SYNERGISTIC EFFECTS OF CONTROLLED ATMOSPHERE STORAGE AND PLANT OIL-BASED COATING FOR EXTENDING JACKFRUIT STORAGE LIFE

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ABSTRACT

Jackfruit (Artocarpus heterophyllus Lam.) is an emerging tropical fruit crop in Malaysia, cultivated on approximately 5,000 ha with an annual production of approximately 46,000 MT. In 2025, Malaysia exported 5,858.4 MT of jackfruit, highlighting its potential for export diversification. However, the short storage life of fresh jackfruit, typically less than two weeks under conventional cold storage, limits its suitability for long-distance sea shipment. Rapid ripening and postharvest fungal infection, particularly by Lasiodiplodia theobromae, are major contributing factors. This study evaluated the effects of controlled atmosphere (CA) storage using a system provided by Daikin Industries, Japan, and an edible plant oil-based coating (EONature®) developed by MARDI on the storage life and quality of J33 jackfruit at 12°C. Four treatments were evaluated: regular atmosphere (RA) control, coating under RA, CA storage alone, and combined CA storage and coating. Fruit quality was assessed during storage and after transfer to RA to simulate post-arrival distribution. The combined treatment was most effective in delaying ripening, reducing disease severity and maintaining visual quality, extending storage life to four weeks under CA conditions. In comparison, coating or CA storage alone provided a storage life of approximately three weeks. Flesh colour, firmness, total soluble solids and ascorbic acid content were not significantly affected by treatment. Acetaldehyde and ethanol concentrations remained low, although ethyl acetate increased moderately under the combined treatment at week four. Sensory evaluation indicated that eating quality remained acceptable. In conclusion, either coating or CA storage alone may be suitable for meeting a three-week export storage requirement, while combining both treatments offers the potential to extend storage life to four weeks without adversely affecting eating quality. CA storage also presents a potential alternative to the existing coating technology for the three-week requirement. These findings highlight the potential of these postharvest technologies to support long-distance sea shipment and improve the export prospects of Malaysian jackfruit

Keywords: Ripening, respiration, low-oxygen, quality, export.

INTRODUCTION

Jackfruit (*Artocarpus heterophyllus* Lam.) is an emerging tropical fruit crop in Malaysia with increasing importance in both domestic consumption and export markets. The crop is cultivated on approximately 5,000 ha, with an annual production exceeding 46,000 MT (Department of Agriculture Malaysia, 2025). Although smaller in scale than major fruit industries such as durian, banana and pineapple, jackfruit has considerable potential for export diversification, with exports reaching 5,858.4 MT in 2023

(Department of Statistic Malaysia, 2025). With a self-sufficiency ratio exceeding 100% (Department of Statistic Malaysia, 2025), domestic demand is well supported. Therefore, future growth of industry depends largely on expanding access to more distant export markets.

Fresh jackfruit is highly perishable, with postharvest losses occurring due to mechanical injury, moisture loss, uneven ripening, chilling injury, microbial decay and physiological deterioration. Among these, chilling injury and postharvest disease are the two major constraints limiting long-term storage and export by sea. Under conventional cold storage conditions, jackfruit can generally be stored for less than two weeks at approximately 12°C. Storage below this temperature induces chilling injury, whereas prolonged storage at 12°C results in rapid quality deterioration due to fungal infection, particularly caused by *Lasiodiplodia theobromae*, together with accelerated ripening associated with high respiration and ethylene production (Cho et al., 2020; Paull & Duarte, 2012; Nunes, 2008). Consequently, the export of fresh jackfruit has traditionally been limited to nearby destinations or costly air freight. For sea shipment to be commercially viable, a minimum storage life of three weeks, followed by an additional distribution period after arrival, is generally required.

To address these limitations, MARDI has progressively developed postharvest technologies for fresh jackfruit over the past few years. Initial studies focused on identifying suitable postharvest disease control measures and packaging systems for cold storage. The combination of fungicide treatment and perforated low-density polyethylene (LDPE) packaging successfully maintained fruit quality for up to two weeks at 12°C while reducing postharvest disease incidence compared with conventional packaging systems (Cho et al., 2020). However, this storage duration remained insufficient for commercial sea shipment to distant export markets.

Building on these findings, subsequent research led to the development of an integrated postharvest handling system incorporating sanitation treatment and application of EONature®, a plant oil-based fruit coating developed by the Malaysian Agricultural Research and Development Institute (MARDI). EONature® was developed to reduce reliance on synthetic fungicides while preserving the cosmetic quality and delaying the ripening of fresh fruits (Nor Hanis Aifaa et al., 2016). The integration of sanitation treatment with EONature® coating successfully extended the storage life of fresh J33 jackfruit to approximately three weeks, enabling successful first sea shipment from Malaysia to China. The technology has subsequently been incorporated into the protocol for exporting fresh jackfruit from Malaysia to China and has been commercially adopted by Malaysian exporters for shipments to China and other destinations with similar transit durations.

Although the existing postharvest technology has enabled successful export to nearby international markets, a storage life of approximately three weeks remains insufficient for more distant destinations. Longer transit times, port congestion, customs clearance and unforeseen supply chain disruptions may extend the total distribution period beyond three weeks, thereby increasing the risk of quality deterioration before the fruit reaches consumers. Further improvement in postharvest technology is therefore required to further delay fruit ripening and suppress postharvest disease during prolonged storage.

Manipulation of the storage atmosphere has been recognized as an effective postharvest approach to complement refrigerated storage in extending fruit shelf life. In controlled atmosphere (CA) storage, produce is maintained in a gaseous environment different from ambient air, typically with reduced oxygen (O_2) and elevated carbon dioxide (CO_2) concentrations (Thompson, 2010). Within the optimum gas composition for a particular commodity, reduced O_2 and elevated CO_2 suppress respiration and ethylene biosynthesis, delay ripening and disease development, and thereby prolong storage life (Kader, 1986). Therefore, integrating CA storage with the commercially established EONature® coating may provide complementary benefits by simultaneously delaying physiological deterioration and reducing disease development, thereby extending the storage life of jackfruit beyond that achievable using the existing postharvest technology.

Therefore, this study aimed to evaluate the combined effects of controlled atmosphere storage and a plant oil-based coating on disease development, ripening behaviour, physicochemical quality and anaerobic volatile compound accumulation of Malaysian jackfruit under simulated export conditions.

MATERIALS AND METHODS

Fruit Materials

Fresh jackfruit (*Artocarpus heterophyllus* Lam. cv. Tekam Yellow, J33) were harvested at approximately 90 days after bagging from a commercial orchard in Selangor, Malaysia corresponding to the commercial maturity stage recommended for export (Cho et al., 2020). Fruits were selected based on uniform maturity, size and the absence of visible physical defects or disease symptoms. Immediately after harvest, the fruits were transported to the Postharvest Complex, Malaysian Agricultural Research and Development Institute (MARDI), Serdang, Selangor, for subsequent postharvest treatments.

Prior to treatment application, all fruits were subjected to the standard postharvest handling protocol previously developed by MARDI for the export of fresh jackfruit. The fruits were washed and sanitized with chlorinated water before the peduncle was trimmed and treated with calcium carbonate to minimize latex exudation and reduce the risk of infection at the cut surface. The fruits were then allowed to air dry before treatment application. These procedures were applied uniformly to all treatments as recommended by Nor Hanis Aifaa et al. (2025)

Experimental Treatments and Storage Conditions

The experiment was conducted using a Completely Randomized Design (CRD) comprising four postharvest treatments with four replications.
The four treatments were as follows:

- T1: Regular atmosphere (RA) storage (control)
- T2: EONature® coating + RA storage
- T3: Controlled atmosphere (CA) storage
- T4: EONature® coating + CA storage

For coating treatments (T2 and T4), fruits were dipped in EONature® coating solution and allowed air to dry before storage.
Fruits under regular atmosphere were stored in a refrigerated container maintained at 12 ± 1°C. Controlled atmosphere storage was conducted at the same temperature using an active CA system (Daikin Active CA System, Daikin Industries Ltd., Japan) with a target atmosphere of approximately 5% O_2 and 10% CO_2. The storage atmosphere was continuously monitored and maintained throughout the storage period. Fruits were stored under their respective storage conditions for up to four weeks. To simulate post-arrival distribution and marketing conditions, fruits remaining after four weeks of CA storage were transferred to regular atmosphere storage at 12 ± 1°C for an additional one or two weeks before ripening under ambient conditions.

Quality Evaluation

Following each storage period, fruits were ripened at ambient temperature (25 ± 2°C) for at least three days prior to quality evaluation. External quality was assessed based on visual appearance, ripening characteristics and disease development. Skin colour and flesh colour were determined using a chromameter (model CR-400, Minolta, Japan), while flesh firmness was measured using a texture analyser (TA TX Plus Texture Analyzer; Stable Microsystems, Surrey, UK).

Postharvest disease severity was visually evaluated upon removal from storage and after subsequent ripening under ambient conditions. The extent of disease incidence and surface lesions (characterised by localised pericarp browning and fungal rot) was assessed using a 1 to 7 disease rating scale adapted from standard postharvest scoring methods for jackfruit, based on the percentage of fruit surface area affected (Table 1). Disease severity scores were recorded individually for each replicate fruit per treatment. Fruits scoring ≥ 4 were considered unmarketable.

Table 1. Rating scale for postharvest disease severity in jackfruit based on affected fruit surface area.

Score	Fruit surface affected	Severity description
1	0	No disease
2	> 0-5%	Very slight
3	>5-10%	Slight
4	>10-25%	Moderate
5	>25-50%	Moderately severe
6	>50-75%	Severe
7	>75-100%	Very severe

Total soluble solids (TSS) were determined using a digital refractometer (Atago ModelDBX-55, Japan) and expressed as °Brix. Titratable acidity (TTA) was determined by titration with 0.1 N sodium hydroxide (NaOH) and expressed as percentage citric acid. Ascorbic acid content was determined using the 2,6-dichlorophenolindophenol (DCPIP) titration method and expressed as mg 100 g^{-1} fresh weight. To evaluate the occurrence of anaerobic metabolism during storage, volatile compounds including acetaldehyde, ethanol and ethyl acetate were analysed using a gas chromatograph (Perkin Elmer Autosystem).

Sensory evaluation of ripe jackfruit flesh was conducted after storage and subsequent ripening to evaluate consumer acceptability across key quality attributes. The panel consisted of trained evaluators who assessed the fruit samples for freshness, colour, texture, taste, aroma, and overall acceptability. Each attribute was scored using a 5-point hedonic rating scale ranging from 1 to 5 (Table 2)

Table 2. Hedonic rating scale for sensory evaluation of jackfruit flesh

Score	Degree of Liking
1	Dislike Very much
2	Dislike
3	Neither Like or Dislike
4	Like
5	Like Very Much

Statistical Analysis

The experiment was arranged in a Completely Randomised Design (CRD). Data was subjected to analysis of variance (ANOVA) using SAS statistical software (Version, SAS Institute Inc., Cary, NC, USA). Treatment means were compared using Duncan's Multiple Range Test (DMRT) at the 5% significance level ($p \leq 0.05$).

RESULTS AND DISCUSSION

Visual Quality, Ripening Behaviour and Disease Development

After three weeks of storage, fruits stored under regular atmosphere without coating (T1) showed early symptoms of fungal infection, characterised by localised browning and lesion formation on the pericarp (Fig. 1). The symptoms became more severe during ripening, with the infection spreading from the pericarp to the internal tissues. This pattern is consistent with latent postharvest infections, particularly those caused by *Lasiodiplodia theobromae*, which can remain inactive during storage and develop when the fruit ripens, as the tissues soften and nutrients become more available (Slippers & Wingfield, 2007; Hasan et al., 2014). The rapid development of decay in T1 suggests that regular atmosphere storage alone was insufficient to control the disease. In addition, T1 fruits developed full yellow colour within three days under ambient conditions, indicating faster ripening. This is consistent with the normal climacteric ripening behaviour of jackfruit, which involves increased respiration and ethylene production (Paull & Chen, 2013).

Under regular atmosphere, coating application (T2) helped to reduce moisture loss and visible decay during storage. Coatings act as semi-permeable barriers that reduce transpiration and modify gas exchange, thereby slowing down metabolic activity (Baldwin et al., 2011; Dhall, 2013). However, disease symptoms still developed during ripening. CA storage (T3) also delayed ripening, with fruits taking approximately five days to ripen after removal, compared with three days for T2. Despite this difference in ripening time, T2 and T3 showed comparable disease development during ripening. This suggests that coating or CA storage alone could delay deterioration but was not sufficient to prevent the development of latent infections once ripening commenced.

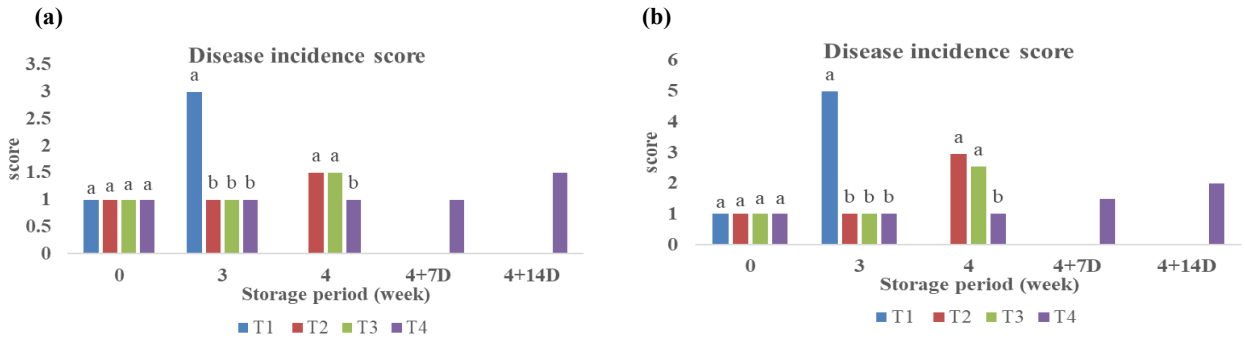
The combined treatment (T4) gave better results in terms of both ripening delay and disease control. Fruits remained free from visible disease upon removal from storage and took approximately six days to ripen. The lower disease incidence suggests that combining CA storage with coating provided additional protection compared with either treatment alone. CA may have slowed down metabolic activity, while the coating helped to reduce moisture loss and modify gas exchange at the fruit surface. Similar benefits from combining atmospheric modification and coating have been reported in other tropical fruits (Ali et al., 2011).

After four weeks of storage, T2 and T3 again showed comparable disease development during ripening, indicating the limitations of using either treatment alone. In contrast, T4 remained free from visible disease upon removal and showed less disease development during subsequent ripening. These findings suggest that the combined treatment was more effective in delaying ripening and reducing disease development under the conditions of this study.

The extended storage assessment provided further information on the potential of T4 for commercial application. After four weeks of CA storage followed by one week under regular atmosphere in a cold room, T4 fruits maintained better overall quality, with lower disease severity and acceptable pulp condition. This indicates that the benefits of the combined treatment were maintained during the initial period after transfer to regular atmosphere.

However, disease symptoms also developed in T4 fruits when storage was extended by another week in the cold room. Although the fruits maintained better external quality than those under the other treatments, the appearance of disease symptoms suggests that latent infections were not completely controlled. Based on the observed disease incidence and fruit quality, four weeks of CA storage followed by one week under regular atmosphere may therefore be considered a practical storage period for maintaining acceptable quality under the conditions tested. Overall, the findings show that combining CA storage with coating can delay ripening and reduce disease development in jackfruit. However, the benefits are limited by storage duration, and further extension may still lead to disease development.

Figure 1. Disease severity score of jackfruit upon removal from storage (a) and after subsequent ripening (b) under different treatments. Disease severity was evaluated using a 1 to 7 scale based on affected fruit surface area (see Table 1 for details). Values represent mean + DMRT at $p \leq 0.05$. Means followed by different letters within the same storage period indicate significant differences according to DMRT



Changes in Skin Colour

Changes in jackfruit skin colour during storage and subsequent ripening are shown in Fig. 2, based on chromaticity values. Negative values indicate green colour, while positive values indicate a shift towards red or yellowish tones as chlorophyll degrades.

Upon Removal from Storage

After three weeks of storage (Fig. 2a), significant differences ($p \leq 0.05$) in skin colour were observed among treatments. Fruits stored under regular atmosphere (T1 and T2) recorded higher a value than those stored under controlled atmosphere (T3 and T4), indicating greater colour changes and chlorophyll degradation. T1 recorded the highest a value, followed by T2, suggesting that coating helped to delay skin yellowing under regular atmosphere conditions. This agrees with Nor Hanis Aifaa et al. (2025), who reported that EONature edible coating helped to delay skin browning and maintain green peel colour during cold storage and sea shipment.

CA storage was more effective in retaining green skin colour, with T3 and T4 recording significantly lower a value than the regular atmosphere treatments. The combination of CA and coating (T4) showed a further improvement in colour retention at week 3. Similar findings on the retention of green peel colour and delayed chlorophyll degradation under low-oxygen conditions or modified atmosphere packaging have been reported in jackfruit by Mata-Montes de Oca et al. (2007), Morelos-Flores et al. (2021) and Cho et al. (2020), as well as in other tropical fruits (Montalvo-González et al., 2021).

After four weeks of storage, the differences among treatments became more pronounced. T2 recorded the highest positive a value, indicating greater skin colour changes during storage. In contrast, T3 recorded intermediate values, while T4 maintained the lowest value among all treatments. These results suggest that combining CA storage with coating was more effective in delaying skin colour changes than either treatment alone. Similar benefits of combined postharvest treatments have been reported by Montalvo-González et al. (2021) and Morelos-Flores et al. (2021), who found that combining atmospheric modification with other treatments helped to delay peel yellowing and surface discolouration.

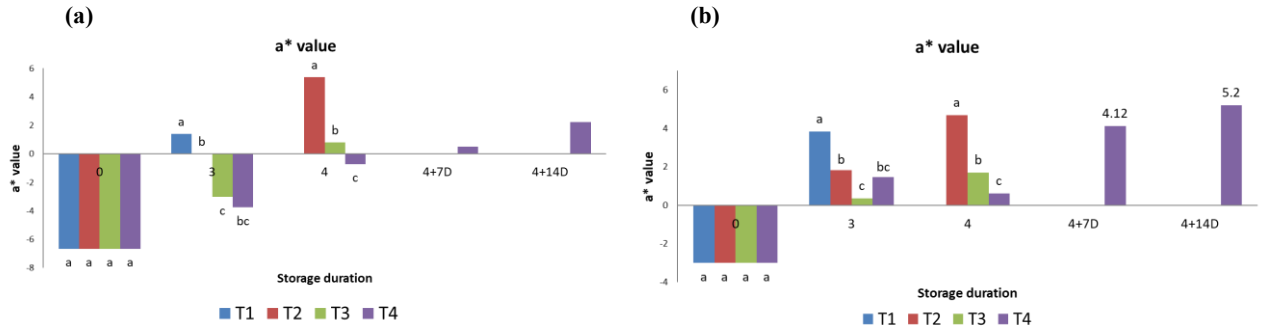
After Ripening

Following transfer to ambient conditions for ripening (Fig. 2b), a value increased across all treatments, reflecting the normal change in skin colour during ripening. However, treatment differences remained significant. At both weeks 3 and 4, fruits from T1 and T2 recorded significantly higher a value than those from T3 and T4, indicating more advanced skin colour development. Fruits previously stored under CA conditions retained lower value even after ripening, suggesting that chlorophyll degradation had been delayed during storage.

During the extended storage assessment, following four weeks of CA storage and subsequent transfer to regular atmosphere for 7 and 14 days, T4 showed a marked increase in value, reaching approximately 5.2. This indicates that colour development resumed after the fruits were removed from CA storage. The result suggests that CA delayed, rather than permanently prevented, the normal colour changes associated with ripening. Similar responses following transfer to ambient conditions have been reported in tropical fruits (Montalvo-González et al., 2021; Morelos-Flores et al., 2021).

Overall, CA storage was the main factor contributing to the retention of green skin colour in jackfruit, while coating provided additional benefits when used in combination with CA. T4 consistently maintained the lowest a value during storage, indicating better colour retention. From a commercial perspective, delaying skin yellowing is beneficial for sea-freight export, provided that the subsequent ripening period is properly managed. However, the increase in value after transferring to regular atmosphere also indicates that colour changes can resume during distribution and marketing

Figure 2. Changes in skin colour (a* value) of jackfruit upon removal from storage (a) and after subsequent ripening (b) under different treatments. Values represent mean + DMRT at p ≤ 0.05. Means followed by different letters within the same storage period indicate significant differences according to DMRT.



Flesh Colour and Firmness

Flesh colour (C)

Flesh colour, expressed as chroma (C), showed no significant differences ($p > 0.05$) among treatments at any storage duration (Fig. 3a). Following storage and ripening at weeks 3 and 4, C values decreased slightly across all treatments, with no consistent differences among treatments. These results indicate that CA storage and coating, either individually or in combination, did not significantly affect flesh colour after ripening. This suggests that delaying external ripening under CA conditions did not adversely affect internal colour development. Similar findings have been reported in jackfruit, where modified atmosphere and coating treatments maintained internal quality while allowing normal colour changes during ripening (Vargas-Torres et al., 2017; Montalvo-González et al., 2021; Saxena et al., 2013).

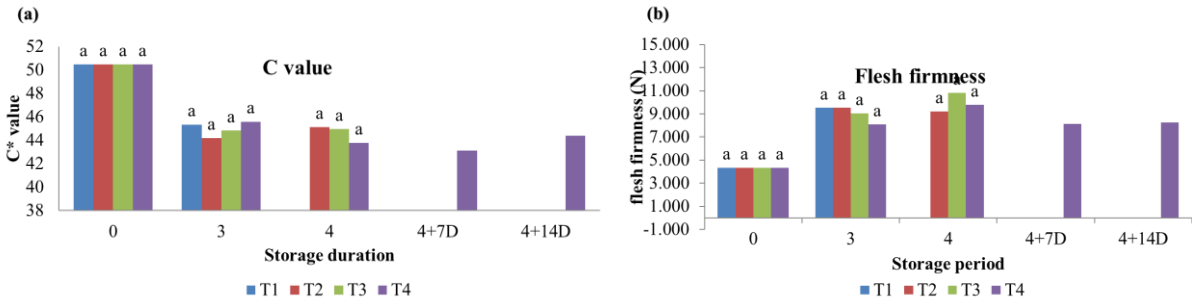
Firmness (N)

Flesh firmness also showed no significant differences among treatments after ripening (Fig. 3b). At week 0, firmness was approximately 4–5 N. Following storage and ripening, firmness values were higher across treatments at weeks 3 and 4. Although the differences were not significant, fruits stored under CA conditions (T3 and T4) tended to have higher firmness than those stored under regular atmosphere (T1 and T2). This trend suggests that CA storage may help to retain flesh firmness by slowing respiration and cell wall degradation during storage

The combined treatment (T4) maintained firmness comparable to the other treatments after ripening, suggesting that the coating did not adversely affect fruit texture. Similar findings have been reported in jackfruit, where coating and atmosphere modification delayed tissue deterioration during storage while allowing the flesh to soften during subsequent ripening (Vargas-Torres et al., 2017; Montalvo-González et al., 2021; Coronado-Partida et al., 2025; Kaur et al., 2024). During extended storage, following four weeks of CA storage and transfer to regular atmosphere for 7 and 14 days, T4 maintained firmness within an acceptable range. This suggests that the combined treatment helped to maintain textural quality during the extended storage period, in line with the delayed ripening observed in the earlier results (Vargas-Torres et al., 2017; Montalvo-González et al., 2021; Coronado-Partida et al., 2025).

Overall, flesh colour and firmness were not significantly affected by the treatments after ripening, despite the differences in external appearance and disease development. The results suggest that CA storage, with or without coating, delayed changes in external quality without substantially affecting these internal quality attributes (Vargas-Torres et al., 2017; Montalvo-González et al., 2021; Cho et al., 2020). From a commercial perspective, maintaining flesh colour and texture while delaying ripening is important for extending the storage period of jackfruit for export and distribution

Figure 3. Flesh colour and firmness of jackfruit after ripening under different treatments: (a) chroma (C*), and (b) firmness (N). Values represent mean + DMRT at p ≤ 0.05. Means followed by different letters within the same storage period indicate significant differences according to DMRT.



Chemical Quality Attributes

Changes in chemical quality attributes, including total soluble solids (TSS), total titratable acidity (TTA) and ascorbic acid content, are presented in Fig. 4.

Total Soluble Solids (TSS)

TSS values remained relatively stable across all treatments throughout the storage period (Fig. 4a). Following 3 and 4 weeks of storage and subsequent ripening, TSS increased slightly across all treatments, reaching approximately 26–28%. This increase may be associated with the conversion of carbohydrates into soluble sugars during ripening, as described by Taj (2013) in jackfruit. However, no significant differences ($p > 0.05$) were observed among treatments within the same storage period. This suggests that CA storage and coating did not significantly affect TSS development under the conditions tested. The relatively stable TSS values also indicate that the treatments did not substantially alter the accumulation of soluble solids during ripening. This is in line with Saxena et al. (2008) who reported that sugar accumulation continued during the ripening of minimally processed jackfruit bulbs under modified atmosphere packaging.

Total Titratable Acidity (TTA)

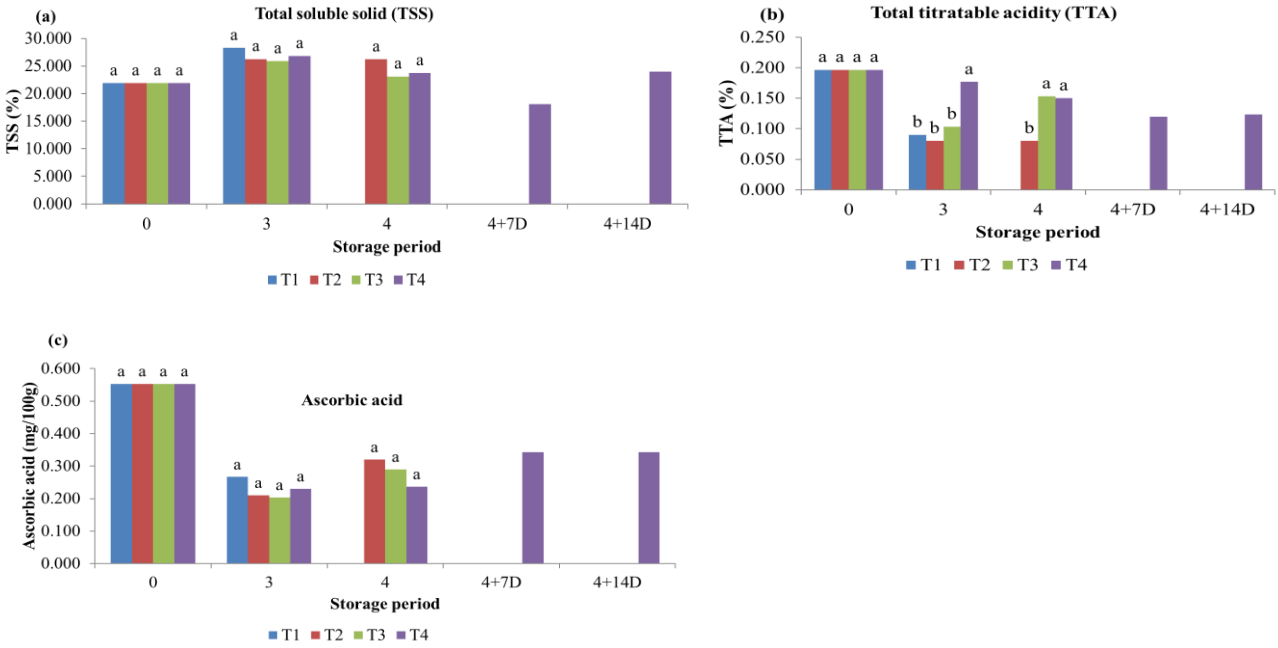
Unlike TSS, TTA varied among treatments (Fig. 4b). After 3 weeks of storage and subsequent ripening, T4 recorded significantly higher TTA than T1 and T2, while T3 showed intermediate values. At week 4, both CA treatments (T3 and T4) maintained higher TTA than the RA treatments. The higher acidity in T4 suggests that the combination of CA storage and coating may have helped retain organic acids during storage and ripening. This could be related to reduced respiratory activity and slower utilisation of organic acids under low-oxygen conditions. Kader (1994) described how atmospheric modification can slow the metabolic changes associated with the breakdown of organic acids in fresh produce. In comparison, fruit stored under RA may have undergone faster metabolic activity, resulting in greater organic acid utilisation during ripening. This interpretation is consistent with the postharvest metabolic changes described by Taj (2013) in jackfruit.

Ascorbic Acid

Ascorbic acid (mg 100 g^{-1} FW) content generally decreased from week 0 to week 3 across all treatments (Fig. 4c), indicating a loss of vitamin C during storage. However, no significant differences ($p > 0.05$) were observed among treatments within the same storage period. At week 4, T2 recorded the highest ascorbic acid content, followed by T3 and T4, although the differences were not statistically significant. These findings suggest that neither storage atmosphere nor coating had a significant effect on ascorbic acid retention under the conditions tested. The decline appeared to be more closely associated with storage duration than with the treatments applied. Taj (2013) noted that ascorbic acid is susceptible to oxidation and may decrease during postharvest storage. Kader (1994) similarly discussed the effects of storage conditions on postharvest quality, although the extent of vitamin C retention may vary depending on the commodity and storage conditions.

Overall, the chemical quality attributes were largely maintained across the treatments. TSS increased slightly during ripening, with no significant differences among treatments, while ascorbic acid content generally declined over the storage period. In contrast, the higher TTA observed in the CA treatments, particularly T4, suggests better retention of organic acids. These findings indicate that combining CA storage with coating helped maintain acidity without significantly affecting TSS or ascorbic acid content. From a commercial perspective, this combination shows potential for extending jackfruit storage life while maintaining key chemical quality attributes. However, the observed differences in TTA should be interpreted alongside the sensory results, which showed no significant differences in taste or overall acceptability among the treatments.

Figure 4. Chemical quality attributes of jackfruit flesh after ripening under different treatments: (a) total soluble solids (TSS, %), (b) titratable acidity (TTA,), and (c) ascorbic acid (mg 100 g^{-1} FW). Values represent mean + DMRT at $p \leq 0.05$. Means followed by different letters within the same storage period indicate significant differences according to DMRT



Anaerobic Volatile Compounds

Changes in volatile compounds associated with anaerobic metabolism, including acetaldehyde, ethanol and ethyl acetate, are presented in Fig. 5.

Acetaldehyde

Acetaldehyde levels remained relatively low across all treatments and storage durations (Fig. 5a). Slight increases were observed after 3 and 4 weeks of storage, but the differences among treatments within the same storage period were not significant ($p > 0.05$). These findings suggest that CA storage and coating did not lead to excessive acetaldehyde accumulation under the conditions tested. Small amounts of acetaldehyde may be produced during normal fruit metabolism, while excessive accumulation can indicate a shift towards fermentative metabolism under oxygen-limited conditions. Burdon et al. (2007) and Shi et al. (2005) reported changes in respiratory and fermentative metabolism in fruit exposed to different storage atmospheres. In the present study, the relatively low acetaldehyde levels suggest that the treatments did not cause substantial changes in this aspect of fruit metabolism.

Ethanol

Ethanol content followed a similar trend (Fig. 5b), with slight increases after storage, particularly in T4 at weeks 3 and 4. However, the differences among treatments were not statistically significant ($p > 0.05$). Under extended storage conditions, comprising 4 weeks of CA storage followed by 7 or 14 days under RA conditions, ethanol levels also remained relatively low. These results suggest that the combined CA and coating treatment did not result in excessive ethanol accumulation. Ethanol production can increase when oxygen availability becomes insufficient to sustain normal aerobic respiration, potentially leading to fermentative off-flavours. Kader (1994, 2003) and Yahia (1998) discussed the importance of gas composition in maintaining postharvest quality and avoiding physiological disorders in fresh produce. In this study, the low levels of ethanol and the absence of significant treatment differences suggest that severe fermentative activity was not evident under the storage conditions applied.

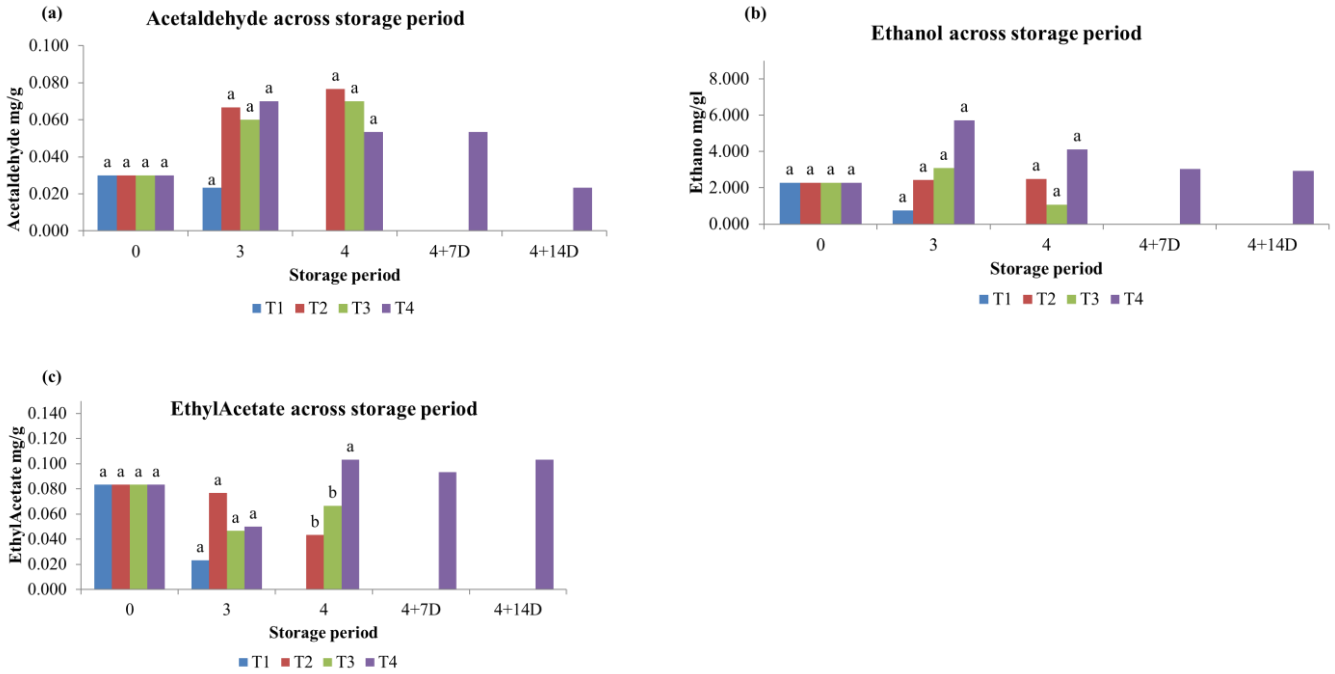
Ethyl acetate

In contrast to acetaldehyde and ethanol, ethyl acetate showed a more distinct response (Fig. 5c). After 4 weeks of storage, T4 recorded significantly higher ethyl acetate content than the other treatments ($p < 0.05$), while T3 showed intermediate values and T1 and T2 had lower levels. Under extended storage conditions, ethyl acetate content in T4 remained elevated, although no excessive further increase was observed. The higher ethyl acetate content in T4 may reflect changes in volatile compound formation under the combined CA and coating treatment. Ethyl acetate can be formed through reactions involving ethanol and acetyl-CoA and is associated with fruit aroma at suitable concentrations. However, its accumulation alone does not confirm that the fruit underwent anaerobic stress, as ester production can also occur during normal fruit ripening. Pesis et al. (1991, 2002) reported changes in volatile production under different postharvest conditions, although the relationship between volatile concentrations and

sensory perception depends on the fruit and the concentrations involved. In the present study, the higher ethyl acetate content in T4 was not accompanied by significant differences in sensory taste, aroma or overall acceptability. This suggests that the observed change did not adversely affect sensory quality under the conditions evaluated.

Overall, acetaldehyde and ethanol levels remained relatively low, with no significant differences among treatments. Although T4 showed significantly higher ethyl acetate content after 4 weeks of storage, this difference was not accompanied by a significant reduction in sensory acceptability as discussed in the next sub section. These findings suggest that the combined CA and coating treatment influenced the accumulation of certain volatile compounds without clear evidence of excessive fermentative activity or deterioration in sensory quality. Nevertheless, the higher ethyl acetate content in T4 indicates that volatile metabolism may have been altered during prolonged storage. Further investigation would be required to determine whether this change was associated with oxygen limitation, normal ripening-related ester formation or a combination of these processes.

Figure 5. Anaerobic volatile compounds in jackfruit flesh after ripening under different treatments: (a) acetaldehyde (mg g^{-1}), (b) ethanol (mg g^{-1}), and (c) ethyl acetate (mg g^{-1}). Values represent mean + DMRT at $p \leq 0.05$. Means followed by different letters within the same storage period indicate significant differences according to DMRT



Sensory Evaluation

Sensory evaluation of jackfruit flesh after four weeks of storage is presented in Table 3. No significant differences ($p > 0.05$) were observed among T2, T3 and T4 for freshness, colour, texture, taste, aroma and overall acceptability. T1 was excluded from the evaluation because the fruits had been discarded after three weeks of storage. Mean scores ranged from approximately 4.1 to 4.8 on the 5-point hedonic scale, indicating that the panellists generally liked the fruit.

T4 (coating + CA) recorded slightly higher scores for colour (4.68) and taste (4.79), while T3 (CA only) obtained marginally higher scores for freshness (4.25) and overall acceptability (4.39). However, these differences were not statistically significant. The high taste scores were consistent with the TSS results, which showed no significant differences among treatments despite a slight increase to 26–28% after ripening. Although TTA was higher in T3 and T4, this did not result in significant differences in taste scores.

Similarly, acetaldehyde and ethanol levels remained relatively low, with no significant differences among treatments. Although T4 recorded significantly higher ethyl acetate at week 4, no significant difference was observed in aroma or overall acceptability. This suggests that the increase in ethyl acetate did not adversely affect sensory acceptance at the levels observed. Overall, the results indicate that CA storage, with or without coating, maintained the eating quality of jackfruit flesh after four weeks of storage.

Table 3. Sensory evaluation of jackfruit flesh after 4 weeks of storage under different treatments. Fruits were stored under T2 = Coating + RA, T3 = CA only, and T4 = Coating + CA. Values represent mean scores based on a 5-point hedonic scale (1 = dislike very much; 5 = like very much. See details in Table 2). Means followed by different letters within the same column are significantly different according to DMRT at $p \leq 0.05$

Treatments	Freshness	Colour	Texture	Taste	Aroma	Overall acceptability
T2	4.17 a	4.57 a	4.45 a	4.52 a	4.22 a	4.19 a
T3	4.25 a	4.45 a	4.16 a	4.44 a	4.39 a	4.39 a
T4	4.13 a	4.68 a	4.39 a	4.79 a	4.37 a	4.28 a

CONCLUSION

This study demonstrated that controlled atmosphere (CA) storage at 12°C, in combination with an edible plant oil-based coating (EONature®), was effective in maintaining the postharvest quality of 'Tekam Yellow' (J33) jackfruit. The combined treatment reduced disease severity, maintained greener peel colour and helped retain flesh firmness during four weeks of CA storage. Eating quality was also maintained, as indicated by satisfactory total soluble solids and sensory acceptability. Low acetaldehyde and ethanol concentrations further suggested that the storage conditions did not cause excessive fermentative changes. For the anticipated three-week export storage requirement, either EONature® coating or CA storage at 12°C may be considered as a potential postharvest option. CA storage also offers an alternative to the existing coating technology for meeting this requirement. Importantly, combining EONature® coating with CA storage extended the potential storage life to four weeks, providing an additional week compared with either treatment alone. This improvement could offer greater flexibility in sea shipment and distribution, supporting the export of Malaysian jackfruit to more distant markets. Further research should focus on improving preharvest sanitation and postharvest disease management to reduce latent fungal infections and minimise disease development during extended storage and distribution. Commercial-scale storage simulations and actual export trials are also needed to validate the effectiveness of these treatments in maintaining fruit quality and marketability under commercial handling, transportation and distribution conditions.

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