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THE IMPACT OF MODIFIED ATMOSPHERE STORAGE TREATMENT ON GLUCOSE LEVELS AND MASS TRANSFER COEFFICIENTS: A STUDY BASED ON FRUIT SKIN THICKNESS

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ABSTRACT
The development of storage by modifying the atmosphere with carbon dioxide can slow down the ripening rate of fruit, but its primary goal was to store one type of fruit. Apart from that, the development of storage by modifying the atmosphere focused on the after-effect to the maturity level and the energy transfer that occur in the storage as a separate investigation. Therefore, this research aims to show the development of Modified Atmosphere Storage (MAP) to store several types of fruit in one storage room, highlight the storage achievements with MAS, and predict the energy transfer inside the storage room. Prototypes, experiments, and finite element approaches are the methods employed in this study. Three different fruits were stored in MAS according to their skin thickness. Statistical tools assist the analyse of relationship between storage methods and glucose levels in fruits. Finite element model predicts the energy transfer inside the MAS storage area. The findings of this study show that fruit stored in MAS has a lower glucose content than fruit stored at room temperature, that fruit with the thickest skin has the lowest Brix value among the other two fruits with thinner skin, and that the uneven distribution of pressure and temperature on the fruit indicates uneven ripening. Our study's findings demonstrate that the MAS prototype can increase the shelf life of different fruit varieties that belong to the same family tree which store in the same compartment,and that the finite element model can forecast the conditions that arise in the storage area.
Keywords : *Modified Atmosphere Storage, Fruit Skin Thickness, Shelf Life, Glucose Level, Maturity Level*

1. Introduction

The quality of post-harvest fruits and vegetables decreases drastically if the respiration process is uncontrollable. Storage conditions, such as temperature, air composition, humidity, and illumination, influence the fruit and vegetable respiration rate. Modified Atmosphere Storage (MAS) is a technology to prolong the shelf life by adding carbon dioxide gas or gas with similar properties so that the conditions in the storage room resemble refrigerating storage. Temperature, oxygen level, and illumination decrease in MAS storage can suppress fruit and vegetable ripening (Pérez López et al., 2020). The ongoing investigation of MAS impact on fruits and vegetables' shelf life and quality has been developed in combination with cutting-edge technology, such as active membrane as gas injector and ozonisation implementation as a sterilization process (Fang & Wakisaka, 2021; Rashvand et al., 2023; Wilson et al., 2019). The MAS performance depends on the composition stability between oxygen and carbon dioxide, and the MAS and cutting-edge technology combination requires high investment. Therefore, it is critical to predict the gas coverage or the respiration rate after injecting the gas into the storage by using a mathematical model at the MAS installation design stage (Badillo & Segura-Ponce, 2020; Guo et al., 2019; Kandasamy, 2017). Researchers conduct an experimental study to verify the prediction result and to explain the cause-effect of MAS implementation on the gas coverage inside the storage or the post-harvest product quality (Jalali et al., 2022; Mangaraj et al., 2021).

Researchers competitively conduct experimental studies to investigate and to prove the MAS impact to one type of fruit or vegetable shelf time. Those lead to an opportunity to develop machine learning process based on the existed experimental data result. But only few researchers investigate MAS effect toward the shelf time of several fruits or vegetables from the same family group with the same treatment inside the same storage compartment, because each fruit or vegetable has different carbon dioxide sensitivity, which will resulted different ripening time (Cefola et al., 2023). Machine learning can be a bridge between complex MAS operation set up variables and the existed experimental data, if the base date set has represented the entire operational and quality outcome parameter. A researcher applies Artificial Neural Networks (ANN) to predict MAS benefit in order to prolong dates shelf time at the conditioning atmosphere with 20% oxygen and 80% nitrogen, thus the application results demonstrate the model able to predict the dates quality which is store inside MAS installation with low Root Mean Square Error (Ahmed et al., 2023). Mathematical model recapitulation for more than a decade to predict the MAS impact on the fruit and vegetable's quality in term of the respiration rate value based on the product weight for its oxygen consumption and carbon dioxide production and the relative humidity value during storage, in line with the measurement result for both values in the experiment. The recapitulation highlights the model can only predict respiration rate and relative humidity value for specific combination of MAS operational parameters, but for others combination with different compartment material that requires further development and that temperature fluctuation inside the storage during MAS implementation un-effective to predict relative humidity on the fruit surface (Mahajan & Lee, 2023).

The same researcher with a diverse team developed a more integrated mathematical model for avocado storage with the aid of numerical solution software, and the model can predict the ethylene-oxygen level inside the storage based on the temperature variance, which resulted in the prediction of ethylene-oxygen concentration is 20% below the experimental result and shows decay is being supress with low ethylene-oxygen concentration (Sonawane et al., 2024). Another method to predict MAS impact visually is numerical simulation application in the storage compartment. A 3D storage compartment model is set as a model to simulate liquid nitrogen circulation inside the piping installation in order to refrigerate the fresh agriculture product, and it employed combination of k-ε turbulent model and first-order implicit transient formulation, afterward the researchers compare the simulation with experimental result, thus the comparison shows turbulence phenomenon occurs during the early stage of injection and the velocity distribution influence the temperature-pressure distribution inside the compartment, also they highlight the simulation can be a reference to optimize the storage design (Guo et al., 2019). The mathematical models with numerical and visual solution development indicate the models are an effective tool to predict the impact of MAS application toward the preserved agriculture product and to optimize the MAS installation design. But those require experimental study verification.

An experiment used a combination of 1-Methylcyclopropone (1-MCP) and MAS to extend the banana shelf life, inside the storage with above room temperature for a week, and the experimental result shows both gases combination able to suppress ethylene production by overseeing the cell wall decay, but 1-MCP is classified as synthetic gas where its application demands other hydrocarbon gas companionship such as carbon dioxide or nitrogen (Li et al., 2023). Another experiment is set to preserve the cherry tomato by injecting carbon dioxide into the packaging, with the result shows the T-test between two group mean data of respiration rate-temperature based on the oxygen and carbon dioxide level measurement is significant, and that statistical correlation forms chemical kinematic model, thus this research can be extended as monitoring and prediction tool for measuring the MAS performance (Zhu et al., 2024). The same approach in an experimental is set to preserve sweet cherry in MAS with an additional air blower, with the purpose to evaluate the mass transfer coefficient and the respiration rate aspect, hence to that the outcome are high mass transfer coefficient trigger the atmosphere changes inside the storage, and mass transfer coefficient changes is resulted no deviation of the gas concentration, but the air blower installation inside a storage requires high airtight process (Keshri et al., 2021). Combination of MAS and odourless gas application to preserve leek is being compared with room temperature storage by measuring its microbial growth, pH, moisture content, colour changes, and smell, with the comparison result highlight the odourless gas additional has no significant effect to the leek shelf time (Hosseininezhad et al., 2023). The development of smart valve to control gas injection into the MAS storage to preserve fruit or vegetable, and that device can improve those shelf time, but the fruit and vegetable must be place in different compartment and preserved at different operational parameter set up (Attilio

Matera, Francesco Genovese, Giuseppe Altieri & Renzo, 2001). An experiment to prove the MAS impact toward orchid shelf life by investigating the correlation between gas composition and temperature inside the storage, and highlight the controlled atmosphere inside the storage compartment have to be maintained at 5% of carbon dioxide and 2% of oxygen (Poonsri, 2020). Plum and apricot preservation are also investigated under the MAS storage for more than one month and show that each agriculture product can be preserved under specific atmospheric conditions, with that an opportunities arise to investigate MAS impact toward more than one agriculture products if it is preserve inside the same MAS compartment at an acceptable range of atmospheric condition based on the existed experiment (Uysal et al., 2023; Varlı Yunusoğlu & Ekinci, 2023). The conducted experiments have a function as a tool to measure MAS impact toward the physical quality of one agriculture product due to the operated gas composition in the storage compartment, but few experiments relate those with the process monitoring and chemical changes.

The previous modelling and experimental studies raise two un-solved problems in optimizing the MAS impact toward the preserved agriculture product, which are a method to predict its impact at the design level and the possibility to preserve several agriculture products in one storage under the same gas compositional set up. Therefore, our research aims to predict the impact by using visual numerical model and set up an experiment to preserve several agriculture products which are classified as one botanical family.

2. The Applied Material And Method

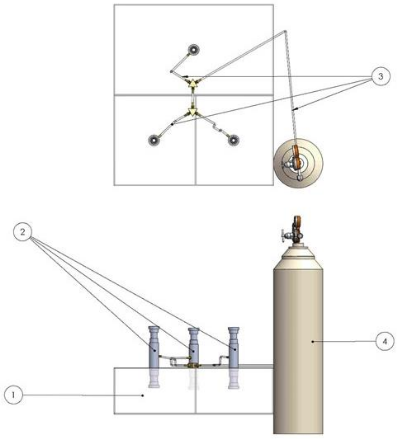
The research activities are consisting of material preparations, experimental set up, and numerical simulation process. The post-harvest fruits with almost identical weight and maturity level are selected to be the object. The maturity level is sorted through colour and weight. Banana, orange, and watermelon are selected based on their skin thickness level (Forney et al., 2022). Thus, the skin thickness level is divided in to three categories, which are thin, medium, and thick. Those fruits are classified under the same botanical family (Pennington & Fisher, 2009).

(a). (b). (c)

Fig. 1. The selected fruits; (a) banana; (b) orange; (c) watermelon

The material preparations are weight measurement, visual colour inspection, and colour measurement. We conduct weight measurement and colour measurement thrice to ensure consistency for each fruit during the purchase in the marketplace or before experiment, also later after the storage period. Figure 1 shows an analogue scale is applied to determine the weight, and before measurement we conduct calibration. The colour measurement process employs Spectrophotometer type DS-200.

Experimental is set up inside the MAS installation with 1000 x 1000 x 400 mm storage, three gas injector with polyvinyl chloride material, and 6 metric cubic capacity of carbon dioxide tank. The glucose level is measured before and after the experiment. The glucose measurement employs handheld Refractometer type ST335A as recommended by similar research (Jaywant et al., 2022). Figure 2 shows the MAS installation layout with three gas injectors placed in series. The installation consists of four main components, which are storage space, gas injector, carbon dioxide tank, and digital thermometer. Storage space has a function as a preservation space. The gas injector has a function to inject carbon dioxide gas with pressure higher than the atmosphere pressure inside the storage space. Carbon dioxide tank has a function to supply the injector. The gas injectors flow in the carbon dioxide into the storage until the carbon dioxide level below 2% (Wei et al., 2021).



No.	Components
1	Storage space
2	Gas Injector
3	Pipe
4	Carbon dioxide tank

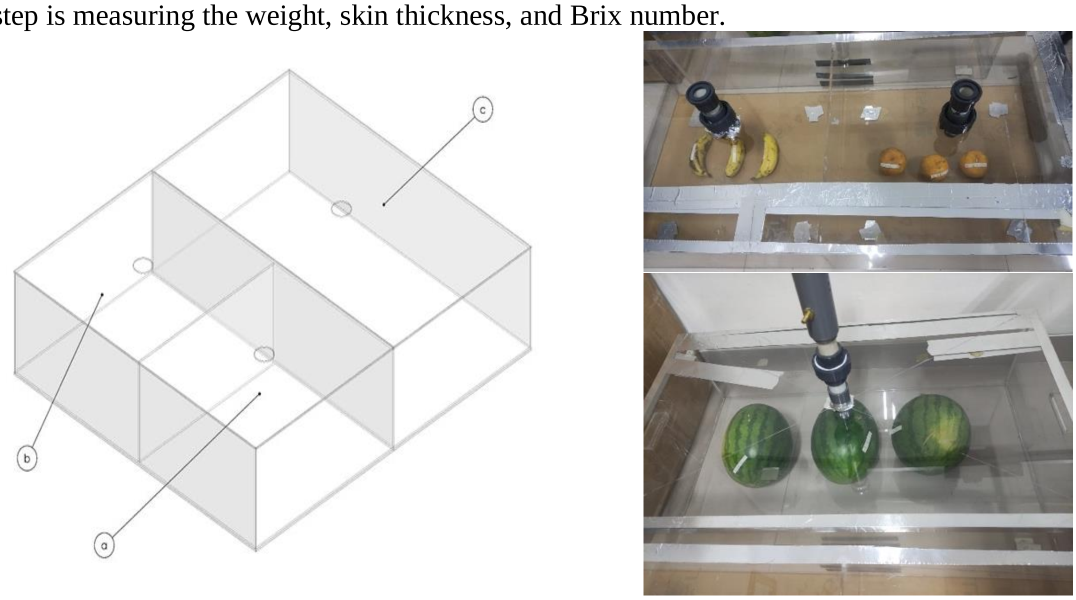
Fig. 2. MAS installation with three compartments

The gas composition level is measured during the experiment by using The Geotech Portable Gas Monitor : Biogas5000. The research adopts DOE full factorial design to build the statistical model with three replications and to obtain the optimized operational parameter (Ntsoane et al., 2020). Table 1 represents the combination of the factors. The factors are skin thickness and treatment. The expected parameters are glucose level. The storage process is conducted for both treatments as mentioned in Table 1, within nine hours.

Table 1 - Design of experimental (DOE)

No.	Factors	Level		
		1	2	3
1	Skin thickness	Thin	medium	thick
2	Treatment	Under room temperature	MAS	-

The procedures to store the fruits in MAS consists of six steps. The first step is to measure each fruit for its weight and skin thickness. The second step is to place the fruits inside the storage space as shown in Figure 3. The third step is to vacuum the storage space by using hand vacuum cleaner. The fourth step is to seal the storage space and make sure no leakage. Then inject the carbon dioxide with the flow around 2 ml/min for the entire nine hours. The last step is measuring the weight, skin thickness, and Brix number.



(a) (b)

Fig. 3. MAS with (a) storage space with three compartments, (b) fruit placement

The expected or respond parameter from the experiment result is analysed with the aid of Minitab. The respond parameter is brix in percentages. The experiment will be set up in accordance with Table 2. The sequence in Table 2, will be the guide to conduct the experiment and measure the respond parameter.

Table 2 - DOE

No.	Skin thickness	Treatment	Brix
1	medium	room temp.	
2	thick	room temp.	
3	thin	MAS	
4	medium	MAS	
5	thick	MAS	
6	thin	room temp.	
7	thin	room temp.	
8	thin	MAS	
9	medium	MAS	
10	thick	room temp.	
11	medium	room temp.	
12	thick	MAS	
13	medium	MAS	
14	thin	MAS	
15	thick	MAS	
16	thin	room temp.	
17	medium	room temp.	
18	thick	room temp.	

The mass transfer coefficient increases along with the increase of the gas flow and becomes the basic principle to determine the absorption level (Tan et al., 2012). The mass transfer coefficient is simulated based on the research to preserve peach and mass transfer modelling from the experimental result (Akkarawatkhoosith et al., 2020; Keshek et al., 2019). ANSYS is used to simulate dan predict the mass transfer coefficient. There are six steps to make the simulation, which are making FE model, input the required parameter and material, set up boundary, meshing, processing, and post processing. The FE model employs 2D CAD model to simplify the gas flow from gas injector into the storage compartment. The compartment material properties are polyvinyl chloride, while the carbon dioxide properties are set based on the food standard. The uniform orthogonal meshing with the skewness below 0.9 is applied to increase the meshing quality. The processing uses a step-by-step method. The applied post processing method are visual and profile or trend outcome.

3. Result And Discussion

a. Result

Table 3 summarizes the experimental result based on the combination in Table 2. Analysis of variance and regression model is presented to describe the relationship. Table 3 shows the brix level for room temperature treatment is between 6.10-23.50%, and for MAS treatment is in between 4.10-23%. MAS treatment resulted lower brix level than room treatment.

Table 1 - Experimental results

No.	Skin thickness	Treatment	Brix
1	medium	room temp.	23.10%
2	thick	room temp.	7.20%
3	thin	MAS	10.60%
4	medium	MAS	22.70%
5	thick	MAS	4.20%
6	thin	room temp.	11.50%
7	thin	room temp.	11.50%
8	thin	MAS	10.40%
9	medium	MAS	22.50%
10	thick	room temp.	7.00%
11	medium	room temp.	23.00%
12	thick	MAS	4.40%
13	medium	MAS	21.20%
14	thin	MAS	11.80%
15	thick	MAS	4.80%

16	thin	room temp.	12.00%
17	medium	room temp.	22.00%
18	thick	room temp.	6.20%

Analysis of variance and regression model is presented to describe the relationship in Figure 4. Figure 4 shows the P value is in between 0.000-0.043 and that less than the significant level, which is 0.05. The P value indicates that treatment and skin thickness have a high probability influence the brix level. The F value for skin thickness, treatment, and skin thickness-treatment consecutively are 1271.84; 19.19; 4.15; and 4.15. The high F value for skin thickness indicates the data variated too wide that it has low correlation with the brix level. The F value for treatment and combination skin thickness-treatment near to one, and that show high correlation with the brix level. The R Square for the regression model is 99.54% and that indicates both skin thickness and treatment fully influence the brix level. The linier regression model shows fruits with thick skin thickness-treatment type have the lowest brix level, and the highest influencer to the brix level among the other skin thickness level. The trend indicates fruits with thick skin thickness are having slow aging process.

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Analysis of Variance
Source                      DF    Adj SS    Adj MS  F-Value  P-Value
Model                        5  0.088420  0.017684   514.23    0.000
  Linear                     3  0.088134  0.029378   854.29    0.000
    Skin thickness           2  0.087474  0.043737  1271.84    0.000
    Treatment                1  0.000660  0.000660    19.19    0.001
  2-Way Interactions         2  0.000285  0.000143     4.15    0.043
    Skin thickness*Treatment 2  0.000285  0.000143     4.15    0.043
Error                       12  0.000413  0.000034
Total                       17  0.088833

Model Summary

        S    R-sq  R-sq(adj)  R-sq(pred)
0.0058642  99.54%     99.34%      98.95%


Regression Equation

Brix = 0.13117 - 0.01817 Skin thickness_thin + 0.09300 Skin thickness_medium
       - 0.07483 Skin thickness_thick + 0.00606 Treatment_room temp. -
 0.00606 Treatment_MAS - 0.00239 Skin thickness*Treatment_thin room temp.
       + 0.00239 Skin thickness*Treatment_thin MAS -
 0.00322 Skin thickness*Treatment_medium room temp.
+ 0.00322 Skin thickness*Treatment_medium MAS
+ 0.00561 Skin thickness*Treatment_thick room temp.
       - 0.00561 Skin thickness*Treatment_thick MAS
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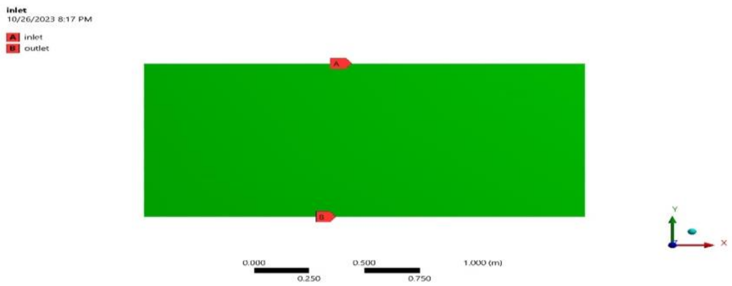
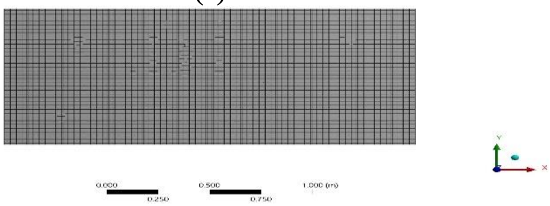
Fig. 4. Variant and regression analysis from statistical software

The Finite Element (FE) model is set to oversee the gas distribution and MAS impact to the temperature, pressure, and gas fraction inside the compartment. Figure 5 shows the FE model and its meshing set up. The model is set as a rectangular plane with the upper part as the inlet and the lower part as the outlet of the gas. Meshing result is 40,301 nodes and 20,000 elements.



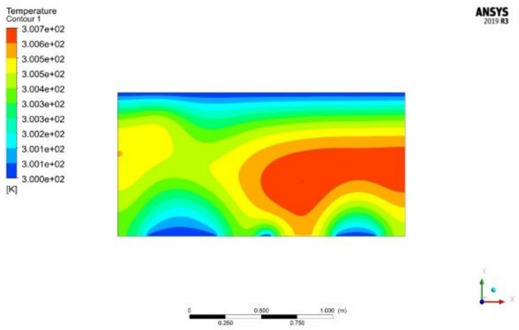
(a)



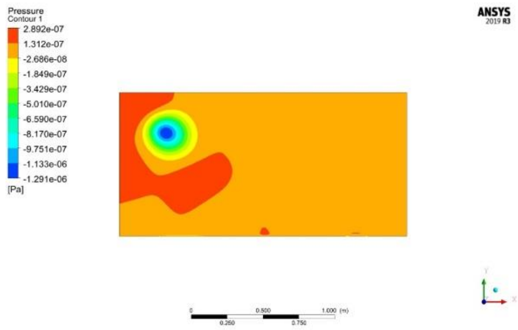
(b)

Fig. 5. (a) Boundary and (b) Meshing set up

Figure 6 show the graphical plotting from the simulation. Figure 6(a) indicates the temperature higher in the middle part of the storage space, that leads to the mixture between carbon dioxide and air is concentrated in the middle part. Figure 6(b) indicates the pressure increase when the most part of the storage, that may lead to un-uniform distribution of carbon dioxide coverage inside the storage. Figures 6(c) and 6(d) indicate the domination of carbon dioxide in the storage, which leads to oxygen at its minimum level during the carbon dioxide injection.



(a)



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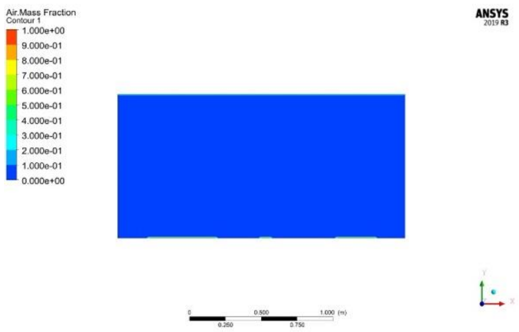
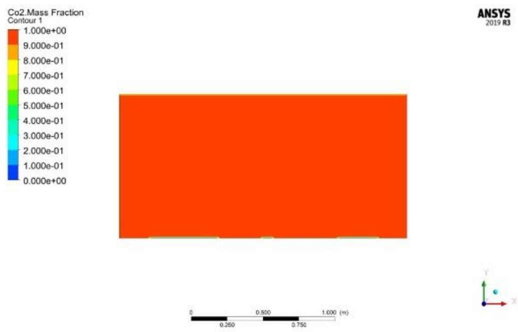


(c)



(d)

Fig. 6. FE result

The FE simulation result can be a guideline to be cautious about temperature increment and un-uniform pressure, which will cause instant ripening or early maturity at the early injection of carbon dioxide into the storage.

3.2. Discussion

The preparation procedures to measure the weight before and after MAS treatment are essential because fruits reservation after almost one month storage is resulted weight reduction

(Dorostkar et al., 2022). The weight reduction can be slow down if the carbon dioxide level inside the storage above 85%, and that shows monitoring gas concentration is mandatory during MAS treatment period (Dehghan-shoar et al., 2008). The rising of carbon dioxide level will cause temperature deceleration inside the storage compartment and the firmness changes on to the fruits wall tissue (Xing et al., 2020). The MAS impact toward the storage fruit or vegetable is presented by the glucose level inside its tissue, and mostly high glucose level indicates tissue decay phenomenon (Wang et al., 2020). Fruit tissue softening starts to occur for the perishable types such as blueberry after 24 hours storage, and so is the skin colour, but the glucose level starts to transform after 48 hours storage (Smrke et al., 2024). The preparation procedures and result development set a preparation standard to prove MAS installation benefit, so the required preparation are weight and gas composition measurement and the storage period, against the glucose level measurement. The carbon dioxide level, preparation procedure for weight and gas composition measurement from the previous research are in line with our preparation procedures in applying MAS installation.

MAS treatment in comparison to non-MAS decrease the glucose level during the bell pepper storage period, also at the same time able to cause tissue softening and weight loss, but the fruit respiration rate and acid formation are not affected (Lwin et al., 2022). Storage method with a combination of gas injector and basil oil spray treatment to preserve banana within 14 days is set up to oversee the MAS impact toward oxygen-carbon dioxide composition, crown rot assessment, and Total Soluble Solid (TSS) in °Brix. Hence the comparison results show the oxygen level is 3.1-3.7%, the crown rot occurred at the non-MAS treatment, and the TSS has lower °Brix than the non-MAS treatment. The results indicates the increase of aroma, respiration rate, and tissue softening, which resulted the increase of glucose level (Siriwardana et al., 2017). A collection of critical review is conducted to see the influence of modified atmosphere toward the fungi growth at fruits and vegetables, and the review shows MAS able to supress the fungi growth and prolong those shelf time (You et al., 2023). Allium cepa L. or known as calçots is preserved for 30 and 60 days inside MAS with the atmosphere set up are1.0 kPa for oxygen and 2 kPa for carbon dioxide, with the result shows the Soluble solids content (SSC), titratable acidity (TA), and pH measurement after 60 days preservation have lower value than the 30 days ones, further more MAS has a possibility to be developed for long term storage and its effect toward microbiological quality (Zudaire et al., 2019). Combination of Argon and carbon dioxide is being injected into MAS storage to preserve broccoli for 9 days, and the atmosphere storage with 90% of Argon content results in better freshness, thus The glucosinolates level at its lowest point (Loredana et al., 2021). The various experimental studies highlight the suppression of oxygen content by injecting carbon dioxide or nitrogen or Argon into the storage, with the purpose to control the parameter which represent freshness quality. Carbon dioxide is the most applied and dominant gas to be applied to supress the oxygen content. Aside that the experimental studies still in the investigation level for stationery storage. Our experiment result in the inverse correlation between oxygen level and Brix value, that present the same achievement as the previous experimental studies. But our experiment has been successful to preserve several fruits under the same operational parameter and inside one compartment.

Respiration rate for carbon dioxide and oxygen during several fruits preservation inside MAS is proposed by using 3D coupled mass and momentum transfer computational model based on Maxwell-Stefan and Navier-Stokes equations, thus the model able to predict the gas exchange and distribution around the gas injector inlet (González-Buesa & Salvador, 2022). 3D model for pear is developed to investigate the gas distribution at the fruit body, and the result shows the carbon dioxide is concentrate at the centre of the fruit whilst the oxygen at the skin, thus the result indicates browning will be started on the skin first and intime spread to centre (Nugraha et al., 2022). 2D model is developed to investigate the effect of atmospheric pressure changes toward the respiration rate of the product inside the storage compartment, with the result show a map of pressure distribution, and it can be used as a tool to select the operational parameter (Vega-Diez et al., 2024). The achievement of those numerical model is the capability to select the operational parameter combination, but the model size is still limited near the gas injector inlet. Our 2D model is compact and can be adjusted to mimicking the actual MAS installation, also it can predict the atmospheric pressure changes as well as temperature and gas fraction.

4. Conclusion

This research stimulates the application of MAS to preserve several fruits or vegetables with the same botanical family, under the same operational parameter and inside the same storage compartment. So, the application benefit can be swift from stationary to transportational storage. Fruit with thick skin has longer shelf time than the thin ones. The increment of Brix values indicates the occurrence of maturity. Therefore, further investigation is required, to built correlation between the operational parameter and nutrition quality content inside the fruits.

The 2D mass transfer model manages to map out the gas distribution and strengthen the correlation between gas composition inside the storage compartment with atmospheric pressure and temperature changes and gas fraction. The gas distribution is centralized in the middle of the storage compartment. The 2D model can be modified up until the actual size, to predict the gas composition and point out the critical part of MAS installation early at the design level.

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