

THE INFLUENCE OF HIGH CARBON DIOXIDE LEVELS IN ALL-IN-ONE MODIFIED ATMOSPHERE STORAGE ON BANANAS, PAPAYAS, AND WATERMELONS' SHELF LIFE

Article history

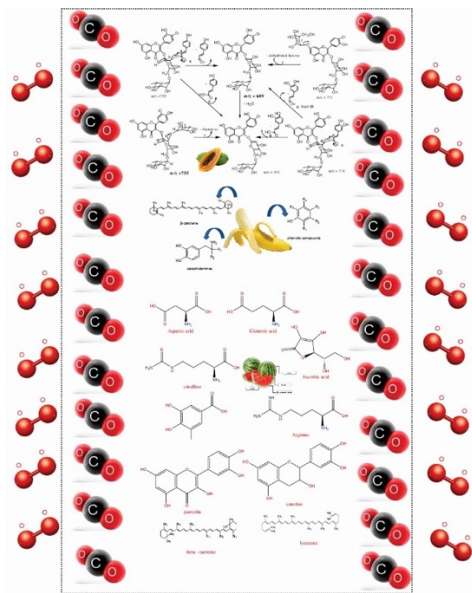
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Agri Suwandi^a, Wina Libyawati^{a*}, Abid Fahreza Alphanoda^a,
Intan Permata Sari^b

*Corresponding author
wina@univpancasila.ac.id

^aMechanical Engineering Department, Universitas Pancasila,
Indonesia

^bPharmacy Faculty, Universitas Pancasila, Indonesia



Abstract

Modified Atmosphere Storage (MAS) can extend the shelf life of fruits. The biological quality assessment of the preserved fruit and the fluid-mechanical phenomena within the compartment determine MAS performance. Most researchers investigate MAS performance for freshly picked fruit compared to post-harvest products, because the former are direct consumption commodities. MAS performance for post-harvest purposes requires a molecular analysis approach to describe the energy release during respiration. Recent technology focuses on single storage for one type of fruit. The carbon dioxide-to-oxygen ratio inside the MAS compartment is a critical controlling factor in suppressing respiration and slowing the decay process. Therefore, this study aims to investigate the application of all-in-one storage for banana, papaya, and watermelon under high-concentration carbon dioxide. An experimental study is set up with three carbon dioxide levels (30%, 40%, and 50% by mass) and skin thickness, hardness, and glucose. A molecular analysis is set up to identify the decay process. This study also explains the direct bandgap energy produced by the fruit. The study results show that MAS treatment is highly effective in retaining mass, skin thickness, and hardness with 30% CO₂ application for banana, and bandgap energy shows that banana has the lowest eV after MAS treatment in comparison to storage under room temperature, and direct bandgap energy is able to describe the fruit respiration rate slowing down during MAS treatment.

Keywords: Carbon dioxide-oxygen ratio, modified atmosphere storage, glucose level, shelf time

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1.0 INTRODUCTION

The modified atmosphere storage sector is evolving rapidly, driven by technological advancements, sustainability initiatives, and changing consumer preferences. As the market continues to grow,

innovations in materials and packaging technologies will play a crucial role in enhancing food preservation and reducing waste. The technologies have to foresee application for long term storage above 30 days, to accommodate post-harvest product transportation [1]. Tropical fruit such as mango,

papaya, banana, and watermelon preference worldwide due to its taste and benefit, but on the other hand those have short shelf life, sensitivity to temperature, and ethylene sensitivity. Modified Atmosphere Storage (MAS) is one of the proven storage techniques to mitigate those weakness [2].

The respiration rate control is the key to obtain the optimum benefit from MAS application for long term storage purposes. The gas composition inside the MAS compartment plays an important role, in determining the speed of fruit respiration rate during storage [3]. The balance Carbon Dioxide (CO₂) and Oxygen (O₂) concentration inside MAS compartment, can slow down the respiration rate because the increase CO₂ can switch the fruit respiration mode from aerobic to anaerobic state and finally suppress the O₂ concentration [4]. The shifting respiration mode consequent low energy production rate [5]. So, the challenge to preserve fruit by using MAS is controlling the CO₂ and O₂ balance inside the compartment storage.

Suppress the O₂ concentration while mango under MAS storage for 28 days, is investigated by varying combination of O₂, CO₂, and N₂ concentration. The most advantages combination in storing mango fruit in terms of selected quality attributes ranged between 5-8% O₂, 5-9% CO₂, 86-91% N₂, and able to retard ripening and mass loss and reduce fruit softening and chlorophyll degradation [6]. Gel absorber and N₂ gas combination is applied to store mango and able to extend the shelf life for another 15 days in comparison to room temperature storage [7]. Another gel absorber application is investigated to store various fruits and vegetables and show the same benefit, at the same highlighted the importance to maintain the balance between O₂ and CO₂ composition [8]. A respiration model for cherry tomatoes at different temperatures, reveals that respiration rates rose with increasing temperature and declined over time. The experimental shows the MAS set up able to retain weight loss and maintained lower permeability, to improved hardness, and to preserve titratable acid (TA), vitamin C (VC), and total soluble solids (TSS) levels. The temperature set up produce 8.6-20.3% O₂ and 0.04-11.2% CO₂ inside the MAS storage [9]. Another MAS application to store tomato is conducted by varying the channel apparatus dimension to release the vapor from the chemical reaction during respiration for experimental study, which are length and diameter. The dimension variation able to maintain the O₂ concentration range 7-15%, with the benefit to prolong the storage time [10]. A stable concentration of CO₂ at 8.6% and 8.2%, in combination with O₂ concentrations of 2.8% and 2.6%, is set to store bananas for 5-7 weeks under MAS treatment, and this is compared to bananas stored at room temperature for 3 weeks. Treatment with MAS reduces weight loss and slows down changes in color, pulp-to-peel ratio, and TSS [11]. Golden papaya stored in refrigerated controlled atmospheres at 13°C with 3% or 6% O₂ and varying CO₂ levels. A standard atmosphere of 20.8% O₂ and 0.03% CO₂ was also

created, alongside a control treatment under ambient conditions, and can delay the ripening rate [12]. The apricot treatment under modified atmosphere relies on a CO₂ - O₂ combination, with concentrations of 10% O₂ and 20% CO₂, 20% O₂ and 10% CO₂, 5% O₂ and 80% CO₂, 80% O₂ and 5% CO₂, and 40% O₂/20% CO₂ was investigated. The elevated CO₂ levels enhanced postharvest characteristics [13]. Recent MAS application development has achieved optimal set up parameter based on its commodity characteristic, ability to predict the fluid mechanics phenomena, and MAS able to extend the shelf life for perishable fruit and vegetable. On contrary MAS application is still underdeveloped for microbial risk and packaging or compartment material.

The overall MAS application focuses on the impact of O₂ and CO₂ composition on the biological properties of fruits and the usage of MAS based on the specific respiration rates of each fruit. However, the application of MAS to store several types of fruits in one compartment is feasible as long as their respiration rates are approximately the same [14], [15]. The research gap based on the challenges, achievement and limitation of MAS development is the correlation between biochemical and physiological response, gas composition control based on commodity diversity, and long-term storage in transportation mode.

Therefore, this study aims to investigate the impact of elevated CO₂ on the biological properties for several tropical fruits and compare those changes to storage under ambient temperature. The respiration rate can be calculated by measuring the intake of oxygen or release of carbon dioxide [16], and using the mathematical approach [17], [18], [19]. Another method to predict the respiration rate is by using the in-direct approach from the UV-Vis measurement. So, the next step of this study is to calculate and plot the direct bandgap energy from the absorbance graph. The integrated investigation of the elevated CO₂ concentration and direct bandgap energy prediction will give contribution in developing the method to evaluate MAS performance.

2.0 METHODOLOGY

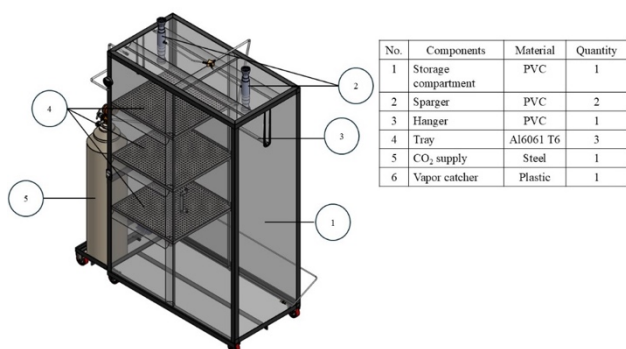
a. Experimental Set Up

An experimental is set up based on the combination of three fruits types and three carbon dioxides level inside the MAS compartment as shown in Table 1. MAS installation structure consists of 6 components as picturized in Figure 1.

Table 1 Parameter combinations for the experimental set up

No	Factors	Level		
		1	2	3
1	Types of fruits	Papaya	Banana	Watermelon
2	Storage types	Under room temperature	MAS	-
3	CO ₂ level	30%	40%	50%

Table 1 represents the full factorial approach to investigate the correlation between carbon dioxides level and the glucose level between the preservation with and without MAS treatment. Figure 1 shown the applied MAS installation. The storage compartment preserves the fruits, and it is divided into four separate compartments. Bananas is set to be tightly dangle to the pole, to mimicking the common method used by farmers. Papayas and watermelons are placed on top of metal tray with perforated pores. Two spargers are installed on top of the storage compartment to inject the carbon dioxides, so the oxygen level decrease gradually. Vapor catcher is set connected to the bottom side of the storage compartment, to channeling the trapped vapor that occurred during the carbon dioxides injection. A fan is installed and operated during the MAS treatment, to avoid carbon dioxide concentration at the bottom part of the storage compartment.

**Figure 1** MAS installation

The procedures to preserve the fruits with MAS in sequences are arranging as follow: store preserved the fruits inside the storge compartment, sealing the door with sealing tape, vacuuming the oxygen concentration inside the storage compartment, injecting the carbon dioxides based on the designated percentage until the oxygen level in storage compartment reach $\leq 0.5\%$, turning off the distribution valve, recording the air composition daily during the three days preservation periods, taking out the fruits after the preservation period over, and at the end measuring the fruits biological and glucose levels. Three repeated measurements at difference spot of

the fruit are conducted. Table 2 summarizes the specification of measurement apparatus.

Table 2 The specification of measurement apparatus

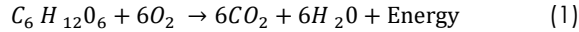
No	Measurement Apparatus	Specification
1	Gas Meter	<ul style="list-style-type: none"> Biogas 5000 – able to measure CH₄, CO₂, and O₂. Measurement in percentage and with accuracy $\pm 0.5\%$ after calibration
2	Glucose meter	<ul style="list-style-type: none"> Measuring range 0-35% Brix Resolution 0.1% Ambient temperature 10-40°C Temperature compensation 10-40°C Accuracy $\pm 0.2\%/\pm 0.5\%$ Refractive index display 1.333-1.426
3	Hardness meter (GY2)	<ul style="list-style-type: none"> Indication scale 0.5-4 kg/cm² ($\times 10^5$ Pa) Pressure Head size $\varnothing 3.5$mm Precision ± 0.2 Insertion depth 10 mm Size 140 x 60 x 30 mm
4	Colorimeter	<ul style="list-style-type: none"> DS- 200 Measuring structure (D/8, SCI) Measurement repeatability ($\Delta E^*ab \leq 0.03$) Measuring aperture (There are 2 stable and agile models in total: $\varnothing 6$mm, $\nabla 6$mm) Color Spaces and Indices (Reflectance, CIE-Lab, CIE-LCh, Hunter Lab, CIE LuV, XYZ, Yxy, RGB, Color difference ($\Delta E^*ab, \Delta E^*cmc, \Delta E^*94, \Delta E^*00$), WI(ASTM E313-00, ASTM E313-73, CIE, ISO2470/R457, AATCC, Hunter, Taube Berger Stensby), YI(ASTM D1925, ASTM E313-00, ASTM E313-73), Blackness (My,dM), Color Fastness) Wavelength range (400-700 nm)

The Brix measurement result from glucose meter represents the ripening level. The hardness measurement result from the fruit skin represents the CO₂ usage impact. The UV VIS result represents absorption level for light by the fruit.

b. Bandgap Energy Approach to Oversee Fruit Respiration Rate

The post-harvest technology to preserve tropical fruit with MAS classified as non-chemical approach and during the preservation the fruit is covered by CO₂. The coverage transforms slow down the respiration rate

during aerobic process. The fruit glucose during preservation temperature contacts the air surround it, and intime it will be ripening. The existence of sharp odour, excessive vapor, and high energy release are an indicator of ripening process. The aerobic respiration reaction [7] is presented as follow:



The CO₂ injection reforms the atmosphere condition inside the storage compartment and suppress the O₂ level as shown in Figure 2. The CO₂ removes or suppresses the O₂ and can slow down the aerobic organisms and also speed up the oxidation reaction [20], [21], [22]. So, when the oxygen level decrease during the aerobic respiration with the carbon dioxide aids then the fruit convert glucose into energy or known as Adenosine Triphosphate (ATP) and reduce the heat as one of the reaction products. The energy balance for MAS application led to lower heat generation and lower overall enthalpy change.

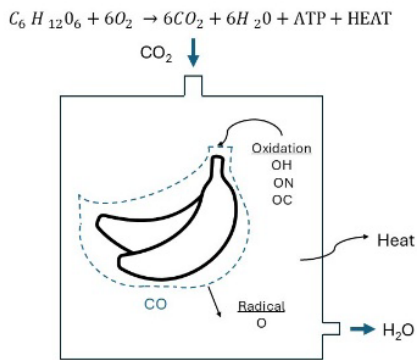


Figure 2 Correlation between aerobic respiration and enthalpy

The enthalpy is calculated based on Hess Law [23], with the following equation:

$$\Delta H^\circ = \sum \Delta H^\circ_{f(\text{products})} - \sum \Delta H^\circ_{f(\text{reactants})} \quad (2)$$

Where ΔH° is the total change in enthalpies, $\sum \Delta H^\circ_{f(\text{products})}$ is the sum of enthalpies for the chemical product, and $\sum \Delta H^\circ_{f(\text{reactants})}$. The applied properties for each enthalpy to calculate the total change in enthalpies is set based on the following table.

Table 3 Enthalpy [24]

Chemical Formula	Enthalpy (kJ/mol)
C ₆ H ₁₂ O ₆	-1273.3
O ₂	0
CO ₂	-393.5
H ₂ O	-285.8

After calculation using Eq.2 the change in enthalpy for this reaction is negative, signifying that it is an exothermic process. The standard enthalpy of

combustion for glucose is roughly -2800 kJ/mol. This calculation result indicates the energy that is liberated when glucose undergoes complete oxidation in the presence of air. So, the enthalpy from empirical approach will be compared with the experimental results from the calorimeter measurement which are converted to bandgap energy. The equation and procedures to calculate the direct bandgap energy is conventional Touc Plot, which partly is adopted from Jubu et. al. [23] for the property and fully adopted for all of the procedures from Alphanoda et.al. [25] until the formation of Tauc's graph. We also conduct Molecular simulations using DFT with orbital semi-core pseudopotentials and the B3LYP functional were performed to investigate the possibility of redox interactions between ethylene and CO₂.

3.0 RESULTS AND DISCUSSION

a. Gas Composition inside MAS Storage

This study, as detailed in the experimental setup, critically assesses the effects of Modified Atmosphere Storage (MAS) treatments at three CO₂ levels: 30%, 40%, and 50%. Accurate measurement of gas composition inside the storage is therefore crucial. Table 4 provides a comprehensive summary of these measurements for each CO₂ level.

Table 4 Gas composition measurement result in MAS storage

Gas	CO ₂ level		
	30%	40%	50%
CH ₄ (%)	0	0	0
CO ₂ (%)	35.3	41.5	54.2
O ₂ (%)	0.5	0	0.4
H ₂ S (ppm)	1	0	0
Others	64.2	58.5	45.4

Previous Research shows that CO₂ concentrations between 10% and 25% significantly affect the storage of fruits like grapes, mangoes, and strawberries. Higher CO₂ levels reduce the O₂ concentration, and that effectively suppressing the ripening process [24], [26], [27], [28].

But the impact of CO₂ concentration above 20% in combination with various fruits store in one storage requires further investigation to accommodate MAS application for shipping purposes. The procedures to achieve those three-level environment control as detailed in the methodology can be a reference for the other researchers to preserve the various fruit in one storage.

b. The Influence of CO₂ Level Toward Fruit Biological Properties

The fruit freshness level during storage is evaluated thorough their biological properties. The MAS treatment can be implemented for shipping purposes

from the farmer to the supplier or directly to the customer. The biological properties held as indicators are mass, skin thickness, hardness, and Brix.

c. The Impact of CO₂ Increases to the Fruit Mass

The covalent of C-O molecular coats the fruit surface as describe in Figure 2. So, the coating can be an effective indicator to measure the impact of CO₂ elevation toward fruit mass after MAS treatment. The mass measurement for all MAS treatment with three level CO₂ and fruit storage under room temperature are shown in Figure 3.

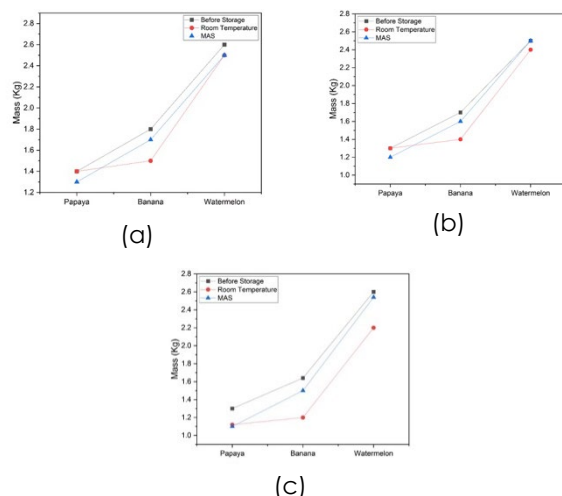


Figure 3 Mass measurement based on fruits variation under (a) 30%, (b) 40%, (c) 50% CO₂ storage

The mass measurement based upon fruit variation for the three levels of CO₂ in Figure 3 shows, fruit under MAS treatment has a lower mass in comparison to a condition before treatment and higher mass if compared to treatment at room temperature, except for papaya with MAS treatment has the lowest value in contrast to the others two treatments. The CO₂ concentration ranging between 30-50% for banana and watermelon under MAS treatment can maintain the fruit mass as the mass decreases slowly, while MAS treatment at all CO₂ levels for papaya is not beneficial. The finding related to papaya in line with the research results from an experimental study for guava which has the same characteristics as papaya and where it was undergoes various MAS treatments with CO₂ set up between 10-30%, and shows CO₂ concentration didn't have any effect to its respiration rate [14]. Papaya incompatibility with MAS treatment is due to its high sensitivity to CO₂.

d. The Impact of CO₂ Increases to the Fruit Skin Thickness

The influence of CO₂ levels ranging from 30-50% during Modified Atmosphere Storage (MAS) treatment can produce dual effects on skin thickness, which shows a direct relationship with the fruit's mass. The browning

effect exemplifies skin damage and serves as a sign of early decay for the fruit under MAS treatment.

Figure 4 illustrates the relationship between various types of fruit and their associated CO₂ level configurations during the MAS treatment. Skin thickness measurements for the MAS treatment at a 30% CO₂ level are presented in Figure 4(a). The papaya under MAS treatment with 30% CO₂ concentration shows a similar skin thickness reduction for both MAS and room temperature treatments compared to pre-treatment conditions. Banana follows the same trend but has thicker skin than in the room temperature treatment. In contrast, watermelon displays a different trend, thickening its skin under MAS treatment as a defense mechanism against CO₂ stress, resulting in a positive outcome. Figure 4(b) and (c) present significant reductions in skin thickness compared to the pre-treatment condition for both MAS and room temperature treatments, where all types of fruit under MAS treatment have thicker skin than those under room temperature treatment. Thus, CO₂ exposure indirectly affects the fruit's skin thickness.

e. The Impact of CO₂ Increases to the Fruit Hardness

MAS application to store various fruits in one storage must accommodate that optimum CO₂ resistance. So, that set up condition can be implemented for shipping purposes and able maintain the fruit firmness.

High CO₂ concentrations ranging 30-50% for MAS treatment as illustrates in Figure 5 shows that the CO₂ increment can maintain the firmness for banana and watermelon in comparison to room temperature storage, but not for papaya. Despite its positive effect to decelerate the fruit ripening process, CO₂ with above 30% concentration storage for certain fruit like papaya cause skin darkening, which is an indicator of early ripening process. The trend result empowers the finding of CO₂ influence toward fruit with highly sensitive to CO₂ is not recommended for MAS application with CO₂ concentration above 30%.

f. The Impact of CO₂ Increases to the Fruit Brix

Brix value is a crucial indicator of fruit sweetness and quality during storage, and it can monitor the ripening process and measure the MAS effectivity in keeping the fruit quality. Fruit during storage undergo biochemical changes that lead to the accelerating of glucose level increment. During ripening the fruits starches are converted into sugar, and that include glucose. Figure 6 illustrates the biochemical changes due to CO₂ concentration increases which is represented by Brix.

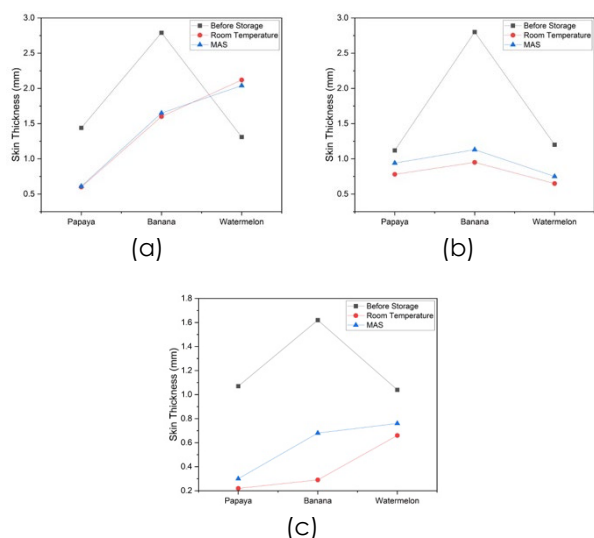


Figure 4 Skin thickness measurement based on fruits variation under (a) 30%, (b) 40%, (c) 50% CO₂ storage

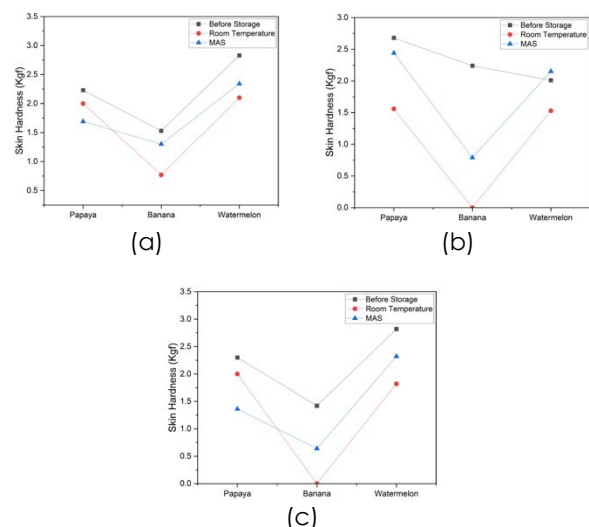


Figure 5 Hardness measurement based on fruits variation under (a) 30%, (b) 40%, (c) 50% CO₂ storage

Each fruit for the experimental evaluation of MAS performance is measured for Brix value in percentage using a glucose meter, as outlined in the methodology section. Figure 6 illustrates the brix values for each storage treatment. Figure 6(a) shows that banana has the highest Brix value across all treatments; papaya and watermelon exhibit higher Brix values after MAS treatment compared to before treatment, while banana's Brix value after MAS treatment is between the before treatment and room temperature results.

This indicates that MAS treatment with 30% CO₂ concentration maintains glucose levels close to pre-treatment conditions but is less effective for papaya and watermelon. Figure 6(b) confirms that banana retains the highest Brix value post-treatment, exceeding both the before treatment and room temperature values, while papaya's Brix value drops below both conditions. Watermelon's Brix value is slightly below room temperature treatment but

remains above the pre-treatment level. Figure 6(c) illustrates the effects observed in papaya and banana during the Modified Atmosphere Storage (MAS) treatment, specifically under a 50% CO₂ concentration.

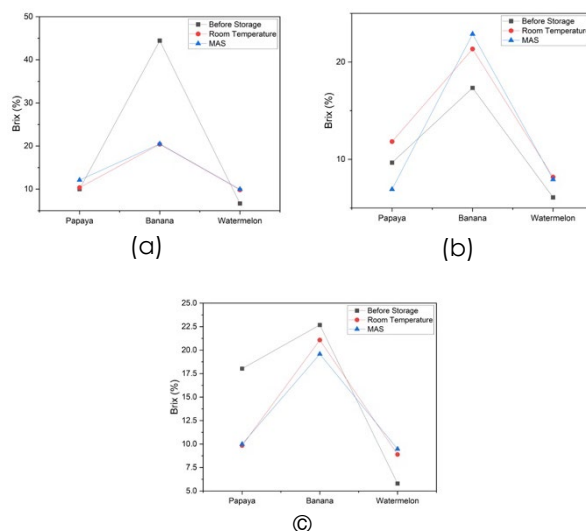


Figure 6 Brix measurement based on fruits variation under (a) 30%, (b) 40%, (c) 50% CO₂ storage

Notably, the room temperature treatment resulted in a Brix value that is significantly lower than the condition recorded prior to the treatment. In contrast, watermelon exhibited a Brix value that diverges from those of papaya and banana, indicating a distinct response to the treatment. The overall trend depicted in Figure 6 leads to the important finding that MAS has a considerable influence on Brix values, which tend to fluctuate and display inconsistencies across different fruit types. The inherent uniqueness of each fruit's Brix contributes to these varied findings, as Brix values are influenced by several factors including the specific fruit type, the growth conditions it was subjected to, and the harvest season. Therefore, it is crucial that the impact of MAS on fluid glucose levels is investigated further, employing uniform procedures that are closely related to the uniformity conditions for the tested fruit, to ensure reliable and comparable results.

g. The Influence of CO₂ Level to the Respiration Rate

In this study, the elevated CO₂ concentration for MAS treatment impact toward the fruit behavior as material properties to absorb light, is evaluated by calculating the bandgap energy from the UV Vis measurement result as stated in the methodology section. Figure 7-15 illustrates the correlation between the type of fruit in combination with MAS treatment with various CO₂ level to absorption ability. Due to the uniqueness of the fruit characteristics the explanation from the experimental results, then the explanation will be divided into three steps of elevated CO₂ level and for each fruit types. Fruits automatically release ethylene during ripening process under MAS or any



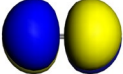
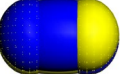


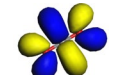
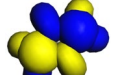


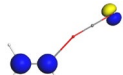
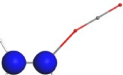


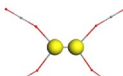
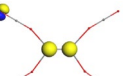
storage method. Radical oxygen formation occurs on the fruits surface along with ethylene release, and both became triggers upon biochemical and physiological changes to the fruits such as texture softening, color changes and sweetening [30]. Carbon Dioxide injection during MAS treatment can delay those changes by disturbing the proton (H⁺) release from the functional group in ethylene [31].

The molecular simulation begins with the transfer of electrons between ethylene and CO₂, resulting in an energy bandgap. During this process, CO₂ reduces protons and breaks a carbon bond within ethylene's functional group. Additionally, this reduction inhibits

oxygen absorption from the surrounding environment, allowing CO₂ to replace ethylene on top of the fruit skin. Table 5 shows the molecular simulation result.

The ripening process in fruit results 5.852 eV during storage under the room temperature. Afterward with the CO₂ intervention the bandgap energy progressively became 0.737 eV. The decelerate bandgap energy represent storage under MAS treatment. After CO₂ totally replace ethylene then the resulted bandgap energy is 0.717. The decelerate trend in Table 5 indicates the delay of ripening process, and that because fruits with MAS treatment experiencing low respiration rate.

Table 5 Molecular simulation for fruit during ripening process

Compound	Energy (kcal/mol)	HOMO (eV)	LUMO (eV)	Bandgap (eV)	Original	HOMO	LUMO	HOMO-LUMO
Ethylene	-558.662	-6.150	-0.298	5.852				
CO ₂	-300.21	-8.868	3.549	12.417				
Ethylene + CO ₂ + H	-11366.176	-14.74	-14.007	0.733				
Ethylene + 4CO ₂	-27347.099	-14.567	-13.85	0.717				

h. The Influence of 30% CO₂ Level for MAS Treatment on to Fruit Types

Figure 7 illustrates correlation between absorbance rate in au with the bandgap energy under MAS with 30% CO₂ concentration with maximum wavelength 470 nm for all treatment and is interpreted as yellow. The bandgap energy of papaya for pre-treatment, room temperature, and MAS in sequence are 1.68 eV, 1.72 eV, and 1.64 eV. The bandgap energy trend show banana with MAS treatment have the lowest bandgap energy that indicates having the lowest energy release to slow down the respiration rate in comparison to pre-treatment and room temperature storage. The trend is in line with the molecular simulation result and strengthen the CO₂ role to suppress the ethylene action.

Figure 8 illustrates the correlation between the absorbance rate in au and the bandgap energy under modified atmosphere storage (MAS) with a 30% CO₂ concentration. subjected to MAS treatment are 420 nm. The maximum wavelength of 420 nm is interpreted as green to yellow, which suggests a shift in the light absorption properties of the banana, while the 470 nm

wavelength is interpreted as yellow, indicating a different state of the fruit prior to treatment.

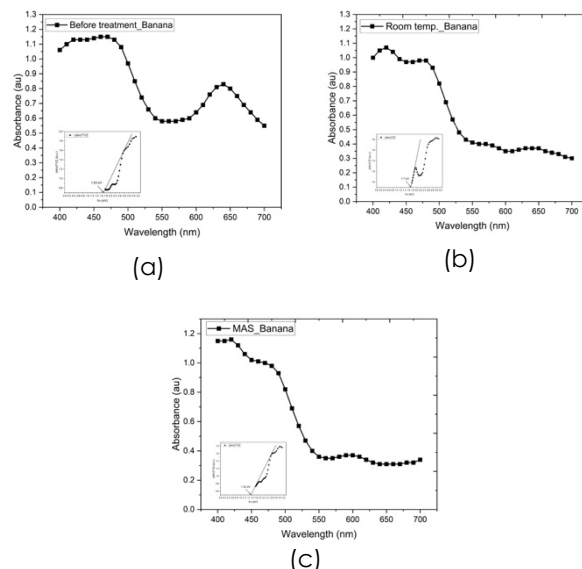


Figure 7 Bandgap energy for Papaya under MAS treatment at 30% CO₂ in sequence (a) 1.68 eV, (b) 1.72 eV, (c) 1.64 eV

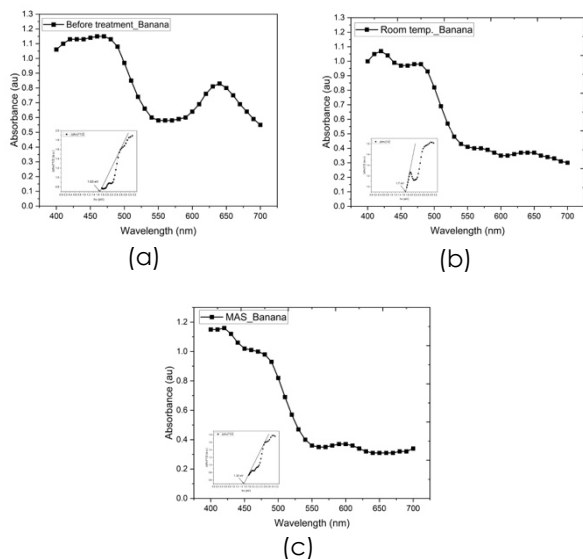


Figure 8 Bandgap energy for Banana under MAS treatment at 30% CO₂ in sequence (a) 1.63 eV, (b) 1.7 eV, (c) 1.32 eV

Notably, the maximum wavelength observed for the banana samples before treatment is 470 nm, while the wavelengths recorded for the samples at room temperature and those

The bandgap energy of banana for pre-treatment, room temperature, and MAS treatment, in sequence, is measured at 1.63 eV, 1.7 eV, and 1.32 eV, respectively. This data reveals a trend in bandgap energy, showing that bananas subjected to MAS treatment exhibit a bandgap energy that is higher than that of the pre-treatment condition but slightly lower than the values observed at room temperature. The comparison of bandgap energy indicates that the MAS treatment applied to bananas is not effective in significantly reducing the respiration rate, which is a critical factor in determining the shelf life and quality of the fruit. This suggests that while MAS may alter certain optical properties, it does not provide the expected benefits in terms of respiration rate reduction, which is essential for maintaining freshness and extending the storage life of bananas.

Figure 9 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 30% CO₂ concentration, with a maximum wavelength of 470 nm for before treatment and 630 nm for room temperature and MAS treatment. The maximum wavelength of 470 nm is interpreted as green-yellow, while 630 nm is interpreted as blue to green. The bandgap energy of watermelon for pre-treatment, room temperature, and MAS, in sequence, is 1.71 eV, 1.74 eV, and 1.65 eV. The bandgap energy trend shows that watermelon with MAS treatment has a bandgap energy lower than the pre-treatment and room temperature values.

The bandgap energy comparison indicates that MAS treatment for watermelon is effective in retaining the respiration rate, suggesting that the application of modified atmosphere storage not only influences the

optical properties of the watermelon but also plays a significant role in enhancing its overall quality and shelf life. This finding is particularly important for the agricultural industry, as it highlights the potential benefits of using MAS techniques to improve the preservation of perishable produce like watermelon, ultimately leading to reduced waste and better marketability.

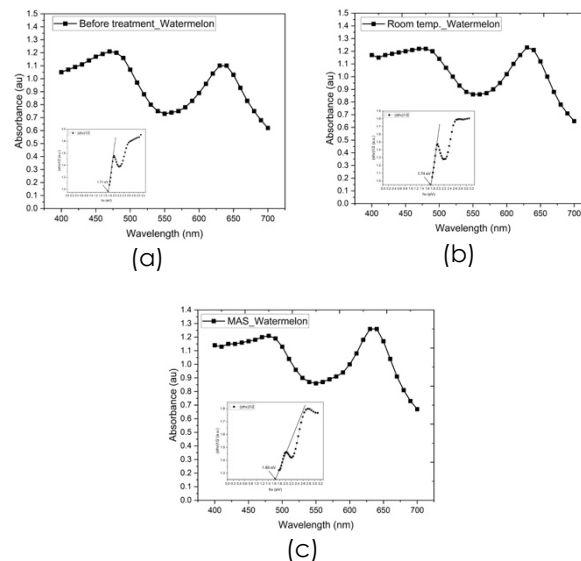


Figure 9 Bandgap energy for Watermelon under MAS treatment at 30% CO₂ in sequence (a) 1.71 eV, (b) 1.74 eV, (c) 1.65 eV

i. The Influence of 40% CO₂ for MAS Treatment on to Fruit Types

Figure 10 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 40% CO₂ concentration, with a maximum wavelength of 430 nm for before treatment and 480 nm for room temperature and MAS treatment.

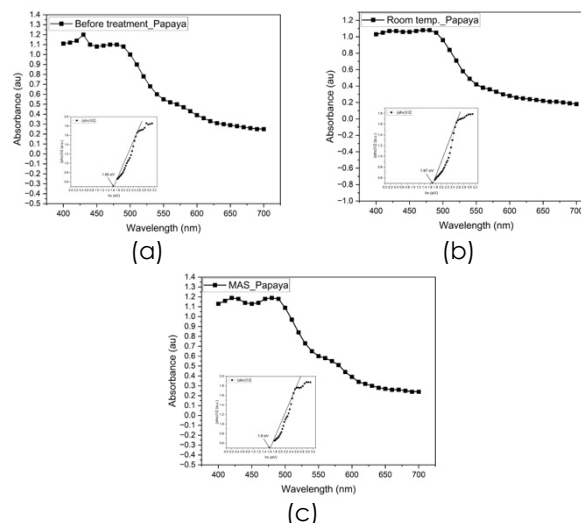


Figure 10 Bandgap energy for Papaya under MAS treatment at 40% CO₂ in sequence (a) 1.65 eV, (b) 1.67 eV, (c) 1.6 eV

The maximum wavelength of 430 nm is interpreted as yellow to green, while 480 nm is interpreted as yellow. The bandgap energy of papaya for pre-treatment, room temperature, and MAS, in sequence, is 1.65 eV, 1.67 eV, and 1.6 eV. The bandgap energy trend shows that papaya with MAS treatment has a bandgap energy higher than the pre-treatment but lower than room temperature values. The bandgap energy comparison indicates that MAS treatment for papaya is slightly effective to retain the respiration rate because its energy release only 0.22% differences to the bandgap energy under room temperature storage. The finding can be used as a caution reference when applying MAS to fruits with high sensitivity to CO₂ like papaya, and when it's store together inside one compartment with others fruit having the opposite sensitivity.

Figure 11 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 40% CO₂ concentration, with a maximum wavelength of 420 nm for pre-treatment, room temperature treatment, and MAS treatment.

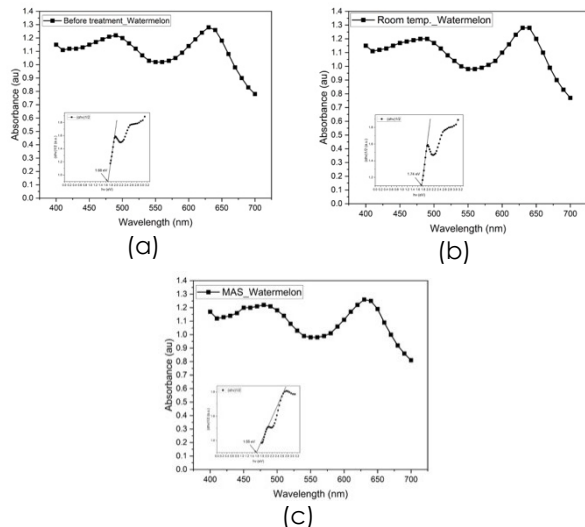


Figure 11 Bandgap energy for Banana under MAS treatment at 40% CO₂ in sequence (a) 1.65 eV, (b) 1.7 eV, (c) 1.6 eV

The maximum wavelength of 420 nm is interpreted as yellow to green. The bandgap energy of banana for pre-treatment, room temperature, and MAS, in sequence, is 1.65 eV, 1.7 eV, and 1.6 eV. The bandgap energy trend shows that Banana with MAS treatment has the lowest bandgap energy than the pre-treatment and room temperature storage. The bandgap energy comparison indicates that MAS treatment for banana is effective to retain the respiration rate.

Figure 12 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 40% CO₂ concentration, with a maximum wavelength of 630 nm for pre-treatment, room temperature treatment, and MAS treatment. The maximum wavelength of 630 nm is interpreted as blue to green. The bandgap energy of watermelon for

pre-treatment, room temperature, and MAS, in sequence, is 1.68 eV, 1.74 eV, and 1.55 eV. The bandgap energy trend shows that watermelon under MAS treatment has the highest bandgap energy than the pre-treatment and room temperature storage. The bandgap energy comparison indicates that MAS treatment with 40% CO₂ for watermelon is not effective to retain the respiration rate.

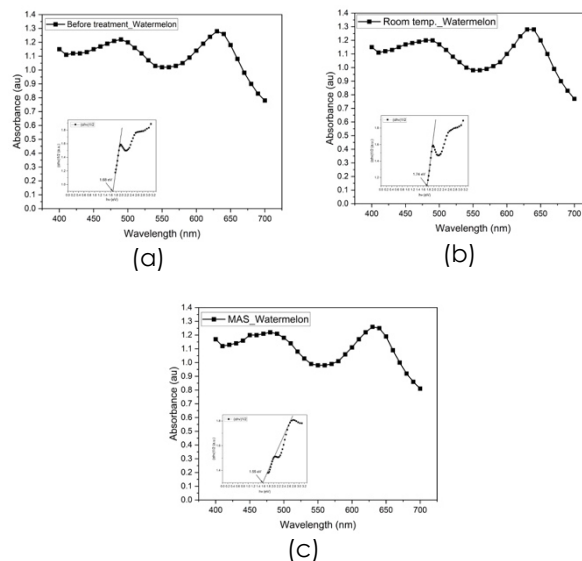


Figure 12 Bandgap energy for Watermelon under MAS treatment at 40% CO₂ in sequence (a) 1.68 eV, (b) 1.74 eV, (c) 1.55 eV

j. The Influence of 50% CO₂ for MAS Treatment on to Fruit Types

Figure 13 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 50% CO₂ concentration, with a maximum wavelength of 420 nm for pre-treatment, room temperature treatment, and MAS treatment. The maximum wavelength of 420 nm is interpreted as yellow to green. The bandgap energy of papaya for pre-treatment, room temperature, and MAS, in sequence, is 1.6 eV, 1.68 eV, and 1.56 eV. The bandgap energy trend shows that watermelon under MAS treatment has band gap energy below the pre-treatment but under room temperature storage. The bandgap energy comparison indicates that MAS treatment with 50% CO₂ for papaya is slightly effective to retain the respiration rate.

Figure 14 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 50% CO₂ concentration, with a maximum wavelength of 420 nm for pre-treatment, room temperature treatment, and MAS treatment.

The maximum wavelength of 420 nm is interpreted as yellow to green. The bandgap energy of banana for pre-treatment, room temperature, and MAS, in sequence, is 1.64 eV, 1.65 eV, and 1.59 eV. The bandgap energy trend shows that banana under MAS treatment has the lowest band gap energy

below the pre-treatment and room temperature. The bandgap energy comparison indicates that MAS treatment with 50% CO₂ for banana can retain the respiration rate.

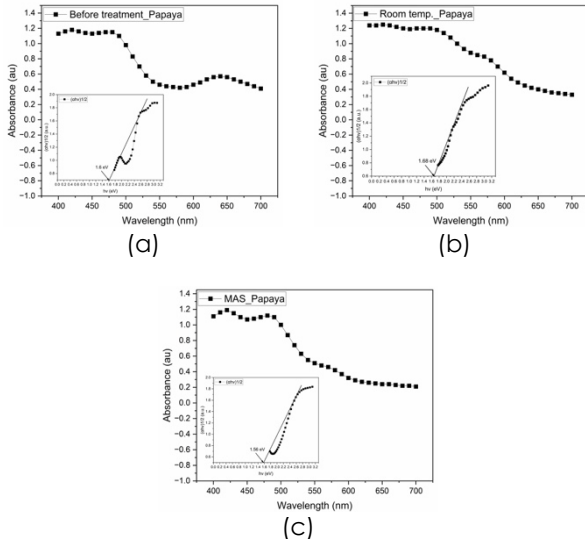


Figure 13 Bandgap energy for Papaya under MAS treatment at 50% CO₂ in sequence (a) 1.6 eV, (b) 1.68 eV, (c) 1.56 eV

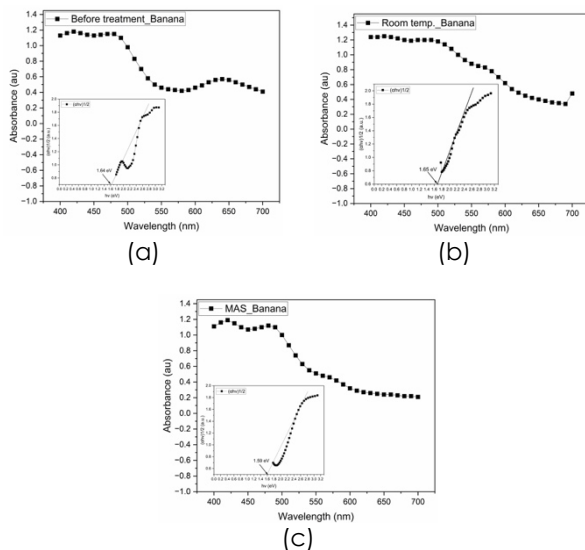


Figure 14 Bandgap energy for Banana under MAS treatment at 50% CO₂ in sequence (a) 1.64 eV, (b) 1.65 eV, (c) 1.59 eV

Figure 15 illustrates the correlation between the absorbance rate in au and the bandgap energy under MAS with 50% CO₂ concentration, with a maximum wavelength of 420 nm for pre-treatment, 630 nm for room temperature treatment, and 400 nm for MAS treatment. The maximum wavelength of 400 nm and 420 nm is interpreted as yellow to green, and 630 nm is as blue to green. The bandgap energy of watermelon for pre-treatment, room temperature, and MAS, in sequence, is 1.7 eV, 1.78 eV, and 1.66 eV. The bandgap energy trend shows that watermelon under MAS treatment has lower bandgap energy than the pre-treatment but higher than room

temperature storage. The bandgap energy comparison indicates that MAS treatment with 30% CO₂ for watermelon is not effective to retain the respiration rate.

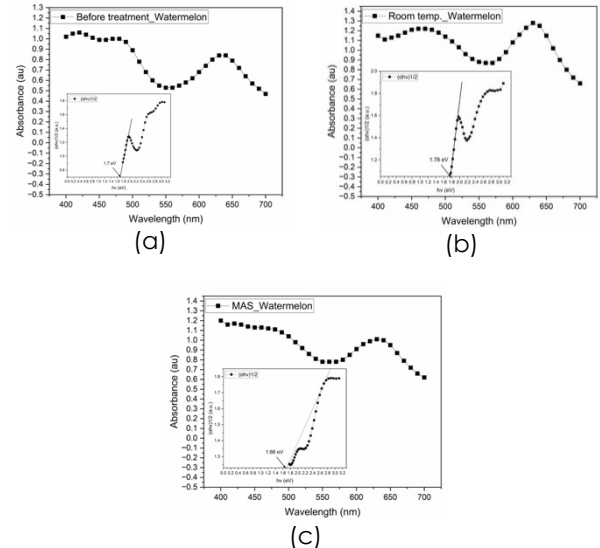


Figure 15 Bandgap energy for Watermelon under MAS treatment at 50% CO₂ in sequence (a) 1.7 eV, (b) 1.78 eV, (c) 1.66 eV

k. The Optimum Parameter for MAS Application

The obtained direct bandgap energy at above section is tabulated and analyses by using statistical software, to seek the optimum MAS parameter in comparison to room temperature storage, set up for each fruit types. The combination is as set in the methodology section at Table 1. Taguchi approach is adopted to analyses the data with the aid of Minitab. The analyses are described by main affects plot for mean and interaction plot for mean. The smallest eV is set as the best for this study target. The smallest eV is set as the best for this study target. The target is set as the best approach due to the correlation between slow respiration rates and low eV for various fruits. So, the optimum parameter combination becomes important to maintain low energy absorption to prolong the fruit freshness.

Figure 16 illustrates the effects of different independent variables (set as treatment, fruit types, and CO₂ concentration) on a dependent variable (set as direct bandgap energy in eV).

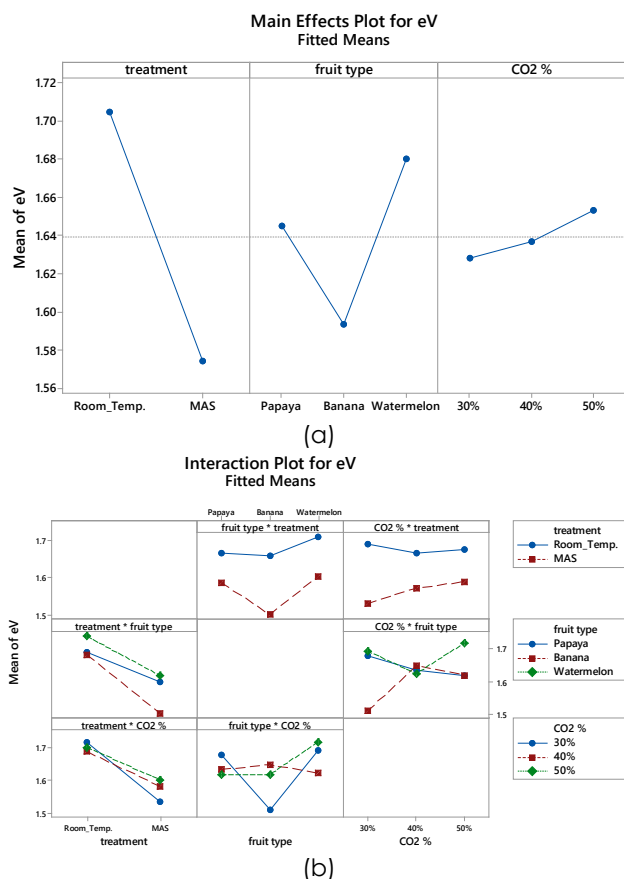


Figure 16 Main effects and Interaction plot for MAS application (a) main effects, (b) interaction plot

Figure 16(a) shows that each sub-group, which consists of several factors that influence the direct bandgap energy, differs in comparison to the overall means. The trends indicate: the overall eV value increases with storage treatment from room temperature to MAS; it also rises with fruit types from papaya to watermelon; and shows a fluctuating trend with increasing CO₂ concentration. This general trend suggests a strong correlation between the eV value and the independent factors in determining direct bandgap energy that influence the respiring rate.

Figure 16(b) illustrates the relationships among sub-groups with direct band gap energy achievement. The experimental results show four relationships: three strong and one weak. Strong relationships indicate the contributions of this research, while weak relationships represent opportunities for further development.

The interaction between the applied CO₂ concentration and the type of fruit shows a strong relationship because the three lines intersect each other. This indicates that MAS treatment can significantly maintain storage time when the CO₂ concentration is set at 40%, where the energy value for respiration is nearly the same across all fruit types. An opposite correlation occurs between the treatment mode and the type of fruit. It shows that papaya and banana have similar characteristics when stored at room temperature, but they have

different sensitivities to CO₂. Another strong correlation occurs between the treatment mode and the level of applied CO₂ concentration. The trend shows the influence of CO₂ levels on the fruit respiration rate in descending order: 30%, 40%, and 50%. The relationship between fruit types and the applied CO₂ concentration is strong, and that indicates MAS gives its best performance to store banana at 30% CO₂ concentration level.

The trends shown in Figure 16(b) reinforce the effectiveness of MAS in prolonging the shelf life of fruits that are highly sensitive to CO₂, with the optimal operation found at a 30% CO₂ concentration level. This setup has also been used in previous studies to extend the shelf life of strawberries and mangoes [32], [33]. However, this study finds that CO₂ concentration levels of 40% and 50% in MAS do not significantly prolong the shelf life of papaya, banana, and watermelon. This study also shows energy band gap which is calculated from UV- VIS measurement as a tool to identify the ripening process occurrence and the CO₂ roles to slow down the respiration rate during storage under MAS treatment.

4.0 CONCLUSION

The development of Modified Atmosphere Storage at high concentration CO₂ to store various fruits in one compartment with single set up parameters in this study, is being investigated its impact to the fruit biological properties and respiration rate behavior. Papaya, banana, and watermelon are chosen as the fruit store under three level CO₂ ranging 30-50%. Fruit mass, skin thickness, hardness, and Brix are measured to represent the biological properties changes under room temperature and Modified Atmosphere Storage treatment. Direct bandgap energy is calculated and plotted from UV Vis measurement.

The experimental result concludes that a 30-50% CO₂ concentration can maintain fruit mass compared to room temperature storage. This CO₂ range increases skin thickness and hardness in papaya, banana, and watermelon, slowing respiration rates. Elevated CO₂ also preserves firmness in papaya and watermelon, indicating reduced respiration. The fluctuating Brix trend suggests it cannot solely determine fruit quality post-storage and has correlation to fruit aroma and flavor. It is recommended to store papaya under modified atmosphere with a 40-50% CO₂ setup. Direct band gap energy from the experimental result concludes that low energy can validate the fruit experiencing slow respiration rates during storage, to delay the ripening process especially for perishable fruit such as papaya.

The development of modified atmosphere storage for fruit must consider biological properties and fruit characteristic as integrated parameter to determine the optimum parameter set up. The methodology set in this study can be a reference to operate modified

atmosphere storage in accordance with the fruit tolerance toward CO₂.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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