a surge of ethylene production.^{37,38} The role and efficacy of

barrier coatings for preserving non-climacteric fruits with no post-harvest ripening are unknown and therefore deserve to be investigated. Furthermore, barrier coating studies on star apple – a non-climacteric fruit – are almost nonexistent. In this sense, this work is novel. Studies indicated that using ethylene production to distinguish climacteric and non-climacteric fruits is an oversimplification.³⁹ We hypothesize that barrier coating can also slow down deterioration of non-climacteric fruit quality by decreasing fruit respiration, similar to ethylene inhibiting treatment on non-climacteric fruits to depress primary metabolic changes.⁴⁰ A dense coating is desirable in terms of preventing water loss to decrease fruit weight loss. However, it was reported that proper regulation of gas respiration during barrier coating of climacteric fruits is important to avoid disrupting the climacteric fruit normal ripening process; for example, a too dense barrier coating of bananas at elevated CMC loadings in formulating MFC and CMC sol resulted in anaerobic digestion induced spoilage.²¹ To maximize the benefits of barrier coating by minimizing gas permeation, it is worth investigating whether a highly dense coating can induce non-climacteric star apples to undergo anaerobic digestion.

The objective of the present study was to evaluate the barrier coating of *Chrysophyllum cainito* fruit using plant-based MFC supplemented with CMC, a commercial food additive, as a sustainable formulation, for preventing gas, especially water vapor, permeation and regulating star apple respiration during storage. The coating formulation used only plant-based cellulosic materials at a substantially low total cellulosic solids loading of 0.75% with a maximal CMC loading of 0.3%, or 40% substitution, to form a cellulosic sol without emulsification and any other chemicals such as surfactants. Our research is aimed at developing general understanding of barrier coating performance for non-climacteric fruits that do not have a post-harvest ripening process. By formulating an economic and effective barrier coating technology using renewable and sustainably produced plant-based materials to substantially extend star apple shelf life, the study also facilitates market expansion for existing and prospective growers including those in South Florida, USA, through long distance shipping with reduced or no refrigeration and associated electricity consumption and environmental impact, while decreasing fruit spoilage in the supply chain to support the United Nations sustainable development goal of 12.3.

2 Materials and methods

2.1 Materials and cainito fruit

A virgin bleached kraft hardwood pulp (BKHP) was supplied by Smurfit Westrock Company (Atlanta, GA, USA). Its chemical composition and moisture content have been described in our previous work.²⁰ Sodium carboxymethyl cellulose with an average M_w of $\sim 700\,000$ was purchased from Sigma-Aldrich Corporation (St. Louis, MO, USA).

Horticulturally mature⁶ ‘Hipolito’ cainito (*Chrysophyllum cainito* L.) was harvested from the Tropical Fruit Grove at the University of Florida, Institute of Food and Agricultural Sciences (IFAS), Tropical Research and Education Center, Homestead,

Florida, in 2024 and 2025. At each harvest, a subsample of 20 dark purple star apples was used to measure the mean fresh weight (269.8 g; range: 229.6–320.1 g), mean diameter (77.3 mm; range: 74.5–82.1 mm), and mean pericarp pressure (5.9 N; range: 4.1–10.3 N). Fruit ripened within three to seven days after harvest, during which they lost an average weight of 20.9 g (7.5%), shrank diameter on average by 2.2 mm (2.8%), and reached a mean °Brix of 12.1 (range, 10.3–15.3 °Brix). The harvested star apples were shipped overnight to the USDA Forest Products Laboratory, Madison, WI, USA.

2.2 Preparation of MFC and MFC/CMC sols

The chemical composition of the BKHP was analyzed in an earlier study²⁰ with a cellulose and xylan content of approximately 72% and 23%, respectively. An aqueous suspension of the BKHP (100 g oven dry weight) at 2% consistency was disk milled in a stone disk grinder (SuperMassColloider (SMC), Model MKZCA 6-2 J, Disk MDGA 6-80#, Masuko Sangyo Co., Ltd, Japan). A MFC was obtained by milling the BKHP suspension at 800 rpm for 4 passes through the SMC as described previously.^{20,41,42} The electric energy consumption was 12.95 MJ kg⁻¹ BKHP (Table S1). The morphology of the resultant MFC was observed (Fig. S1) using light microscopy and SEM as reported earlier.²¹

The prepared MFC at approximately 2% solids concentration was diluted with distilled water to 0.75 wt% determined based on the wettability of MFC on the star apple surface through contact angle measurements (Table S2). CMC was dissolved in water after thorough stirring. A CMC solution of 0.75 wt% was used to substitute portions of MFC at substitution ratios of 13%, 27%, and 40% to obtain three MFC/CMC sols with MFC to CMC concentration ratios: 0.65 : 0.10 wt%, 0.55 : 0.20 wt%, and 0.45 : 0.30 wt%. The total cellulosic mass concentration was kept the same as the pure MFC formulation of 0.75 wt%. The prepared MFC and MFC/CMC sols were stored in a refrigerator until use.

2.3 Star apple barrier coating and quality analysis

Upon receiving, each star apple was carefully washed with tap water to remove visible dirt and wipe-dried with paper towels before barrier coating. Each coating run was a subset of 14 star apples. Each washed and dried star apple was dipped into the prepared MFC or MFC/CMC sol for 3 min and was then taken out and air-dried overnight under ambient conditions (~23 °C and 50% RH). The drying time can be shortened by using forced-air ventilation to increase convection mass transfer without significant energy input. The following day was designated as day 0 for subsequent storage and quality evaluations. After drying, the coated and control star apples were stored under the same ambient conditions to simulate real on-shelf conditions in supermarkets rather than the refrigeration conditions in packing houses and shipping trucks. Our aim is to eliminate and/or decrease refrigeration to save electricity and its associated environmental impact in the supply chain for sustainability considerations.

The exterior appearances of the coated and uncoated star apple were recorded by photo-imaging each day during storage. Their interior appearances were also observed and photo-

imaged every other day after cutting transversely. Two star apples were selected for each cutting time in each coating group, considering that a limited number of qualified star apples (these star apples were required to have similar size, ripening status, color, *etc.*) were available for the study. The cut star apples were also used for destructive tests such as TSS and firmness. The weight losses of the star apples were gravimetrically determined daily during storage. The firmness of each star apple was measured on the fruit pericarp using a high accuracy fruit hardness tester (FR-5105, Ace Instruments, Lutron Electronic Enterprise Co., Ltd, Taiwan), equipped with a 3-mm penetrometer tip (FRTP-3). Three points were evenly selected on the pericarp transverse equator for measurements. The reported firmness values in force (N) were the averages of three measurements.

Star apple juice was obtained by squeezing the pulp of the fruit. The TSS in the juice was measured in °Brix using a digital handheld pocket refractometer (3810 PAL-1, Cole-Parmer, Atago Co., Ltd, Tokyo, Japan).

2.4 SEM imaging

Small pieces of the rind (about 1 cm²) were cut with a sharp razor blade from uncoated (control) and coated star apples to observe the differences in the coating film physical structure among the coating formulations. In addition, barrier coating film fragments were gently peeled from coated fruit surfaces. The samples were mounted on carbon tape, lyophilized, sputter-coated with 5 nm gold, and imaged at 2–3 kV with a Zeiss Evo 15 (LaB6) SEM or a Zeiss Gemini 450 FE-SEM (Carl Zeiss AG, Oberkochen, Germany).

2.5 Star apple respiration measurements

Star apple respiration and ethylene release were measured daily. Before measurement, each star apple was weighed first and then placed in an 86-oz plastic container. The container was sealed with plastic wrap and then covered with a perforated lid, where the perforation served as a gas-sampling port, and stored under ambient conditions. After a preset equilibrium time (1 h for the present study), the concentrations of ethylene (C₂H₄), oxygen (O₂), and carbon dioxide (CO₂) in the container were measured through the sampling port on the lid using a three-gas analyzer (F-950, Felix Instruments, Camas, WA, USA). Measurements were carried out daily. After each measurement, the star apple was taken out of the container and placed back in the same storage condition/position before the measurement. Time-dependent ethylene release and oxygen and carbon dioxide respiration data were calculated by subtracting the ambient C₂H₄, O₂, and CO₂ concentrations from their respective values measured in the container. Details of the calculation method were described in an earlier study.¹⁴ For oxygen respiration, positive values were reported.

2.6 Statistical analysis

All the experiments were carried out using at least two replicate star apples. For example, there were 14 replicate star apples on day 1, which decreased by 2 every other day for cutting and

destructive TSS tests to end up with only 2 star apples for day 14. The averages and standard deviations are reported. A *t*-Test was carried out to determine the statistical significance of the observed difference in barrier coating performance in terms of star apple weight loss, pericarp firmness, and TSS in the fruit pulp, as well as the gas (ethylene, oxygen, and carbon dioxide) respiration of the star apples during two-week storage (Tables S3 and S4). Because these performance measures were inherently dependent on storage time, which violates the key assumption of data independence for applying the *t*-Test, a pre-whitening transformation (linear normalization – a good approximation based on data) was applied to remove the time-dependent trend. Detailed descriptions of the transformation procedure and its theoretical basis are provided (SI and Table S5).

3 Results and discussion

3.1 Stability of the plant cellulosic sols

The stability of MFC and MFC/CMC sol was demonstrated by a sedimentation test. No settling was observed after standing for over 24 h. Furthermore, the Tyndall effect was observed when a laser light was shone onto the MFC and MFC/CMC suspensions (Fig. S2), indicating that these coating formulations are truly in the form of sol with excellent stability.

3.2 Exterior appearance of star apple

Prior to storage, the epidermis of the ‘Hipolito’ star apple was dark reddish-purple, smooth and glossy. During storage, the epidermis of the star apple underwent visible changes in color (Fig. 1 and S3). The exocarp of the control star apple (without the coating, Fig. 1A) began to desiccate and turn purplish-brown to brownish-yellow by day 4, light brown by day 8, and continued to shrivel. The epidermis was mostly black by day 10. The control star apple shrank quite significantly by day 14, resulting in a much less spherical shape. The images taken from the star apple harvested in 2024 were very similar to those harvested in 2025 (Fig. S3) with very similar weight losses in two weeks after harvest (Fig. S4).

The star apples coated with the pure MFC showed a white film on the exocarp surface, perhaps due to the lack of adhesion of the coating film to the star apple exocarp surface (Fig. 1B). Six days after treatment (DAT), the exocarp of the star apple began to desiccate, wrinkle, and gradually separated from the coating film. By 8 DAT, the exocarp surface was visibly wrinkled and started to shrink. By 14 DAT, the star apple became less spherical, faded to a lighter purple, and did not turn into a dark color. The star apple did not completely dry out either.

The star apple coated with an MFC/CMC of 0.65 : 0.10 at the lowest CMC substitution of 13% had a much less visible whitish film on the surface compared to that coated with the pure MFC barrier coating (Fig. 1C), suggesting improved adhesion of the



Fig. 1 Comparisons of the external appearance of star apples with and without barrier coatings during 14 days of storage: (A) control; (B) MFC 0.75; (C) MFC/CMC 0.65 : 0.10; (D) MFC/CMC 0.55 : 0.20; (E) MFC/CMC 0.45 : 0.30.

coating layer to the star apple exocarp surface. The coating did shield the luster of the star apples, which appeared less shiny even on day 0. More importantly, the extent of desiccation and wrinkling of the exocarp was significantly decreased compared to the control (non-coated, Fig. 1A) and MFC coated (Fig. 1B) star apples during the entire storage time. The epidermis color fading was delayed to 10 DAT compared with 4 DAT and 8 DAT for the control and MFC coated star apples, respectively. By 10 DAT, the wrinkling of the exocarp became pronounced, and by 14 DAT, the peel adjacent to the peduncle area showed a light pinkish-white color.

Increasing CMC substitution eliminated the whitish color of the coating film, indicating improving coating adhesion, and brought back the glossy luster of the star apples as seen from the star apples coated with MFC/CMC 0.55 : 0.20 and 0.45 : 0.30 on day 0, as shown in Fig. 1. The visible scars (discoloration spots) on the star apples with these two high CMC substitutions (27% and 40%) were due to the storm damage before harvest. The exocarp color fading was not visible even at 14 DAT; however, the color did turn into a more dark reddish purple compared with dark brown for the control and light pinkish-white color for the star apples coated with MFC or low CMC substitution, *i.e.*, MFC/CMC 0.65 : 0.10 at 14 DAT. The wrinkling and shrinkage of the exocarp were also alleviated, as it can be seen that the star apples were more rounded than the control or MFC coated ones (Fig. 1).

The rind of the 'Hapolito' star apple coated with MFC or MFC/CMC and held under laboratory ambient conditions had less exocarp desiccation, color fading, and wrinkling than uncoated fruit. This suggests that combining the coatings with the current practice of cold room storage would prolong star apple shelf-life even more than non-coated fruits. Based on the fading peel color changes over time, the MFC and low CMC substitution MFC/CMC barrier coatings extended the shelf life of star apple by 5 and 7 days under laboratory ambient conditions, respectively. Increasing CMC loading to 27 and 40% MFC substitutions further extended the shelf life to over 12 days. It could be seen that the MFC/CMC barrier coating, especially at higher CMC substitutions, had a better visual effect and preservation ability than the pure MFC barrier coating that had a whitish color for star apples.

3.3 The appearance of star apple pulp

A transversely cut star apple shows its pulp with a star-shape, which is probably why it is called star apple. The edible pulp

near the exocarp is pinkish-purple, adjacent to the inner star-shaped jelly-like milky-white plump and translucent pulp, which surrounds three to 11 seeds, as shown in Fig. 2. Star apple has a bitter latex that exudes from the inner exocarp, and thus care should be taken in not spreading the latex to the sweet edible pulp.

Over the 14-day exposure to laboratory ambient conditions, the pulp of uncoated star apples desiccated and the exocarp became thinner (Fig. 3A). By day 6, the pulp color changed from white to pinkish-purple and the red-purple exocarp began to shrink and separate from the pulp, and by day 12, the pulp desiccated and the red-purple exocarp started to turn pink, white and eventually yellow. In contrast, the pulp of the MFC coated fruit was relatively plump and juicy up to 8 DAT (Fig. 3B). Desiccation of the pulp accelerated and the pulp was separated from the inner exocarp by 8 DAT and was notably drier by 14 DAT. By 10 DAT, the color of the inner exocarp began to fade from purple to pink and by 14 DAT, it was pinkish-white and the edge of the exocarp was beginning to turn light purple and pink.

The pulp of the star apples coated with the lowest CMC substitution of 13%, *i.e.*, MFC/CMC 0.65 : 0.10 (Fig. 3C) remained relatively plump and juicy compared to the uncoated and MFC-coated star apples up to 14 DAT. Some of the pulp color changed from white to pink. There was some limited detachment from the inner exocarp. In addition, over the period of 14 days, the exocarp desiccated and the color faded from purplish-pink to pinkish-white. This suggests that even a small amount of CMC substitution in the barrier coating extended star apple shelf life and may maintain star apple pulp quality under laboratory ambient conditions for up to 14 days.

Increasing CMC substitutions improved barrier performance. This can be clearly seen from the color of the pulp and the exocarp of the star apples coated with 27% CMC substitution, *i.e.*, MFC/CMC 0.55 : 0.20 (Fig. 3D) and 40% CMC substitution 0.45 : 0.30 (Fig. 3E). No color fading was observed compared with day 0 (Fig. 2) by 14 DAT, a clear improvement over the low CMC substitution (13%) coating MFC/CMC 0.65 : 0.10 (Fig. 3C). The pulp remained plump and juicy even by 14 DAT. It appears that the color fading is even less with MFC/CMC 0.45 : 0.30 than MFC/CMC 0.55 : 0.20. This indicates that a great CMC substitution (40%) barrier coating at MFC/CMC 0.45 : 0.30 is preferred for star apple preservation.

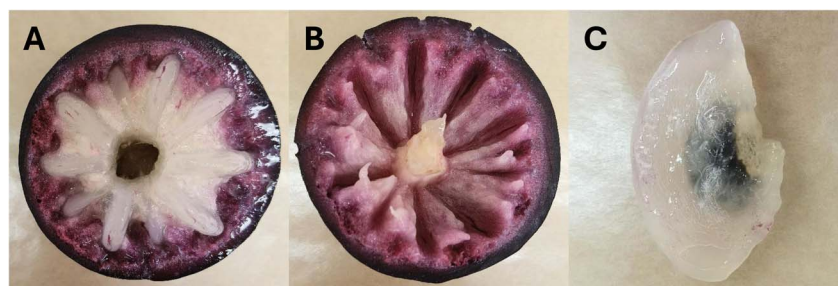


Fig. 2 The interior appearance of a freshly cut star apple on day 0 (as received). (A) and (B): pericarp with pulp; (C): pulp.



Fig. 3 Effects of a barrier coating on the interior appearance of cut star apple with pulp and pulp removed during 14 days of exposure to laboratory ambient temperature: (A) control; (B) MFC 0.75; (C) MFC/CMC 0.65 : 0.10; (D) MFC/CMC 0.55 : 0.20; (E) MFC/CMC 0.45 : 0.30.

The effectiveness of the barrier coating, especially the coating with MFC/CMC can also be clearly seen by comparing the pericarp without the pulp, as shown in Fig. 3. At 14 DAT, the star apples coated with MFC/CMC especially at elevated CMC substitutions (27% and 40%), *i.e.*, MFC/CMC 0.045 : 0.20 and 0.45 : 0.30, still had a well-defined physical structure of the inner pericarp, similar to the star apples from day 4 without the coating (Fig. 3A). The fading of color was obvious for the control, MFC, and low CMC substitution MFC/CMC 0.065 : 0.10 coated star apples. The well-defined structure gradually shrank and lost its spherical shape at 6 DAT for the star apples coated with pure MFC. However, the star apple coated with MFC/CMC 0.45 : 0.30 showed no color fading and no structure shrinkage/deformation (Fig. 3E). These observations clearly indicate that there is no respiration-limit induced star apple spoilage even with the coating using 40% CMC substitution, in contrast to that observed anaerobic digestion induced spoilage of bananas coated with elevated CMC substitutions using the same MFC and CMC.²¹ This suggests that non-climacteric star apples are much more tolerant to a dense coating under limited respiration conditions than climacteric bananas. Perhaps this is attributed to the key characteristic of non-climacteric fruits without having a post-harvest ripening process and going through intense physicochemical changes. The differences in the basic biochemical compositions and biological behavioral sensitivity to respiration among different types of fruits may also contribute to the observed difference. Future studies are needed to better understand the mechanisms affecting fruit tolerance to limiting gas respiration.

3.4 Star apple weight loss, firmness, and total soluble solids

Star apple weight loss is an important measure that directly affects the economic benefits of growers and grocers as star apples are mostly sold by weight. The variations in fruit weight losses among the control and MFC and MFC/CMC coated star apples were small in the first two days (Fig. 4A). However, by day 14, the weight loss of the control increased rapidly to approximately 35% compared to 27% and 25% for MFC and MFC/CMC 0.65 : 0.10 coated fruits, respectively. The weight loss data obtained from 2024 showed excellent agreement with those obtained in 2025 with a nearly perfect correlation ($y = 1.081x$, $r^2 = 0.998$, Fig. S2). Increasing CMC substitution had a small impact on decreasing star apple weight loss (Fig. 4A), *i.e.*, weight loss at 14 DAT decreased to 23.4% with a 40% CMC substitution (MFC/CMC 0.45 : 0.30) coating compared with 27% without CMC substitution. The great weight loss is perhaps due to the death of the pericarp cells, resulting in lost ability to control the gas, including water vapor permeation. The barrier coating decreased weight loss primarily due to decreasing water vapor permeation through the star apple pericarp. Thus, barrier coatings were effective in delaying and decreasing the extent of desiccation of the peel and pulp compared with uncoated fruits held under laboratory ambient conditions.

The observed improvements in decreasing star apple weight loss by MFC/CMC barrier coatings were substantiated by statistical analysis with more than 99.9% probability based on *t*-Tests between the data sets for the control (uncoated) and the

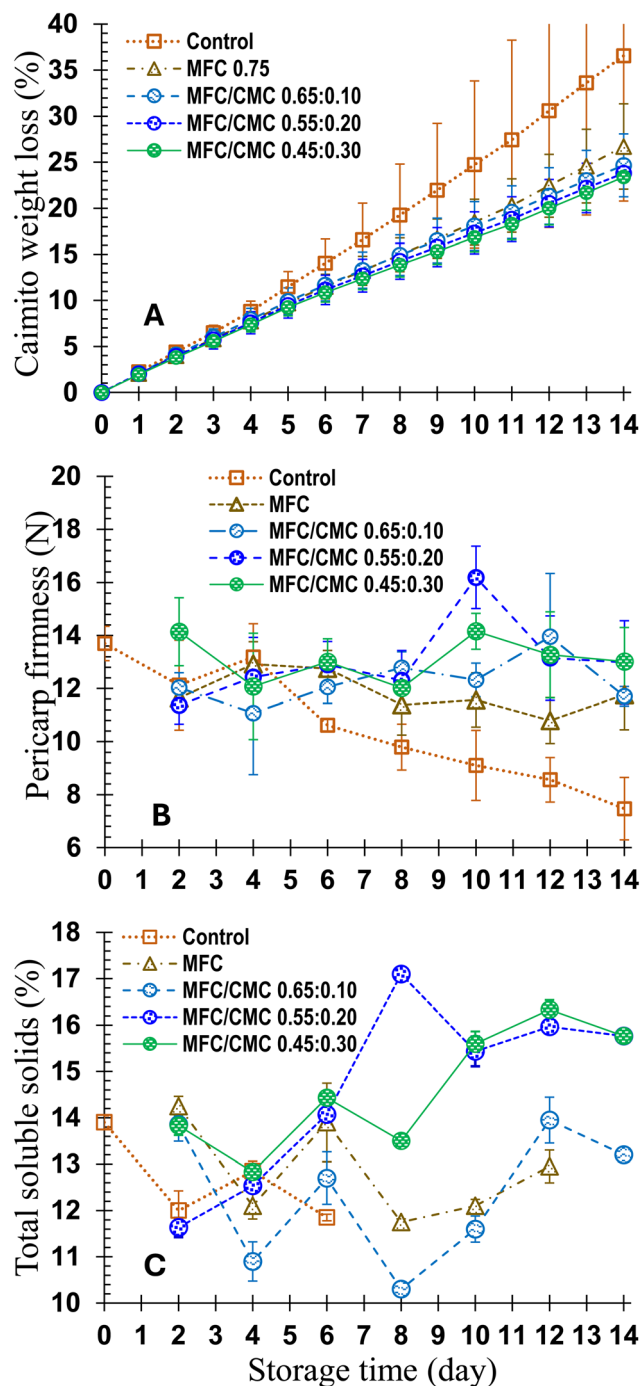


Fig. 4 Effects of barrier coatings on star apples during 14 days of exposure to laboratory ambient conditions: (A) fruit weight loss; (B) pericarp firmness; (C) fruit pulp total soluble solids.

barrier coating runs (Table S3). When comparing the MFC/CMC coating runs with the pure MFC coating without CMC substitution, the observed differences in star apple weight loss from the run with a low CMC substitution of 13% (MFC/CMC 0.65 : 0.10) were not statistically significant with a t value of only 0.472 ($<t = 0.694$ at 50% probability). Increasing CMC substitution improved the statistical significance of the observed differences in measured weight loss data. Specifically, the calculated t

values for the 27% and 40% CMC substitution runs were 2.891 and 4.806 (Table S4), respectively, corresponding to greater than 98% and 99.9% probability of statistical significance. It is also noticed that the weight loss data for the control (uncoated) star apples by day 6 had much greater standard deviations than the corresponding data with barrier coatings for the star apples harvested in both 2024 and 2025 (Fig. 4A and S4), corresponding to the star apple pulp starting to change color (Fig. 3A). This suggests that the deterioration of the star apple will induce large variations in fruit weight loss, perhaps due to the variabilities in the progress of the deterioration process among different star apples. An increase in the standard deviations of the weight loss data for the pure MFC and MFC/CMC coating run was also observed (Fig. 4A and S4); however, this increase was delayed and was much smaller due to the delay in the deterioration process caused by the coating. This suggests that the barrier coating decreased the variabilities in weight loss among star apples.

The pericarp firmness of the control star apples decreased continuously with time and by 45.5% at 14 DAT exposure to laboratory ambient conditions (Fig. 4B). This may be due to the death of pericarp cells. The pericarp firmness of the star apples coated with MFC and MFC/CMC 0.65 : 0.10 decreased by only approximately 14% after 14 DAT. The decrease in firmness primarily took place in the first 4 days and then stabilized. Increasing CMC substitution, such as using MFC/CMC 0.55 : 0.20 and 0.45 : 0.30 barrier coatings, can retain pericarp firmness during storage for at least 14 days, suggesting that a good barrier coating can avoid star apple pericarp desiccation. This agrees with what was observed from the star apple external appearance shown in Fig. 1. Statistical analysis confirmed the observed difference in pericarp firmness between the control (uncoated) and the maximal CMC substitution 40% coating run, *i.e.*, MFC/CMC 0.45 : 0.30, with 98% probability (Table S3).

The edible pulp of star apples is characterized by a sweet highly pleasant flavor and smooth texture. Overripen fruit will have a sour and astringent taste with a high fiber texture, accompanied by a stinging sensation on the tongue. The TSS or °Brix on day zero was approximately 14 for all the star apples. By day 6, when the fruit started to change color, the TSS of the control star apple fruit declined to approximately 11.9 (Fig. 4C). Recall, the pulp of uncoated fruit was desiccated or was not of a typical milky-white color and the fruit was not palatable by day 8 (Fig. 3). The taste of the pure MFC coated star apple fruit began to deteriorate and was unpalatable by 10 DAT. In contrast, the MFC/CMC 0.065 : 0.10 coated fruit remained palatable during the 14 DAT. In general, a coating with pure MFC or low CMC substitution of 13% (MFC/CMC 0.60 : 0.10) resulted in a similar TSS profile with storage time (Fig. 4C), which is substantiated by the t -Test with a valid null hypothesis (Table S3). Increasing CMC substitution to 27% and 40%, *i.e.*, MFC/CMC 0.55 : 0.20 and 0.45 : 0.30, slightly increased the measured TSS of the star apples to approximately 16% at 14 DAT, as shown in Fig. 4C. The t -Test indicates that the observed difference between the control and the coating run with 40% CMC substitution, MFC/CMC 0.45 : 0.30, is true with a probability of 90% (Table S3). Visual observation indicates that the

pulp remained fresh and juicy with a similar color to that of freshly picked fruit on day 0 (comparing Fig. 3D and E with Fig. 2A and B). Based on the taste of the pulp, the pulp shelf life of the MFC coated fruit was extended to about 6 days, whereas the MFC/CMC 0.55 : 0.20 and 0.45 : 0.30 coated fruits lasted at least 14 days.

3.5 Star apple respiration

Literature data on star apple respiration are very limited. Reported data were obtained in the star apple growth and ripening stages before they were picked. Ethylene production was found in the range of 10–100 nL kg⁻¹ h⁻¹ before ripening.⁴³ A rise in ethylene production to over 1000 nL kg⁻¹ h⁻¹ was accompanied by the rise in carbon dioxide respiration as the star apple began to decay. A more recent study found that ethylene production of on-plant star apples varied 50–60 nL kg⁻¹ h⁻¹ during the period from the mature to the ripening stage.⁶ Here, the peak ethylene production after picking (post-harvest) was orders of magnitude greater than those measured when star apples were on-plant between the growth and ripening stages reported in the literature. Due to the detection limit of 0.15 ppm in ethylene measurements of the gas analyzer used, the minimum measurable ethylene production was over 1 µL kg⁻¹ h⁻¹. As shown in Fig. 5A, the barrier coating with MFC/CMC significantly decreased ethylene release/production. Specifically, an appreciable low amount of ethylene production at ~2.0 µL kg⁻¹ h⁻¹ was measured on day 5 for the control star apples, but only measurable until day 11 at ~4.5 µL kg⁻¹ for the star apples

coated with MFC/CMC 0.45 : 0.30. It is interesting to notice that the barrier coating with pure MFC increased ethylene release compared with the control run with a statistical probability of 99% by the *t*-test (Table S3). This was perhaps due to the poor adhesion of MFC onto the star apple exocarp, as shown by the whitish color for the star apple coated with pure MFC (Fig. 1), which created a space as an ethylene reservoir with accumulated ethylene concentration, which may have affected biochemical reactions in the star apple. Studies using 1-methylcyclopropene, an ethylene inhibitor, to treat harvested non-climacteric fruits indicated that endogenous ethylene naturally produced by non-climacteric fruits played a physiological role in regulating some aspects of ripening and/or activation of stress-tolerance mechanisms, affecting fruit quality.⁴⁴ Except for the pure MFC coating, the barrier coating using MFC/CMC in general delayed and significantly decreased ethylene production at the end of the experiment of 14 DAT (Fig. 5A). The *t*-Test indicates that the observed differences in the ethylene production between the control and MFC/CMC (Table S3) and between the pure MFC coating and the MFC/CMC coating runs (Table S4) were all statistically significant with a 99.9% probability.

Examining the ethylene release in Fig. 5A together with star apple fruit pulp (Fig. 3) suggests that the postharvest ethylene surge from star apples appears to correlate with fruit deterioration/decay. This agrees with an earlier study on the growth and ripening of on-plant star apples, which suggested that the surge of ethylene was accompanied by fruit decay.⁴³

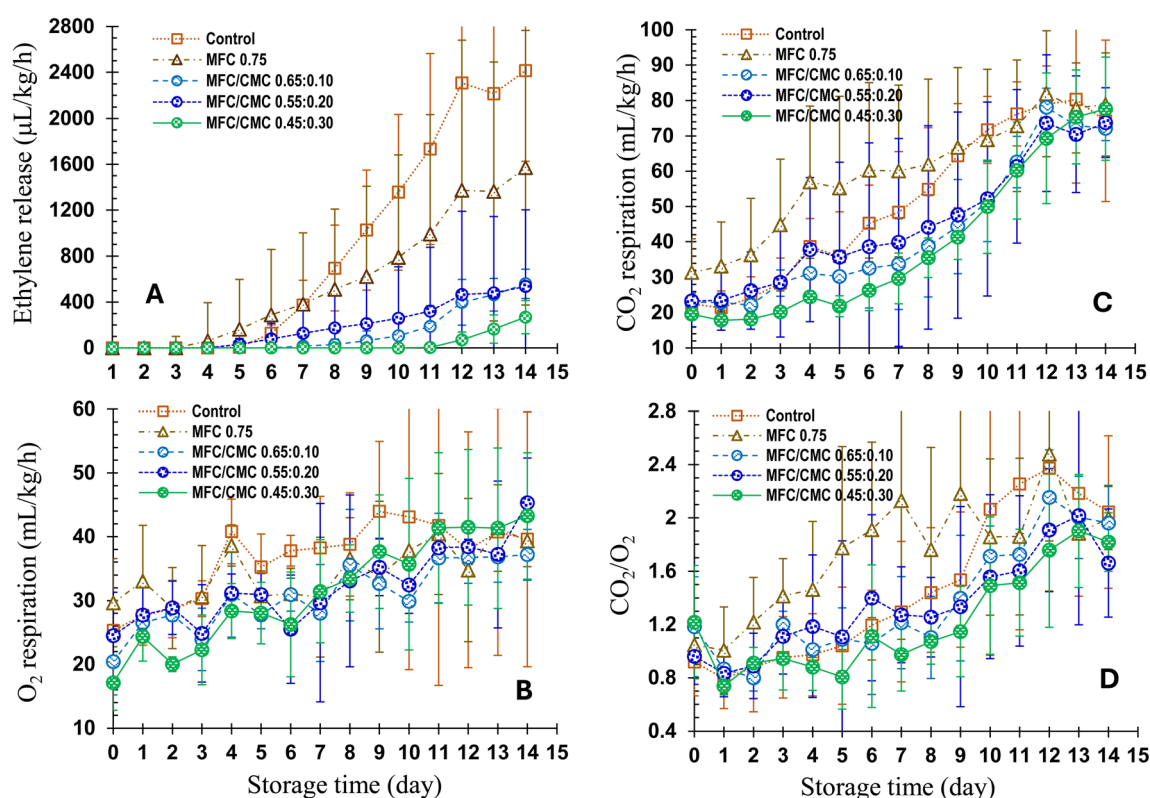


Fig. 5 Time-dependent star apple respiration: (A) C₂H₄; (B) O₂; (C) CO₂; (D) CO₂/O₂.

Therefore, delayed rapid ethylene production by the MFC/CMC barrier coating is another indirect indication of the performance of MFC/CMC coatings in preserving non-climacteric fruit quality. It is also noticed that ethylene release is linearly correlated with star apple weight loss (Fig. S5), similar to banana, a climacteric fruit, as reported previously.¹⁴ However, the correlation data for different barrier coating formulations did not fall to a universal curve, which was observed from the barrier coating of bananas.

Oxygen and carbon dioxide respirations increased with storage time, as shown in Fig. 5B and C, respectively. O₂ respiration doubled in the two-week study, while CO₂ respiration increased by 3 to 4 times. Furthermore, the rapid rise of CO₂ was much earlier on day 1 or 2 for the control and the pure MFC coated star apples than on 8–10 DAT for those coated with MFC/CMC. Except for the pure MFC coating run, the barrier coating in general slightly decreased O₂ and CO₂ respiration. Statistical analysis, however, indicates that only the observed decrease in O₂ respiration between the control and the greatest CMC substitution 40% coating run (MFC/CMC 0.45 : 0.30) was significant with greater than 99% probability (Table S3). Similar to that observed in ethylene production (Fig. 5A), CO₂ respiration for the pure MFC coating run was greater than that for the control (Fig. 5C) with 99% probability of statistical significance (Table S3). Again, the poor adhesion of MFC onto the star apple exocarp as shown by the whitish color on the pure MFC coated star apples (Fig. 1) created a space as a reservoir for CO₂ accumulation. The ratios of the measured CO₂ and O₂ respiration (Fig. 5D) were mostly less than unity in two weeks of storage time, indicating that harvested star apples experienced oxygen deficient respiration.

3.6 Physical microstructure of the barrier coating films on the pericarp of star apples

Barrier performance of the coating films not only depends on the film gas permeability but also on the adhesion of the coating film to star apple exocarp. An earlier study showed that the water vapor gas permeation of casting films made of MFC/CMC sol increased with increasing CMC substitution,²¹ which appears to contradict gas respiration measurements discussed above, perhaps due to the increasing hydrophilicity of the casting films. SEM imaging of the coating films peeled off from the star apple exocarp surface can provide direct information on film structural properties for improving the understanding of coating adhesion. Although photographic imaging indicated that the star apple exocarp outer surface is very smooth (Fig. 1), SEM imaging revealed that a dried star apple exocarp was not flat but rather uneven with valleys and a network of ravines as shown in Fig. 6Ac (control). The distances between two neighboring ravines were on the orders of tens to hundreds of micrometers. The exocarp of an uncoated star apple had a uniform grain nano-texture pattern with an elementary grain size on the order of 50–100 nm, which can be seen under a large magnification (Fig. 6A'e). The barrier coating with MFC/CMC appeared to be associated with thicker and smoother (less shrinkage) exocarps, as shown earlier in Fig. 3. Long cellulosic

microfibrils (several micrometers) can be clearly seen in the coated exocarp under large magnification (Fig. 6A'0–A'3). The microfibril diameters were between tens and hundreds of nanometers and completely covered the uniform grain pattern observed on the control (uncoated) exocarp (Fig. 6A'c). Voids between microfibrils can be seen from coatings without CMC (Fig. 6A'0) or with low CMC substitution (Fig. 6A'1). The voids were gradually filled with CMC by increasing the CMC substitution (comparing Fig. 6A'0 with Fig. 6A'2 and A'3), indicating decreased porosity (increased density) of the coating films, consistent with our earlier study that found increased MFC/CMC casting film density with increasing CMC substitution.

The cross-sectional SEM imaging revealed the cellular structure of the inner layers of the rind (inner exocarp and pericarp) (Fig. 6B(c)) with a typical cellular size of the freeze-dried (for SEM) samples on the order of 20 to 30 micrometers. A natural coating of the exocarp (probably latex or cuticle) obscured the cellular structure of the epidermis (Fig. 6A(c) and B(c)). A frequent separation between the exocarp surface and the coating film formed using pure MFC 0.65 was clearly observed from the cross-sectional SEM images (Fig. 6B0). The gaps created by this separation caused the whitish appearance of the star apple coated with pure MFC (Fig. 1B) due to the difference in the refraction indices between the air in the gap and the cellulosic coating film. The space created by this separation acts as a reservoir for gas (C₂H₄ and CO₂) accumulation. This may explain the measured higher C₂H₄ release and CO₂ respiration for the pure MFC coating run than the control (Fig. 5A and C). Substitution of MFC with CMC alleviated this film separation. Gaps remained however at the low CMC substitution of 13% (Fig. 6B1). At great CMC substitutions of 27% and 40%, the star apple pericarp and the coating film were not differentiable (Fig. 6B2 and B3). The cross-sectional SEM images clearly indicated that increased CMC substitution increased the adhesion of the coating film with the star apple exocarp and therefore increased the barrier properties because the spacings or gaps between the coating film and star apple exocarp can act as a gas reservoir to facilitate fruit gas respiration and disrupt barrier performance, as discussed in the previous section on gas respiration.

3.7 Preliminary estimations of coating material cost and refrigeration energy savings

MFC and CMC coating material usage can be estimated using the coating film grammage and the measured average star apple dimensions. From the measurements of a subset of 20 star apples reported earlier in Section 2.1 and the estimated coating film grammage of 10 g m⁻², the amount of MFC and CMC needed is estimated at 0.188 g per star apple, or 0.696 g kg⁻¹ star apple. Assuming that MFC and CMC both cost \$5 per kg, the material cost for coating is 0.35 cents per kg star apple, which should not add significant cost to the grocers.

Based on measured specific MFC fibrillation energy of 13 MJ kg⁻¹ or 3.6 kWh kg⁻¹ (Table S1) and literature electricity needs for producing CMC of 1.5 kWh kg⁻¹ CMC,⁴⁵ electricity needs for

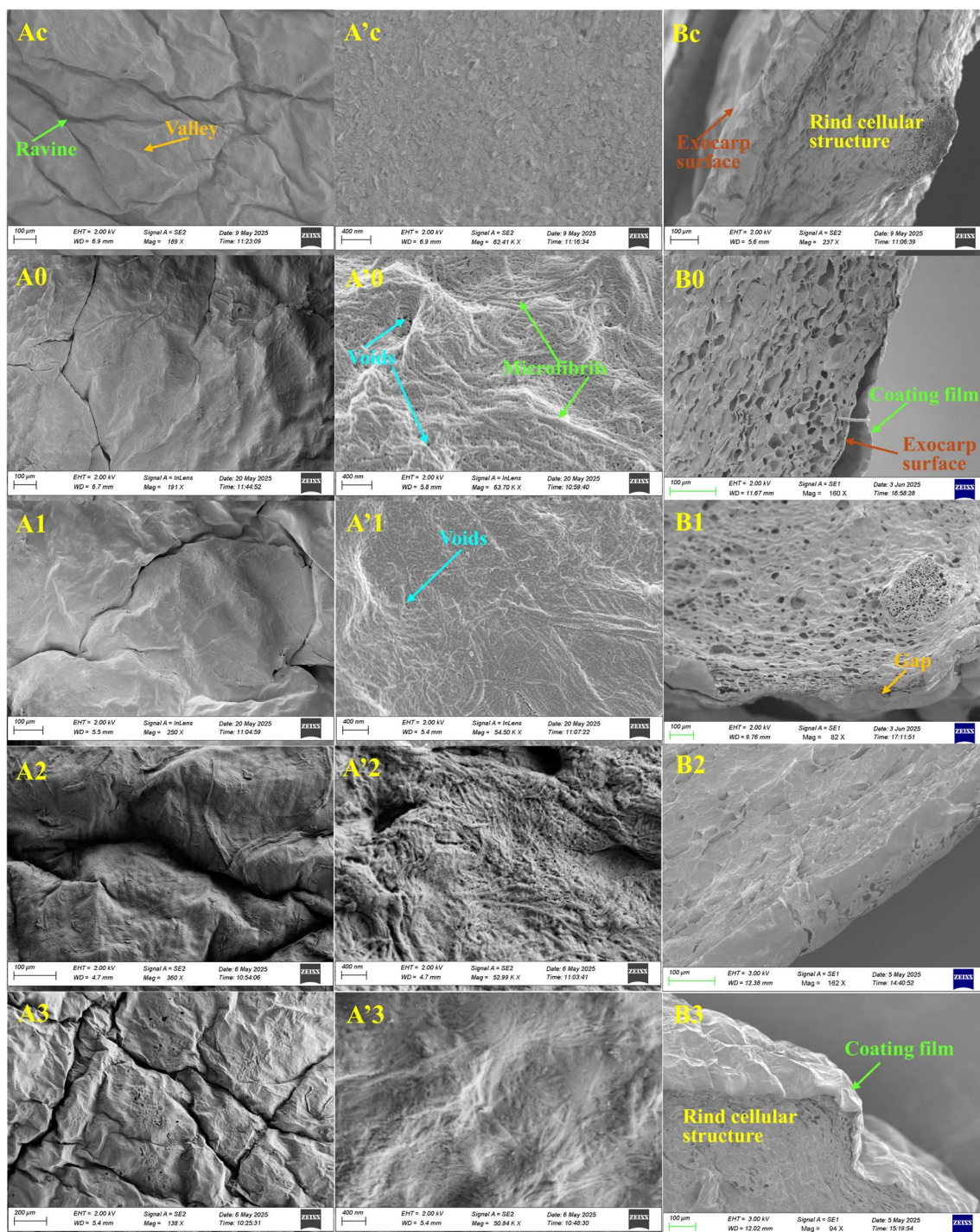


Fig. 6 SEM images of the coating film from the star apple pericarp. Each image is labelled using column names (A) (surface image with low magnification), (A') (surface image with large magnification), and (B) (cross sectional image), and row designations c, 0, 1, 2, and 3 representing the control (no coating) and coatings with MFC 0.75, MFC/CMC 0.65 : 0.10, 0.55 : 0.20, and 0.45 : 0.30, respectively.

coating material production can be estimated at 1.92 Wh kg^{-1} star apple based on 40% CMC substitution (MFC/CMC 0.45 : 0.3).

Electricity energy input for refrigeration at 5°C without barrier coating to extend shelf-life can also be estimated. Assuming an outside temperature of 30°C , a fruit specific heat of $3.5 \text{ kJ (kg}^{-1} \text{ K}^{-1})$, and a refrigeration coefficient of performance

(COP) of 4, cooling star apple from 30°C to 5°C needs 21.88 kJ kg^{-1} star apple or 6.08 Wh kg^{-1} star apple. Assuming that with the barrier coating the star apples can now be refrigerated at 20°C (based on the present study at 23°C), the electricity input for cooling to 20°C is estimated at 2.43 Wh kg^{-1} star apple. Therefore, electricity savings by using the MFC/CMC barrier coating

are 1.73 Wh kg⁻¹ star apples vs. using the current commercial practice of refrigeration at 5 °C. This estimate does not include the savings in electricity for maintaining at 5 °C vs. maintaining at 20 °C with the barrier coating for the entire storage time.

4 Conclusions

This work evaluated a pure plant cellulose-based sol as a barrier coating for shelf-life preservation of a non-climacteric fruit – star apple (*Chrysophyllum cainito* L.). Star apples were dip coated using an aqueous sol of microfibrillated cellulose (MFC) produced from mechanical fibrillating a commercial bleach kraft pulp without chemical processing and a commercial food additive carboxymethyl cellulose (CMC). Substitution of MFC with CMC improved the adhesion of the coating layer on the star apple exocarp surface and substantially decreased gas permeation through the star apple pericarp to result in a longer shelf life and better fruit quality measured by visual observation, pericarp firmness, weight loss, and total dissolved solids. Specifically, coating with pure MFC can extend shelf life by about 4 days compared with the control (uncoated) star apples. Increasing MFC substitution with CMC to MFC/CMC 0.55:0.20 or greater can extend shelf life by more than 12 days. Furthermore, barrier coating decreased fruit weight loss by approximately 15 percentage points or by approximately 40% after two weeks of harvest. It is also noted that significant variability (large standard deviation) in star apple weight loss is associated with fruit decay. Gas respiration measurements indicate that star apples have an post-harvest ethylene production surge, though they are non-climacteric fruits, which was found to signal the decay of the star apple fruit. The barrier coating with MFC/CMC substantially delayed and decreased star apple post-harvest ethylene production to result in a significantly extended shelf life and improved fruit quality. By using sustainably produced cellulosic materials without petroleum derived compounds in the coating formulation and extending the shelf life of fruits, and by decreasing electricity input for refrigeration in storage, the present study facilitated meeting the United Nations sustainable development goals. Future studies should focus on pilot scale and field studies by working with farmers or packing houses and applications for different non-climacteric fruits.

Author contributions

Geng conducted most experimental investigations and wrote the manuscript draft. Crane and Li were responsible for caimito tree farming and star apple harvest and initial evaluation and selection of fruits for the study. Kitin conducted SEM analysis. Stark supervised barrier permeation evaluation. Zhu and Zhang conceptualized the study and designed and supervised the experiments. Zhu supervised barrier coating experiments. Zhu, Crane, and Jing contributed to drafting the manuscript. Zhu also supervised barrier coating experiments. All authors contributed to manuscript writing and editing.

Conflicts of interest

The authors Geng, Stark, Zhu and Zhang are co-inventors of a provisional U.S. patent application.

Data availability

Some data are available upon request.

Supplementary information (SI): Fig. S1–S5 that included SEM images of the MFC, experimental repeatability between the 2024 and 2025 study, and correlations between ethylene production and star apple weight losses for different coating runs; Tables S1–S5 that included mechanical fibrillation energy for producing MFC, wettability of star apple exocarp by the MFC/CMC sols, and statistical analysis by *t*-Test through pre-whitening transformation. See DOI: <https://doi.org/10.1039/d6fb00169f>.

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