TRANSACTIONS ON SCIENCE AND TECHNOLOGY

Effects of 1-Methylcyclopropene and Hexanal vapor treatments on ^{1}H NMR-Based metabolomic profiles of Durian (*Durio zibethinus* L.)

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ABSTRACT Durian (*Durio zibethinus* L.) is one of the most important seasonal crops in Malaysia which has high economic value due to high demand. The shelf-life of durian fruit is very short about 2-3 days after naturally dropped from the tree stored at ambient temperature. This affects the profitability of durian sellers. Cold storage could prolong the shelf-life of fruits. However, it requires high investment and also can reduce the quality of the fruits by altering the original taste as well as inducing cold or chilling injury to the fruit. Therefore, it is important to develop a new postharvest technique with lower cost and easier to apply which can prolong the shelf-life of durian fruit at ambient storage. 1-methylcyclopropene (1-MCP) and hexanal vapors treatments were reported to be able to improve the shelf-life in many tropical fruits. The effectiveness of these treatments on D24 durian was unclear. The effect of these treatments on metabolic profile of the edible flesh is unknown. The objectives of this study are to investigate the effectiveness of 1-MCP and hexanal treatments on D24 durian at ambient temperature and to determine the metabolic changes of the flesh due to the treatments. In this study, the freshly dropped fruit was treated with 0.048% 1-MCP and 100 ppm hexanal vapors for 16 hours and stored at ambient condition. The physical appearance was observed from day 0 to 5. The metabolites extracted from the flesh were subjected to nuclear magnetic resonance (NMR) analysis. The results show that the treatments can prolong the shelf life of the fruit up to 5 days by delaying the husk dehiscence. The NMR analysis did not show significant metabolic changes in the flesh. In conclusion, the treatments could inhibit the metabolic changes in the husk but not significantly affect the flesh metabolic activity.

KEYWORDS: Durian; 1-methylcyclopropene; Hexanal vapors; Postharvest storage; NMR metabolomics
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INTRODUCTION

Durian (*Durio zibethinus* L.) is an edible seasonal crop with high economic value in Malaysia and southeast Asian region. D24 is one of the most popular cultivars in Malaysia due to its good quality and standard for international market (Osman *et al*., 2022). In Malaysia, the durian fruit was harvested after natural detachment from the tree. The shelf-life of the fruit at the harvesting stage is limited about 2-3 days at ambient temperature (Tan *et al*., 2019). This causes postharvest losses and reduces the profitability of durian sellers. The cold or chill storage is widely used technique to prolong the shelf-life of many fruits including durian. However, this technique is expensive and could induce cold or chilling injury to tropical fruits such as durian. The storage of durian at 7°C and conventional freezing method (-18°C) induce injury that reduces the quality of the fruit (Razali *et al*., 2022). In addition, low temperature can alter the original taste and aroma of the fruit. The consumers often preferred fresh durian. Hence, it is important to find cheaper and easier method to prolong the shelf-life of the fruit at ambient temperature.

1-methylcyclopropene (1-MCP) widely known as ethylene inhibitor by binding to the ethylene receptors resulted in delayed ripening as shown in many fruits such as banana (Chang & Brecht, 2023)

and apple (Lv *et al*., 2023). However, the effectiveness of 1-MCP treatment varies among species, cultivars, concentration and harvesting stages. The application of 1-MCP on Monthong durian prolonged the shelf-life for up to 30 days stored at 15°C (Amornputti *et al*., 2014). However, the effectiveness of 1-MCP treatment on other cultivar such as D24 at different temperature is unknown. Hexanal treatment is reported to be able to enhance the shelf life in tropical fruits such as banana (Yumbya *et al*., 2018) and mango (Silué *et al*., 2022). Hexanal delayed membrane degradation by inhibiting the activity of phospholipase D (PLD) during ripening resulted in prolonged shelf life (El Kayal *et al*., 2017). The effect of hexanal treatment and the combination with 1-MCP on D24 durian at ambient temperature is not reported to date. The metabolic response in edible flesh due to the treatments is unknown.

Nuclear magnetic resonance (NMR) is powerful spectroscopic technique used to study metabolic changes in fruits as reported in mango (Gil *et al*., 2000) and strawberry (*Fragaria* × *ananassa*) (An *et al* 2018). However, the NMR metabolomics study on durian flesh is still very limited. Hence, the objectives of this study are to determine the effectiveness of 1-MCP, hexanal vapour and their combination (mix) treatments on the shelf-life of D24 durian fruit at ambient temperature as well as to investigate the metabolic changes of the edible flesh of the fruit in response to the treatments by using NMR spectroscopy.

METHODOLOGY

Sample Collection

Freshly dropped D24 durian fruits were collected from wholesaler sourcing from Raub, Pahang. The fruit was transported to the laboratory at Universiti Putra Malaysia, Serdang, Selangor. The fruit was selected based on the size, weight, colour and free from any defects for the treatments.

1-Methylcyclopropene and Hexanal Vapor Treatments

The fruits were divided into two groups, where one group was used for physical evaluation and the other for color, weight loss and NMR analysis. The study was conducted in three independent experimental runs. For metabolomic analysis, six fruits from the first run were selected and subjected to NMR spectroscopy. For physical appearance evaluation, six fruits were used per run (n = 18). For color (flesh and husk) and weight loss measurements, three fruits were used per run, and the mean value of each run was used for statistical analysis (n = 3 independent runs). For 1-MCP treatment, the fruit was incubated with two sachets (0.028%) 1-MCP (SmartFresh™, USA) in 71 L tightly sealed polystyrene box. For hexanal vapors treatment, the fruit was incubated with 100 ppm hexanal vapors. The incubation period was 16 hours at ambient condition (30 °C and 60–70% relative humidity). Then, the fruit was removed from the box and placed on the bench. The physical appearance such as the husk dehiscence was observed from day 0 to day 5.

Weight loss

The weight loss of the fruit was measured by using a weighing balance from day 0 to day 5 of storage. Three fruits were used from each treatment and control in each experimental run. The experiment was done in triplicate (n=3). The percentage of weight loss is often calculated with this formula:

$$\text{Weight Loss (\%)} = [(\text{Initial Weight} - \text{Final Weight}) / \text{Initial Weight}] \times 100$$

Color Changes

The color of the durian husk and flesh was determined using a portable colorimeter (Konica Minolta Chroma Meter CR-400, Konica Minolta Inc., Osaka, Japan). Color measurements were recorded in the CIELAB color space, expressed as L* (lightness), a* (redness/greenness), and b* (yellowness/blueness). Prior to measurements, the colorimeter was calibrated using a standard white calibration tile supplied by the manufacturer (Y = 93.7, x = 0.3156, y = 0.3323), following the manufacturer's instructions. Color measurements were carried out on day 0, 1, 2, 3, 4, and 5 of storage at ambient temperature. For flesh color determination, the durian was carefully opened, and the edible aril was separated from the seed. Three fruits were used from each treatment and control in each experimental run. The experiment was done in triplicate (n=3).

^{1}H Nuclear Magnetic Resonance (NMR) Spectroscopy

The NMR spectroscopy analysis of the flesh extract from day 1 and 3 was done based on a method reported by Pei *et al.* (2022) with modifications. The flesh extract (25 mg) was mixed with 375 µL methanol-d4 and vortexed until completely dissolved. Then, KH_2PO_4 buffer (375 µL) containing 0.1% (w/v) trimethylsilyl propionic acid-d_4 sodium salt (TSP) prepared in deuterium oxide (D_2O) was added to the mixture. The mixture was sonicated for 15 minutes at room temperature followed by centrifugation at 13000 rpm (~12,000 × g) (Eppendorf, Germany) for 10 minutes. The supernatant (600 µL) was transferred to NMR tube. The ^{1}H-NMR spectra were acquired using a Varian 500 MHz NMR spectrometer. All spectra were recorded at 298 K (25 °C). A standard one-dimensional proton NMR pulse sequence with water suppression was used. Spectra were acquired with 64 scans. Chemical shifts were referred to the TSP signal at δ 0.00 ppm. All NMR spectra were processed using Chenomx v. 5.1 (Alberta, Canada). The PCA and PLS were performed by using SIMCA-P (Umetrics, Sweden).

RESULT AND DISCUSSION

The result shows that 1-MCP and hexanal vapour treatments were able to extend the shelf-life of durian at ambient temperature by delaying husk dehiscence for up to 5 days of storage as shown in Figure 1.

Figure 1. The dehiscence of the husk from day 0 to 5 of storage.

The control group shows normal progression of durian fruit senescence which involves fruit softening leading to husk dehiscence or splitting on started on day 2 of storage. The degradation of lipid membrane plays important role during fruit softening. Phospholipase D (PLD) was widely reported as a key enzyme in lipid membrane degradation (Amornputti *et al*., 2016). PLD hydrolysing membrane phospholipids, phosphatidylcholine (PC) to form choline and phosphatidic acid (PA). This process can be regulated by ethylene signaling during senescence and ripening (Amornputti *et al*., 2016). The presence of 1-MCP, the ethylene signaling was inhibited, therefore the husk softening was delayed. The application of 1-MCP was reported as effective method to prolong the shelf-life which improves the firmness in many fruits such as 'Cripps Pink' apple and 'Cavendish' bananas (Talamini *et al*., 2022; Li *et al*., 2023). Similarly, hexanal inhibits the activity of PLD by interfering with the calcium signaling by affecting the calcium channel on the lipid membrane (El Kayal *et al*., 2017). Hexanal treatment helps to improve the firmness as reported in apple (Sriskantharajah *et al*., 2021) and banana (Yumbya *et al*., 2021). In addition, the mix treatment (1-MCP + hexanal vapors), also delayed the husk dehiscence without synergistic effects.

The percentage of weight loss of the whole fruit was determined from day 0 to day 5 of storage as shown in Figure 2.

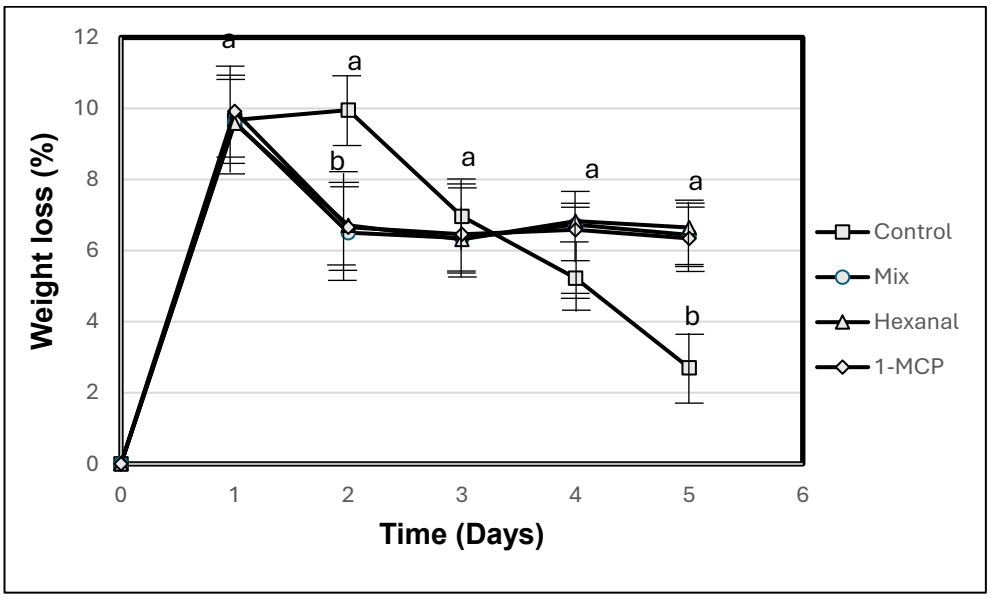

Figure 2. The percentage of weight loss of the whole fruit from day 0 to 5 of storage. Values are expressed as mean ± SD (n=3). Each experimental run consisted of three fruits per treatment and control, and the experiment was repeated three times. Different letters indicate significant differences at the same storage day ($p < 0.05$).

The control, 1-MCP, hexanal vapour and mix treatments did not show any significant differences in percentage of weight loss ($p > 0.05$) on day 1. The physiological changes associated with senescence are still minimal in day 1. The weight loss during the initial day of storage mainly due to transpirations which influenced by the temperature and relative humidity of the storage condition. This also suggested that all fruits were at similar physiological maturity prior to treatment. In addition, the structural changes in the husk during early storage was still limited. The cuticular or cellular breakdown and tissue softening leading to the husk dehiscence which can accelerate water loss was not yet observed by day 1. Hence, 1-MCP and hexanal vapour treatments have insufficient time to cause differences in mass loss. In prickly pear (*Opuntia ficus-indica*), the weight loss was significantly reduced by maintaining the humidity during storage (Trindade *et al*., 2023). Higher temperature and lower humidity can increase transpiration causes moisture loss from the fruit

leading to weight loss. Therefore, fruit weight loss was mainly due to transpiration during the initial days of storage. In control fruit, the moisture loss due to transpiration continued to occur as a normal ripening and senescence processes by day 2 which was significantly higher than all treated fruits. This indicated that 1-MCP, hexanal vapour and mix treatments were able to reduce physiological water loss. The higher respiration rate and membrane degradation in control fruit may contribute to higher weight loss.

In 1-MCP treated fruit, the inhibition of ethylene signalling causes lower respiration rate and ethylene-dependent membrane degradation leads to lower percentage of weight loss. The application of 1-MCP caused a significant weight loss in Rose apple fruits (*Syzygiumjambos Alston*) cv. Tabtim Chan (Plainsirichai *et al*., 2010). This indicates the effect of 1-MCP treatment on the weight loss. In hexanal treated fruits, the membrane degradation was delayed through the inhibition of phospholipase activity such as PLD which reduced water loss from fruit tissues. In hexanal treated mango (*Mangifera indica*), a significant reduction of weight loss was reported compared to control (Anusuya *et al*., 2016). This demonstrated the effect of hexanal treatment on the weight loss of fruits. However, the mix treatment did not differ significantly from the single treatments in weight loss.

In control fruit, the declining of percentage of weight loss from day 3 to day 5 mainly contributed by the reduction of transpiration and respiration rate as the fruit already proceeds to senescence stage. The tissue softening and husk opening of control fruit led to the dehydration of the fruit which reduces further water loss. Meanwhile, the weight loss of all treated fruits was constant from day 3 to day 5 indicates the delayed ripening and senescence processes by the treatments. The lack of significant differences between the control and treated fruits on days 3 and 4 indicates that, at certain points during storage, the rate of weight loss can be similar even when fruits are at different physiological stages. The percentage of weight loss observed in the control fruits by day 5 was significantly lower than all treatments can be attributed to the advanced stage of senescence. This can be linked to the higher percentage of husk dehiscence observed in the control fruits on day 5. The structural changes associated with senescence causes dehydration of fruit tissue. Therefore, weight loss due to water or moisture loss was lower.

Changes in husk and flesh colour were monitored from day 0 to day 5 of storage. Changes in husk and flesh colour are presented in Table 1 and Table 2 respectively. The husk colour in control fruit, the L* value (lightness) increased significantly from day 0 to day 5 of storage, rising from 37.45 ± 1.34 to 46.50 ± 1.19 ($p < 0.05$). For the 1-MCP, hexanal vapors and mix treatments, the L* value increased significantly from day 0 to day 5 of storage ($p < 0.05$), rising from 37.53 ± 1.43 to 42.76 ± 1.06, from 37.61 ± 1.89 to 42.53 ± 1.25 and from 37.60 ± 0.28 to 42.54 ± 1.12 respectively. In addition, the L* value of the control fruit was significantly higher than that of all treated fruits on day 5 ($p < 0.05$), whereas no significant differences were observed among the treatments (1-MCP, hexanal vapors and mix treatments). The a* value of the control fruit on day 5 was significantly higher than that of all treated fruits ($p < 0.05$). In addition, the b* value of control fruit was significantly higher than that of all treated fruits ($p < 0.05$) on day 5 of storage.

Table 1. The color changes of the husk from day 0 to 5 of storage. Results are expressed as the mean ± standard deviation (SD). Each experimental run consisted of three fruits for the control and each treatment, and the experiment was repeated three times (n = 3). Different letters indicate statistically significant differences within the same column at $p < 0.05$.

	Time (Days)	L	a	b
		Mean + SD	Mean + SD	Mean + SD
Control	0	37.45 ± 1.34 c	-2.11 ± 1.34 c	22.12 ± 1.33 c
	1	37.59 ± 1.22 c	-2.32 ± 1.22 c	21.32 ± 1.76 c
	2	42.61 ± 1.21 b	1.22 ± 1.45 b	24.43 ± 1.21 b
	3	42.73 ± 1.18 b	1.32 ± 1.32 b	24.76 ± 1.17 b
	4	46.58 ± 1.19 a	4.76 ± 1.33 a	31.23 ± 1.66 a
	5	46.50 ± 1.19 a	4.79 ± 1.26 a	31.31 ± 1.22 a
1-MCP	0	37.53 ± 1.43 c	-2.32 ± 1.82 c	22.28 ± 1.43 c
	1	37.39 ± 1.52 c	-2.44 ± 1.67 c	22.87 ± 1.28 c
	2	38.10 ± 1.23 c	-2.31 ± 1.32 c	22.98 ± 1.32 c
	3	42.77 ± 1.09 b	1.34 ± 1.88 b	24.87 ± 1.17 b
	4	42.68 ± 1.22 b	1.42 ± 1.33 b	24.97 ± 1.06 b
	5	42.76 ± 1.06 b	1.49 ± 1.09 b	25.01 ± 1.19 b
Hexanal	0	37.61 ± 1.89 c	-2.65 ± 1.33 c	22.16 ± 1.87 c
	1	37.87 ± 1.74 c	-2.71 ± 1.77 c	22.56 ± 1.22 c
	2	37.84 ± 1.76 c	-2.27 ± 1.88 c	22.78 ± 1.43 c
	3	38.47 ± 0.65 c	-2.18 ± 1.87 c	22.98 ± 1.76 c
	4	42.59 ± 1.22 b	1.35 ± 1.55 b	24.97 ± 1.25 b
	5	42.53 ± 1.25 b	1.44 ± 1.76 b	24.78 ± 1.22 b
Mix	0	37.60 ± 0.28 c	-2.38 ± 1.12 c	22.63 ± 1.43 c
	1	37.66 ± 1.20 c	-2.54 ± 1.32 c	22.45 ± 1.22 c
	2	37.63 ± 1.20 c	-2.16 ± 1.38 c	22.77 ± 1.76 c
	3	38.20 ± 1.21 c	-2.15 ± 1.22 c	22.12 ± 1.86 c
	4	39.50 ± 1.25 c	-2.10 ± 1.18 c	22.76 ± 1.28 c
	5	42.54 ± 1.12 b	1.76 ± 1.88 b	24.71 ± 1.77 b

Table 2. The color changes of the flesh from day 0 to 5 of storage. Results are expressed as the mean ± standard deviation (SD). Each experimental run consisted of three fruits for the control and each treatment, and the experiment was repeated three times (n = 3). Different letters indicate statistically significant differences within the same column at $p < 0.05$.

	Time (Days)	L	a	b
		Mean + SD	Mean + SD	Mean + SD
Control	0	77.95 ± 0.95 a	-8.45 ± 0.37 a	40.63 ± 0.58 a
	1	78.08 ± 0.26 a	-8.40 ± 0.14 a	40.96 ± 0.58 a
	2	77.59 ± 0.73 a	-8.25 ± 0.20 a	40.87 ± 0.79 a
	3	78.02 ± 1.06 a	-8.16 ± 0.24 a	40.99 ± 0.41 a
	4	77.54 ± 0.80 a	-8.47 ± 0.40 a	41.17 ± 0.50 a
	5	77.55 ± 0.92 a	-8.18 ± 0.23 a	41.47 ± 0.45 a
1-MCP	0	78.54 ± 0.50 a	-8.46 ± 0.21 a	41.21 ± 0.65 a
	1	77.69 ± 0.70 a	-8.22 ± 0.56 a	40.99 ± 0.25 a
	2	78.28 ± 0.30 a	-8.15 ± 0.19 a	41.44 ± 0.42 a
	3	77.95 ± 0.77 a	-8.28 ± 0.40 a	41.18 ± 0.30 a
	4	77.89 ± 0.73 a	-8.27 ± 0.30 a	40.89 ± 0.55 a
	5	77.59 ± 0.60 a	-8.23 ± 0.27 a	41.04 ± 0.48 a
Hexanal	0	77.99 ± 0.79 a	-8.08 ± 0.53 a	41.32 ± 0.48 a
	1	77.79 ± 0.66 a	-8.31 ± 0.51 a	41.28 ± 0.85 a
	2	77.79 ± 0.64 a	-8.07 ± 0.47 a	41.35 ± 0.47 a
	3	78.09 ± 0.86 a	-8.28 ± 0.64 a	41.09 ± 0.33 a
	4	77.66 ± 0.91 a	-8.11 ± 0.47 a	41.15 ± 0.19 a
	5	77.87 ± 1.04 a	-8.10 ± 1.47 a	41.67 ± 0.24 a
Mix	0	77.42 ± 1.09 a	-8.26 ± 0.60 a	41.37 ± 0.41 a
	1	77.99 ± 0.87 a	-8.12 ± 0.40 a	41.18 ± 0.41 a
	2	77.37 ± 0.84 a	-8.36 ± 0.50 a	41.44 ± 0.42 a
	3	77.99 ± 1.19 a	-8.31 ± 0.52 a	41.39 ± 0.30 a
	4	77.32 ± 0.94 a	-8.45 ± 0.56 a	41.36 ± 0.27 a
	5	78.18 ± 0.60 a	-8.44 ± 0.45 a	41.33 ± 0.51 a

The L* value reflects an overall lightening of the husk surface. In control fruit, a rapid degradation of chlorophyll pigments in the husk tissue causes significant reduction of the L* value compared to all treated fruits. In lemon (*Citrus limon* L. Osbeck), the L* value increased during de-greening process of the fruit due to chlorophyll degradation (Conesa *et al.*, 2019). The ethylene signaling induced the expression of chlorophyll-degrading enzymes. For example, the chlorophyll catabolic genes (CCGs) such as NYE1, NYC1 and PAO were induced by ETHYLENE INSENSITIVE3 (EIN3) as demonstrated in *Arabidopsis thaliana* leading to the de-greening and senescence of the leaf (Qiu *et al.*, 2015). Therefore, the husk loses its dark green color due to chlorophyll breakdown resulted in an increase of lightness (L*) value. 1-MCP and hexanal reduced chlorophyll breakdown through the inhibition of ethylene signaling and preserving membrane integrity. Hence, the L*, a* and b* values were lower than control.

For the flesh color, the L, a* and b* values of the control, 1-MCP, hexanal vapor-treated and mix treatment fruits remained statistically unchanged from day 0 to day 5 of storage. During this period, L*, a* and b* values ranged from 77.32 ± 0.94 to 78.54 ± 0.50, −8.07 ± 0.47 to −8.47 ± 0.40 and 40.63 ± 0.58 to 41.67 ± 0.24 respectively. The lack of significant changes in the L*, a* and b* values of the durian flesh from day 0 to day 5 suggested that the husk and flesh may have different ripening regulation

and tissue physiology. These findings indicate that, at this harvesting stage (naturally abscised fruit) the flesh and husk undergo distinct biochemical trajectories. The husk exhibits rapid senescence-associated metabolic changes whereas the flesh shows minimal further metabolic alteration.

The different response between the husk and flesh towards the treatments suggests a physiological dichotomy between these two tissues. The husk serves as the protective outer layer which is directly exposed to the treatments (1-MCP and hexanal). In contrast, the flesh may be less influenced by external vapors treatments. At the time of treatment application, the flesh is suggested to have reached full maturity. Therefore, metabolite changes may not be significant. The ripening-associated genes are transcriptionally stabilized. In addition, ethylene-responsive transcription factors such as ERF, NAC and MYB families are suggested to be lower in the flesh compared to husk. Therefore, the presence of ethylene inhibitors (1-MCP and hexanal) may not affect the biochemical changes of the flesh.

The representative full NMR spectrum of the flesh extract is presented in Figure 3. The list of identified compounds is presented in Table 3, and the relative quantification of the identified metabolites is shown in Table 4.

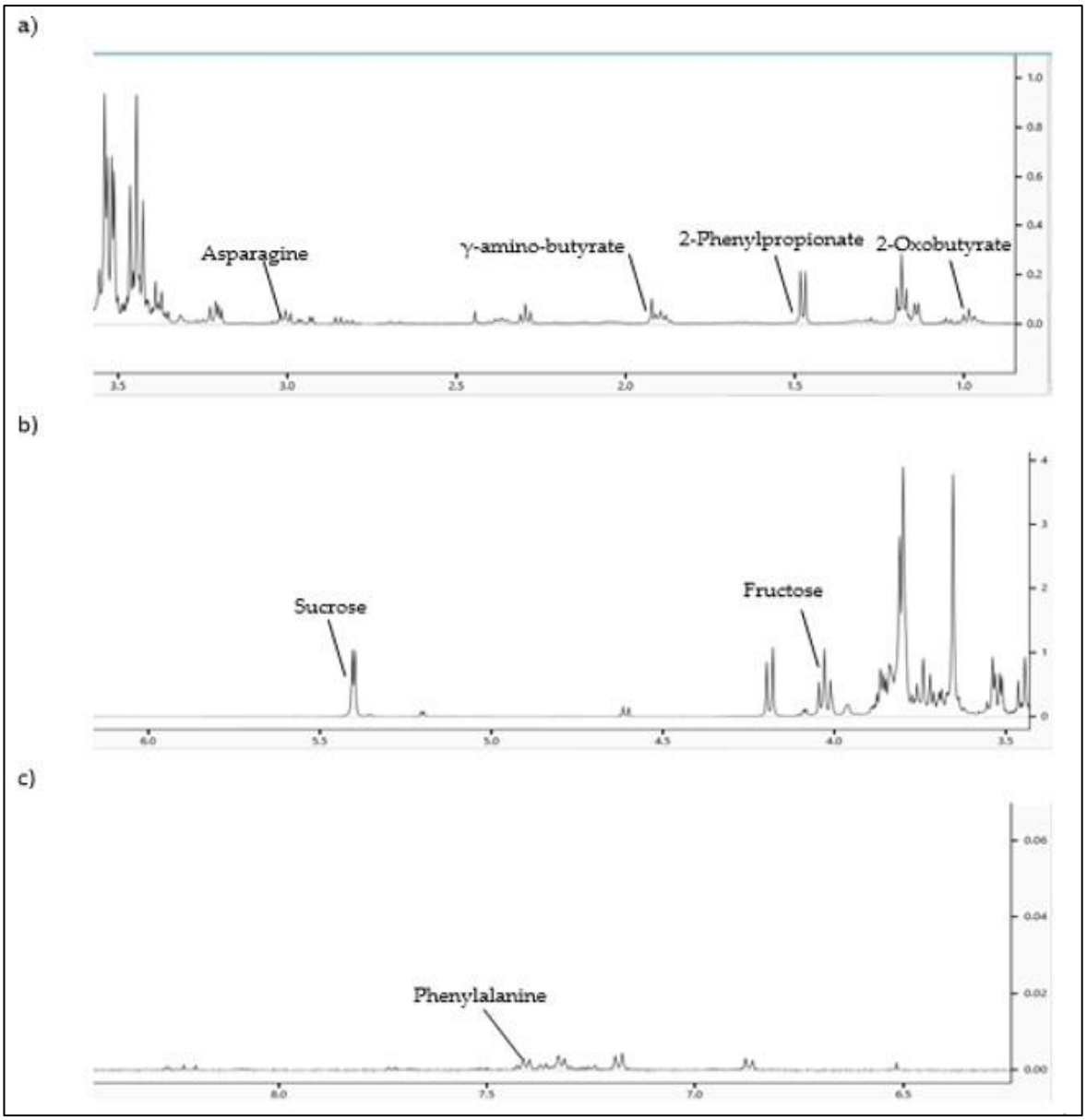

Figure 3. Representative ^{1}H NMR spectrum of flesh extract in the regions 1.0–3.5 ppm (a), 3.5–6.0 ppm (b) and 6.5–8.0 ppm (c).

Table 3. The identified metabolites in the flesh extract by NMR

Compound	δ (ppm)	Multiplicity	Proton Assignment
2-Oxobutyrate	0.90	t	CH_3
	2.55	m	CH_2
	2.78	s	CH
2-Phenylpropionate	7.10–7.35	m	5H
	3.60	q	CH
	1.45	d	CH_3
Sucrose	5.40	d	H1
	3.20–4.20	m	Multiple CH/CHOH
Fructose	4.00–4.20	d	H1, H3
	3.20–4.10	m	(H2 to H6)
Asparagine	3.95	dd	CH
	2.80–2.95	m	CH_2
	7.0–8.0	s	NH_2
γ-Aminobutyric acid (GABA)	3.00	t	CH_2, NH_3^+
	2.30	m	CH_2
	1.90	t	CH_2
Phenylalanine	7.20–7.35	m	5H
	4.00	dd	CH
	3.10–3.25	dd	CH_2

Table 4. The relative quantification of identified metabolites from the flesh extract. Results are expressed as mean ± standard deviation (SD). Six fruits were used for the control and for each treatment (n = 6) in the NMR analysis. Different letters within the same row indicate statistically significant differences at $p < 0.05$.

	Relative quantification (mM)							
	Control		Hexanal		1-MCP		Mix	
	Day 1	Day 3	Day 1	Day 3	Day 1	Day 3	Day 1	Day 3
2-Oxobutyrate	0.18 ± 0.05 a	0.17 ± 0.08 a	0.17 ± 0.06 a	0.13 ± 0.08 a	0.18 ± 0.07 a	0.14 ± 0.06 a	0.16 ± 0.08 a	0.15 ± 0.08 a
2-Phenylpropionate	0.52 ± 0.08 a	0.64 ± 0.06 a	0.58 ± 0.09 a	0.53 ± 0.06 a	0.61 ± 0.05 a	0.53 ± 0.08 a	0.64 ± 0.06 a	0.62 ± 0.07 a
Sucrose	11.51 ± 0.45 a	11.92 ± 0.35 a	12.21 ± 0.63 a	12.77 ± 0.33 a	11.87 ± 0.41 a	11.38 ± 0.76 a	12.65 ± 0.43 a	11.77 ± 0.73 a
Fructose	10.32 ± 0.35 a	10.85 ± 0.97 a	10.67 ± 0.45 a	10.43 ± 0.88 a	10.38 ± 0.44 a	10.51 ± 0.72 a	10.37 ± 0.52 a	10.38 ± 0.91 a
Asparagine	0.24 ± 0.06 a	0.29 ± 0.07 a	0.26 ± 0.04 a	0.24 ± 0.07 a	0.27 ± 0.05 a	0.31 ± 0.08 a	0.26 ± 0.08 a	0.23 ± 0.07 a
γ-amino-butyrate (GABA)	4.33 ± 0.37 a	4.98 ± 0.62 a	4.21 ± 0.78 a	4.18 ± 0.88 a	4.76 ± 0.58 a	4.18 ± 0.55 a	4.62 ± 0.73 a	4.66 ± 0.72 a
Phenylalanine	0.38 ± 0.06 a	0.35 ± 0.08 a	0.33 ± 0.05 a	0.37 ± 0.09 a	0.36 ± 0.05 a	0.41 ± 0.06 a	0.38 ± 0.08 a	0.37 ± 0.06 a

The principal component analysis (PCA) model was illustrated in Figure 4.

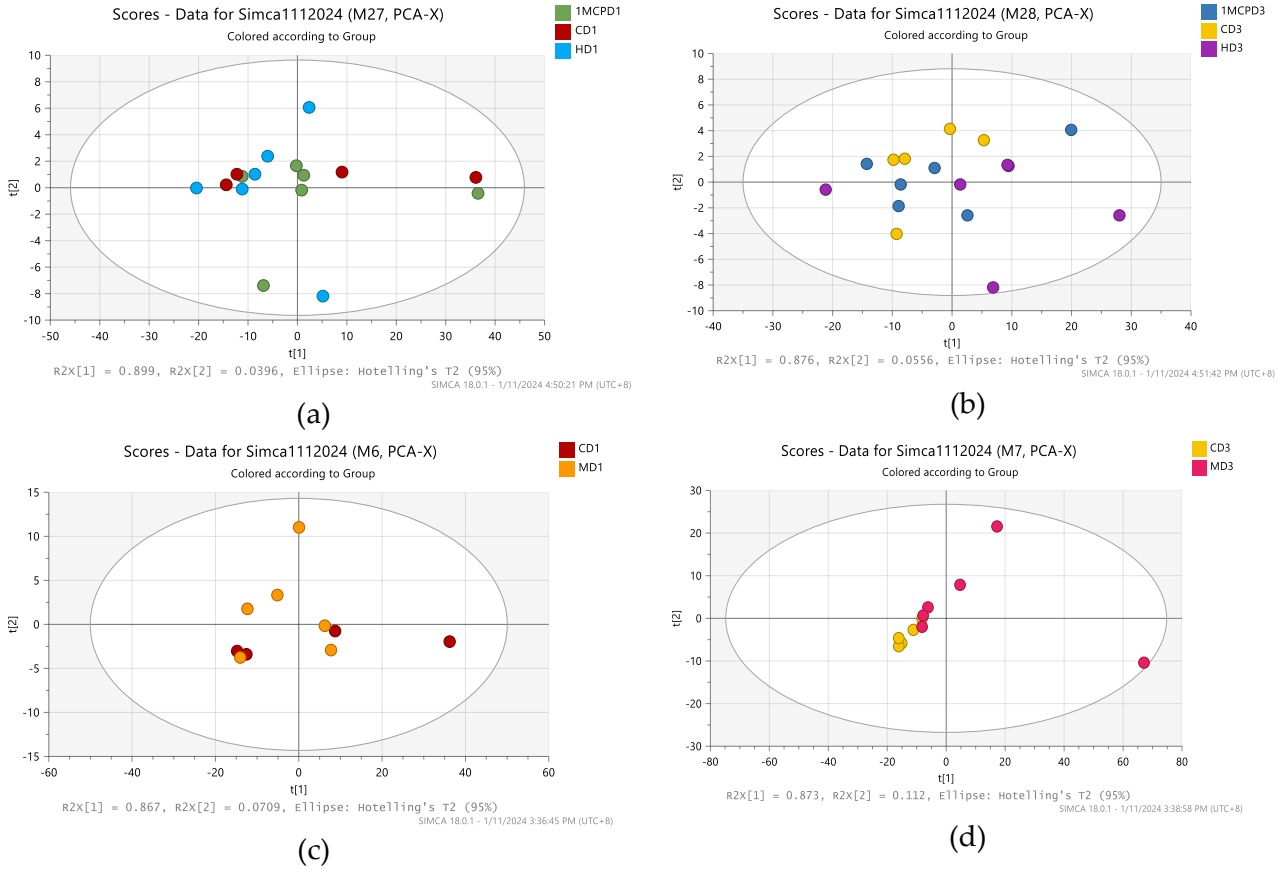

Figure 4. The principal component analysis (PCA) analysis of metabolites extract from the flesh for day 1 and 3 of storage.

From the NMR analysis, several metabolites were identified including oxobutyrate, 2-phenylpropionate, sucrose, fructose, asparagine, γ-aminobutyric acid (GABA) and phenylalanine according to their chemical shifts (δ, ppm) and signal multiplicities in the NMR spectrum available in the Chenomx NMR suite database (Chenomx Inc., Canada) and existing literatures (Liu *et al.*, 2023; Mangiwa *et al.*, 2025). The PCA analysis did not shows significant saperation between control and all treatments groups. This suggest lack of metabolic changes in the flesh during harvesting stage. The relative quantification of identified metabolites also did not shows any significant differences between day 1 and day 3 of storage.

CONCLUSION

The application of 1-MCP and hexanal vapors on D24 durian at ambient temperature can extend the shelf-life by delaying the husk dehiscence for up to 5 days of storage. The treatments also helped to delay weight loss, and the color changes of the husk. However, the color of the flesh was not affected by the treatments. The NMR analysis demonstrated that there were no significant changes in the metabolites of the flesh. Therefore, future studies should focus on investigating metabolite alterations in the husk, particularly those associated with husk dehiscence.

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