

Improving cold resistance and shelf life of *Carica papaya* Linn through 1-methylcyclopropene and geranium oil applications

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Abstract

The perishability and susceptibility to chilling of *Carica papaya* Linn have impeded its long-distance exportation, posing challenges to international trade investments. This study explores the efficacy of 1-MCP and geranium oil (GO) treatments in enhancing papaya's cold tolerance. Designated concentrations for 1-MCP were 300 and 600 mg/L, and for GO, 2% and 4% (v/v), with exposure times set at 30 and 60 mins. Subsequently, the fruits were stored at 4°C for 16 days, and various parameters such as chilling injury (CI), weight loss (WL), respiratory rate (RR), firmness, colour, total soluble solids (TSS), titratable acidity (TA), pH, and ripening index (RI) were assessed at 4-day intervals. The results demonstrated a significant reduction in chilling damage in treated fruits. Specifically, the 60-minute exposure to 600 mg/L 1-MCP (MCP600+60) delayed the development of CI symptoms by at least 4 days compared to the control. At day 16, MCP600+60 exhibited the least WL (1.93%), O₂ consumption (4.19±0.25 mL/kg/hr), and CO₂ production (4.05±0.17 mL/kg/hr). Treated fruits, especially MCP600+60 and 30-minute exposure to 4% (v/v) GO (GO4+30), preserved firmness and colour. In GO treatments, GO4+30 showed the least increase in TSS (1.69-fold) and pH (1.09-fold). The highest TA and RI were reported in MCP600+60 and GO4+30. Overall, MCP600+60 emerged as the most effective treatment for enhancing papaya's cold tolerance and storage quality based on our study.

1. Introduction

In Malaysia, a variety of tropical fruits, including banana, mango, pineapple, rambutan, durian, and papaya, are readily available for both domestic consumption and international trade. *Carica papaya* Linn is widely consumed in its raw form, processed into various products, and incorporated into dishes. Being a perishable climacteric fruit, papaya experiences rapid deterioration post-harvest due to its high respiratory rate. Its popularity stems from its rich nutritional profile, serving as an excellent source of carbohydrates, vitamin C, phytochemicals, and antioxidants, contributing to human health. Globally, papaya exports witnessed an 8% increase in 2021 (FAO, 2022). Traditional cold storage (CS) is commonly employed for cost-effective sea shipping to extend shelf life and preserve the fruit's physical appearance and nutritional attributes. However, CS is not advisable for tropical and subtropical fruits

with high cold sensitivity, potentially causing irreversible damage (Heyes, 2018).

Papaya, being tropical, is susceptible to chilling injury (CI) when exposed to prolonged cold temperatures beyond safety limits, leading to symptoms such as scald, hard lumps, pitting, soggy flesh, abnormal ripening, and increased susceptibility to microbial decay (Sevillano *et al.*, 2009). The literature indicates that papaya is susceptible to chilling injury if prolonged exposure to temperatures below 10°C, whereas the typical storage temperature range is 2-4°C. Therefore, perishability and CI pose significant constraints on long-distance transport and commercial exploitation. Upon transfer from low to ambient temperatures, the fruit experiences a prompt increase in ethylene production and respiration rates, coinciding with the development of chilling injury. The reasons for this rapid increase are debated, with it being

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either a result of chilling damage or closely linked to established damage (Macrae, 1987). Nevertheless, the fruit's respiration rate serves as a physiological measure for monitoring and detecting the severity of chilling injury (Wang, 1989). Respiration rate and fruit metabolism play a crucial role in determining fruit quality during ripening, particularly in terms of colour and firmness (Ohashi *et al.*, 2016).

Postharvest 1-MCP treatment is widely recognized for its effectiveness in delaying ripening and senescence, maintaining fruit appearance, and reducing respiration rate and ethylene production (Ding and Ng, 2008). It has been applied to prevent CI in various fruits such as bananas (Chang *et al.*, 2022), persimmon (Li *et al.*, 2018), peach (Tilahun *et al.*, 2022) and pear (Cheng *et al.*, 2015). Additionally, 1-MCP enhances energy metabolism enzyme activity, ensuring cellular energy at sufficient levels for cell survival during cold stress (Cheng *et al.*, 2015). During CS, ethylene sensitivity can promote CI and induce signal cascades leading to secondary events, including cellular structure changes, pectin solubilization, and degradation (Li *et al.*, 2018). 1-MCP treatment aids in improving the activity of reactive oxygen species (ROS) scavenging enzymes associated with redox state alteration within cells facing cold stress (Zhang *et al.*, 2010). Recently, there has been growing interest in essential oil (EO) application in the food industry for additive and flavouring purposes, driven by their antioxidant and antimicrobial properties, as well as their safety and non-toxicity to human health. Geranium oil (GO), known for its rosy scent, has been extensively used in food flavouring as a cost-effective substitute for rose oil. EO, with its antioxidant and antimicrobial nature, has been explored for controlling postharvest diseases in fruits and vegetables. For example, oils from *Thymus vulgaris* and *Satureja montana* have shown potential in sustaining the postharvest quality of sweet cherries (Maghenzani *et al.*, 2018). The preserved fruit quality during CS is attributed to the high terpene content, exhibiting high bioactivity against food spoilage microorganisms and providing a protective effect against membrane disruption (Eguchi *et al.*, 2016).

The surplus production and export limitations have adversely affected papaya pricing in the domestic market, making it unprofitable for planters and farmers. Consequently, postharvest treatments such as 1-MCP and essential oil application have been proposed due to their efficacy in enhancing fruit cold tolerance and metabolic response. In this study, a high dose of 1-MCP and essential oil was employed in an endeavour to lessen exposure time compared to conventional vaporisation treatment on fruit. Additionally, an ultrasound-assisted misting technique was adopted to trigger a faster release

of volatiles accompanied by fine mist into the air to surround and adhere to the fruit surface, creating a thin film on the fruit surface. Despite limited studies on the misting application of 1-MCP and geranium oil on papaya, this study aims to provide further insights into the misting effects of these treatments on cold stress-related physicochemical changes in papaya.

2. Materials and methods

2.1 Plant materials and treatments

Carica papaya Linn was harvested from a commercial farm in Lanchang, Pahang, Malaysia. The fruits were chosen based on uniform size (1300-1500 g), absence of physical defects, and being at the second maturity stage (mature light green with a slight yellow colour tinge, adhering to the standards set by the Federal Agricultural Marketing Authority Malaysia (FAMA), were individually wrapped in white paper and packed in corrugated paper boxes. Subsequently, they were transported to the processing laboratory at Universiti Putra Malaysia.

Upon arrival, the papayas underwent a thorough cleaning process, starting with washing in tap water to remove impurities. Subsequently, they were immersed in a 2% (w/v) sodium chloride solution for 5 mins and rinsed with distilled water. The fruits were air-dried at room temperature ($25 \pm 2^\circ\text{C}$) for 1 hour until completely dry. Based on preliminary studies, the fruits were randomly divided into nine equal groups and subjected to different treatments as follows:

1. Group 1: Control (no treatment received)
2. Group 2: 30-minute misting of 300 mg/L 1-MCP (MCP300+30)
3. Group 3: 60-minute misting of 300 mg/L 1-MCP (MCP300+60)
4. Group 4: 30-minute misting of 600 mg/L 1-MCP (MCP600+30)
5. Group 5: 60-minute misting of 600 mg/L 1-MCP (MCP600+60)
6. Group 6: 30-minute misting of 2% v/v geranium oil (GO2+30)
7. Group 7: 60-minute misting of 2% v/v geranium oil (GO2+60)
8. Group 8: 30-minute misting of 4% v/v geranium oil (GO4+30)
9. Group 9: 60-minute misting of 4% v/v geranium oil (GO4+60).

The misting treatments were carried out within a camping tent ($180 \times 120 \times 110$ cm) to create a closed controlled chamber with a relative humidity of 85 - 90%.

All closures were sealed with cellophane tape, and an ultrasonic diffuser (2.4 MHz, 30 mL mist/h) from REDBUZZ, Malaysia, was placed in the centre of the tent to facilitate the misting process. The 1-MCP solution, prepared from a 3.5% active ingredient of 1-MCP (Panpan Industry Co. Limited, China), followed the manufacturer's instructions. The geranium oil (NOW®, Bloomingdale, USA) was measured and obtained from the ready supply.

Post-treatment, the fruits were removed from the camping tent and stored at 4°C for 16 days. Fruit samples were randomly extracted from cold storage at 4-day intervals, allowing them to return to ambient temperature (20±2°C) for approximately 2 hrs before analysis. All analyses were conducted in triplicate, and the final reading was considered the conclusive value.

2.2 Chilling injury index measurement

At intervals of every four days, the symptoms of chilling injury (CI) visible on the fruit surface were examined, captured, and analysed using image processing software, Image J (v1.53i, NIH Image, National Institutes of Health, Bethesda, MD, USA). The CI index was computed using the following formula:

$$\text{CI Index} = \frac{\text{total area of CI}}{\text{total fruit surface area}} \times 100 \% \quad (1)$$

2.3 Respiration rate determination

The papaya's respiration rate was assessed using a closed system approach, employing a headspace gas analyser (Gspace advance G3, Systech Instrument, UK). For the measurement, a specified weight of papaya was placed within a sealed, airtight container (6.0 L). A hole, matching the probe's diameter, was created in the container's lid to prevent gas outflow during connection to the gas analyser. The sealed container was then incubated at 4±2°C for 24 hrs. Following incubation, the concentrations of O₂ and CO₂ in the headspace were measured and recorded. The respiration rate, expressed in terms of O₂ consumption and CO₂ evolution, was quantified in mL kg⁻¹ h⁻¹ fresh weight (FW) and computed using the formulas (2) and (3) provided below (Fonseca *et al.*, 2002):

$$\text{RO}_2 (\text{mL kg}^{-1} \text{ h}^{-1}) = \frac{(\text{pO}_2^{\text{in}} - \text{pO}_2^{\text{f}}) V_v}{100 \times W \times (t^{\text{f}} - t^{\text{in}})} \quad (2)$$

$$\text{RCO}_2 (\text{mL kg}^{-1} \text{ h}^{-1}) = \frac{(\text{pCO}_2^{\text{f}} - \text{pCO}_2^{\text{in}}) V_v}{100 \times W \times (t^{\text{f}} - t^{\text{in}})} \quad (3)$$

where pO₂ and pCO₂ = partial pressure of oxygen and carbon dioxide gas, %; V_v = void volume, mL; W = weight of fruit, kg; t = time, hour; superscript *in* and *f* = initial and final

The void volume was measured by using the water displacement method and the void volume was calculated from the difference between the total volume of the air-tight container and the total volume of water displaced by papaya out from the container fully filled with water.

2.4 Weight loss

The initial weight of each papaya was recorded before placing it in cold storage, and subsequent weight measurements were taken at four days intervals to evaluate fruit weight loss. The weight loss (WL) was computed using the following formula:

$$\text{WL} (\%) = \frac{\text{initial fruit weight} - \text{final fruit weight}}{\text{initial fruit weight}} \times 100 \% \quad (4)$$

2.5 Fruit firmness and colour

A papaya fruit with a skin thickness of 0.3 cm² was peeled, and the fruit pulp was divided into three equal portions: top, middle, and bottom. The firmness of these portions was evaluated using a texture analyzer (TA HA plus, Stable Micro Systems, UK) equipped with an SMS P/2N needle probe set to a 10 mm depth of penetration. The firmness value of the papaya was determined by averaging the readings from the three portions, expressed in grams.

For fruit colour assessment, measurements were taken at four-day intervals using a Chroma Meter (CM-700d, Minolta Corporation, Japan) in an environment maintained at 20±2°C. The L*, a*, and b* values of papaya were recorded at the top, middle, and bottom regions. The final colour representation was derived from the average reading of these values. The non-destructive colour measurement was consistently performed on the same papaya throughout the storage period. The analysis was conducted in triplicate.

2.6 Titratable acidity

The determination of titratable acidity (TA) in papaya utilized the titrimetric method outlined by Ranganna (1986) with modifications. In this procedure, 50 g of thawed papaya pulp was homogenized in 200 mL of distilled water and subsequently filtered through cotton wool. A 10 mL aliquot of the filtrate was titrated with 0.1 N NaOH, and 2 drops of 1% phenolphthalein indicator were introduced. The volume of titrant required for the colour shift of NaOH to pink, indicating the endpoint at pH 8.2, was recorded. The papaya's titratable acidity was expressed as the percentage of citric acid (CA) per 100 g of fruit. The percentage of CA (with an equivalent weight of 64 g) was determined using the formula provided below:

$$\text{CA} (\%) = \frac{\text{volume of NaOH used} \times 0.1 \text{N NaOH} \times \text{product volume} \times \text{CA equivalent weight} \times 100}{\text{sample weight} \times \text{sample volume used} \times 100} \quad (5)$$

2.7 Measurement of pH, total soluble solids and ripening index

Before blending, a 100 g portion of fruit was cut into cubes. These fruit cubes were then processed using a blender (MX900M, Panasonic, Malaysia). The resulting juice was collected for the measurement of its total soluble solids (TSS) and pH levels. A refractometer (N1, Atago Co. Ltd., Tokyo, Japan) was employed to determine the TSS content, expressed in degrees Brix ($^{\circ}\text{Bx}$), using two drops of juice. pH measurements were carried out with a digital pH meter (FE20, Mettler Toledo, Schwerzenbach, Switzerland), calibrated with pH 4 and pH 7 buffers before use. The ripening index was calculated by dividing the TSS value by the TA value.

2.8 Statistical analysis

Each analysis was conducted in triplicate, and the results are presented as the mean \pm standard deviation. Statistical analyses were carried out using Minitab version 21 statistical software (Minitab Inc., Coventry, UK). A two-way analysis of variance was applied, with the significance difference level set at $p < 0.05$. To identify true differences among the means for treatment and storage days, a post hoc Tukey-Kramer multiple comparison test was employed.

3. Results

3.1 Chilling injury index and fruit visual appearance

A statistically significant interaction effect ($p < 0.05$) between treatments and storage days was observed for changes in the Chilling Injury (CI) index over 16-day storage (DOS). The alterations in the severity of fruit CI

and its corresponding visual changes are depicted in Figure 1. During the initial 4 DOS, the chilling damage of papaya remained below 7%. The control group exhibited the highest level of chilling damage over the 16 DOS ($23.99 \pm 2.63\%$). When comparing among the 1-MCP and geranium oil (GO) treatments, the most prominent CI symptoms were reported in MCP300+30 ($21.72 \pm 1.78\%$) and GO2+30 ($23.96 \pm 1.44\%$), respectively. By day 16, the most substantial reduction in CI symptoms was observed in MCP600+60 ($11.98 \pm 1.00\%$) for 1-MCP treatment and in GO4+30 ($17.00 \pm 1.34\%$) for GO treatments. Notably, MCP600+60 showed the potential to ameliorate and delay the development of CI by at least 4 days compared to the control.

3.2 Respiration rate of papaya

The respiration rate (RR) of papaya was monitored and measured in terms of oxygen (O_2) consumption (Figure 2a) and carbon dioxide (CO_2) release (Figure 2b) throughout a 16-day storage period. As the storage duration progressed, both the rates of O_2 consumption and CO_2 release exhibited an increase. A noteworthy interaction between treatment and storage day was observed for both gases.

On day 16, the control exhibited the highest RR, with an O_2 consumption rate of $5.62 \pm 0.42 \text{ mL kg}^{-1} \text{ h}^{-1}$ and a CO_2 gas release rate of $5.61 \pm 0.42 \text{ mL kg}^{-1} \text{ h}^{-1}$. The lowest CO_2 gas release rate was recorded in MCP600+60 ($4.05 \pm 0.17 \text{ mL kg}^{-1} \text{ h}^{-1}$), representing a 0.72-fold reduction compared to the control. The treatments MCP600+60 ($4.19 \pm 0.25 \text{ mL kg}^{-1} \text{ h}^{-1}$), MCP600+30 ($4.23 \pm 0.26 \text{ mL kg}^{-1} \text{ h}^{-1}$), and GO4+30 ($4.81 \pm 0.51 \text{ mL kg}^{-1} \text{ h}^{-1}$)

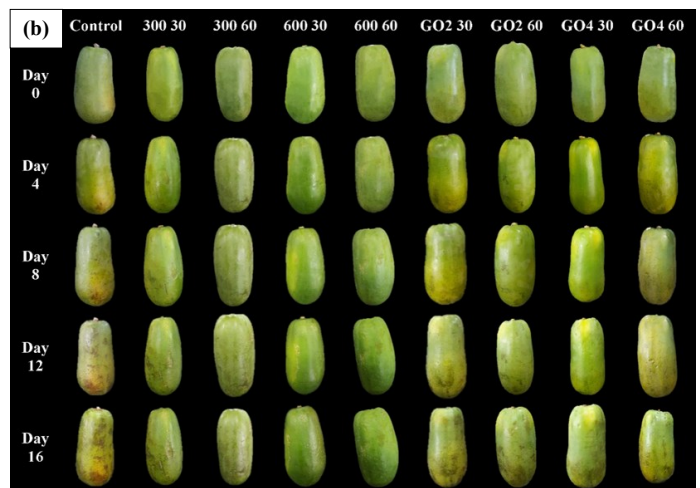
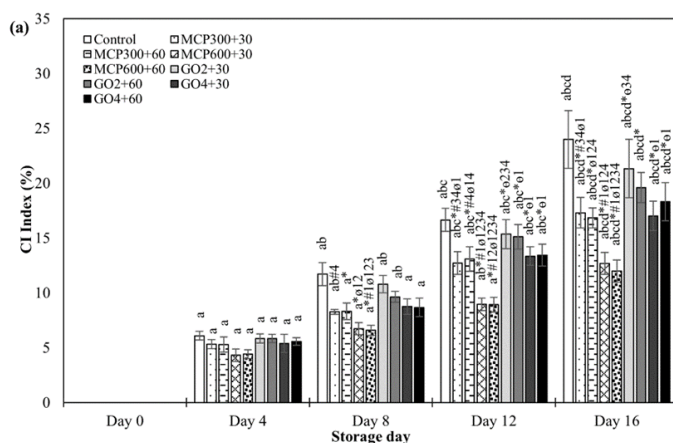


Figure 1. The changes in (a) chilling injury (CI) index and (b) related visual appearance in papaya receiving no treatment, 1-MCP and GO treatments over 16 days of storage (DOS) at 4°C . Data are presented as the mean \pm SD and significant differences among fruits are denoted by different letters using Tukey's test ($p < 0.05$). The letters a-d indicate the significance with respect to Day 0-12, respectively. The symbol "*", "#", "ø" and "ø" designated significance with respect to control, among 1-MCP treatments, among GO treatments, and between 1-MCP and GO treatments, respectively. The #1-4 indicated significance versus MCP300+30, MCP300+60, MCP600+30 and MCP600+60, respectively, whereas ø1-4 and ø1-4 indicates significance versus GO2+30, GO2+60, GO4+30 and GO4+60 respectively. The error bars represented the standard deviation of the means of triplicate measurements.

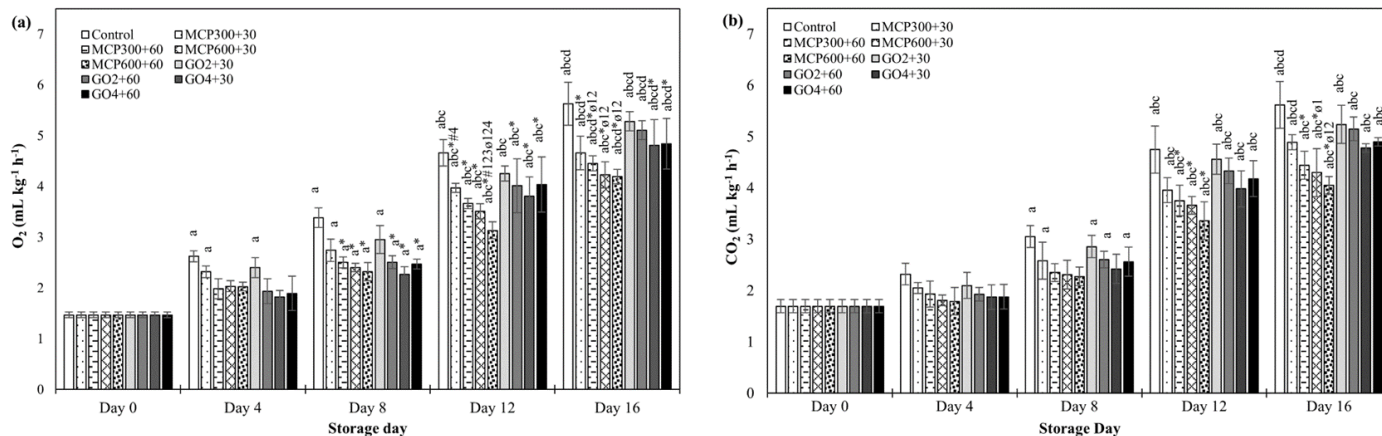


Figure 2. The respiratory rate changes of (a) oxygen gas, O₂ consumption and (b) carbon dioxide, CO₂ gas released in papaya for each treatment over 16 DOS at 4°C. Data are presented as the mean±SD and significant differences among fruits are denoted by different letters using Tukey’s test (p < 0.05). The letters a-d indicate the significance with respect to days 0-12, respectively. The symbol “*”, “#”, “ø” and “ø” designated significance with respect to control, among 1-MCP treatments, among GO treatments, and between 1-MCP and GO treatments, respectively. The #1-4 indicated significance versus MCP300+30, MCP300+60, MCP600+30 and MCP600+60, respectively, whereas ø1-4 and ø1-4 indicates significance versus GO2+30, GO2+60, GO4+30 and GO4+60 respectively. The error bars represented the standard deviation of the means of triplicate measurements.

1 h⁻¹) demonstrated efficacy in reducing the O₂ consumption rate after storage.

3.3 Weight loss in fruit

Both the treatment and storage days significantly influenced the fruit's weight loss (WL), with less than a 5% loss observed throughout the 16-day storage period (Figure 3). The WL exhibited a notable increase from the 12th day of storage. On day 16, the control showed the highest fruit weight loss (4.21±0.38%), closely followed by GO2+30 (3.63±0.27%). Generally, with the exception

of MCP300+30, the 1-MCP treatments demonstrated greater efficacy in maintaining fruit weight compared to the GO treatment. In comparison to the control, the least WL reported for 1-MCP and GO treatments were MCP600+60 and GO4+30, with respective losses of 1.93±0.11% and 2.69±0.08% (equivalently representing a 2.18-fold and 1.57-fold decrease).

3.4 Fruit pulp firmness and colour changes

The firmness of the fruit gradually decreased as storage progressed, significantly influenced by both treatments and storage days (Figure 4a). In the initial 8 days, a reduction of less than 10% in firmness was observed, with an exception in the control (10.28%). The most significant loss in fruit firmness occurred on day 8, ranging from 2.09 to 3.11-fold. The control exhibited the highest decline in fruit firmness over storage (28.06%). Among the 1-MCP and GO treatments, MCP600+60 (15.59%) and GO4+30 (20.60%) showed the least decrease in firmness on day 16. Notably, only the 600 mg/L 1-MCP treatments were comparatively effective in preserving pulp rigidity, providing a higher firmness value than the control.

Over time, the papaya fruit skin brightened, de-greened, and turned greenish-yellow. The changes in lightness (L*), redness/greenness (a*), and yellowness/blueness (b*) values of papaya over storage are illustrated in Figures 4b, 4c, and 4d. No significant interaction effect was found between treatment and storage day for L*, a*, and b* values (p > 0.05). Throughout storage, the control exhibited the lightest colour, with a 1.51-fold increase (64.81±1.79), while the least increase was observed in MCP600+60 (52.03±3.68) and GO4+30 (55.25±2.58), with a 1.22 and 1.29-fold

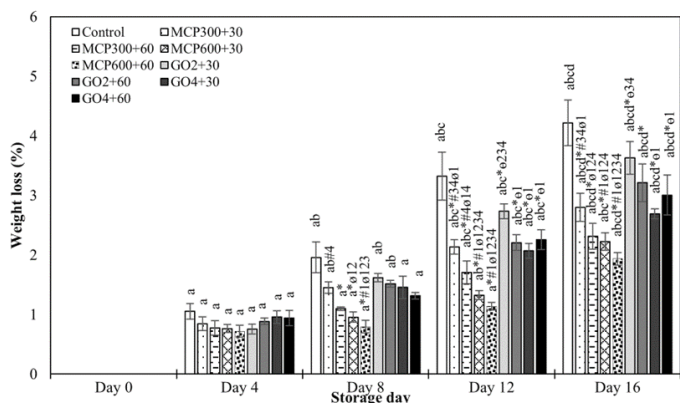


Figure 3. The fresh weight loss changes in papaya for each treatment over 16 DOS at 4°C. Data are presented as the mean±SD and significant differences among fruits are denoted by different letters using Tukey’s test (p < 0.05). The letters a-d indicate the significance with respect to days 0-12, respectively. The symbols “*”, “#”, “ø” and “ø” designated significance with respect to control, among 1-MCP treatments, among GO treatments, and between 1-MCP and GO treatments, respectively. The #1-4 indicated significance versus MCP300+30, MCP300+60, MCP600+30 and MCP600+60, respectively, whereas ø1-4 and ø1-4 indicates significance versus GO2+30, GO2+60, GO4+30 and GO4+60 respectively. The error bars represented the standard deviation of the means of triplicate measurements.

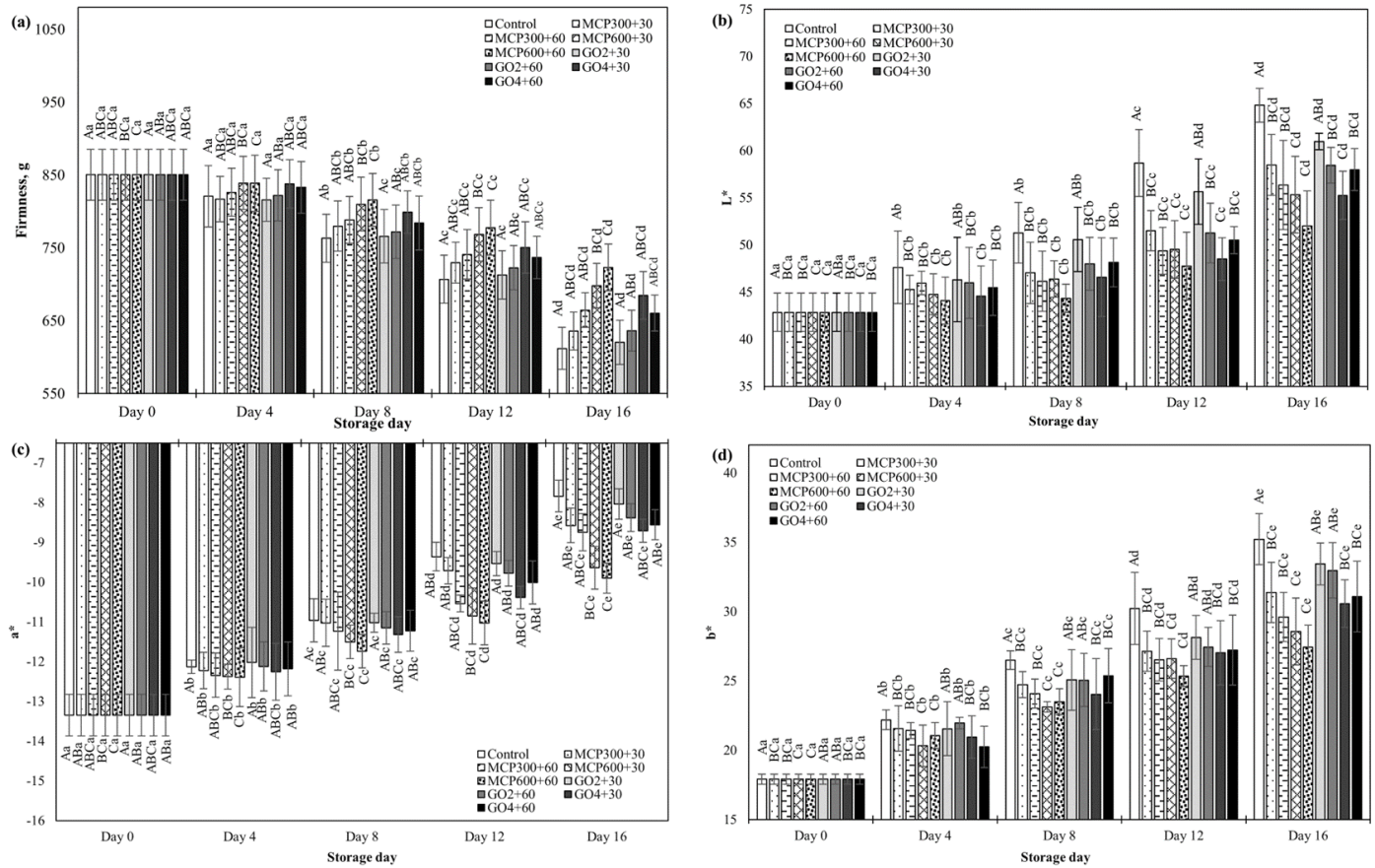


Figure 4. The changes in (a) firmness, (b) L*, (c) a* and (d) b* in papaya for each treatment over 16 DOS at 4°C. Data are presented as mean value±SD and the different capital and small letters denote the significant differences among treatments and storage day by using Tukey's test ($p < 0.05$), respectively. The error bars represented the standard deviation of the triplicate mean.

increase, respectively. On day 16, the control displayed the most significant colour change, with the highest increase of 1.75-fold in a* (-7.34 ± 0.40) and a 1.95-fold increase in b* value (35.21 ± 1.84). The fruit colour was better preserved in MCP600+60 and GO4+30, with only a 1.33 and 1.54-fold increase in a* and a 1.46 and 1.68-fold increase in b* value, respectively.

3.5 Changes in total soluble solids, pH, titratable acidity and ripening index

The total soluble solids (TSS) content in papaya increased during storage, with no significant interaction effect detected between treatment and storage day (Figure 5a). On day 16, the control exhibited the greatest increase in TSS (rose by 1.91-fold), closely followed by GO2+30 (rose by 1.89-fold). Meanwhile, the least increase was observed in MCP600+60 (1.66-fold increase). All treatments experienced the highest increase in TSS on day 8, with the exception of the 600 mg/L 1-MCP treatments, which appeared on day 12.

The pH of papaya increased significantly during progressive storage (Figure 5b). Only MCP600+60 showed a statistically significant difference from the control. On day 16, the lowest pH value was reported in MCP600+60 (5.94 ± 0.09), followed by MCP600+30 (6.06 ± 0.04) and GO4+30 (6.07 ± 0.06). Less than 10%

increase in pH value was reported in MCP600+30 (9.05%), MCP600+60 (6.89%), GO4+30 (9.17%), and GO4+60 (9.95%).

The titratable acidity (TA) content in papaya significantly decreased over storage, and the statistical difference was only reported in the pair of control and MCP600+60 (Figure 5c). Over storage, the highest decrease in TA was observed in the control (2.15-fold), followed by a 2-fold decrease in GO2+30 and MCP300+30. On day 16, the highest TA value was reported in MCP600+60 ($0.20 \pm 0.02\%$), closely followed by MCP600+30 ($0.19 \pm 0.03\%$).

The ripening index (RI) of papaya proportionally increased with storage days and was significantly affected by both treatment and storage days (Figure 5d). The RI of the control increased by 2.12-fold on day 8 and by 4.18-fold on day 16. The RI in other fruits steadily increased during the first 8 DOS, ranging from 1.53 to 1.91-fold. Over storage, the control had the highest RI (91.15 ± 11.93), while MCP600+60 had the lowest RI (53.82 ± 6.36).

4. Discussion

Papaya, being a climacteric and chilling-sensitive fruit, is susceptible to chilling injury (CI) during cold

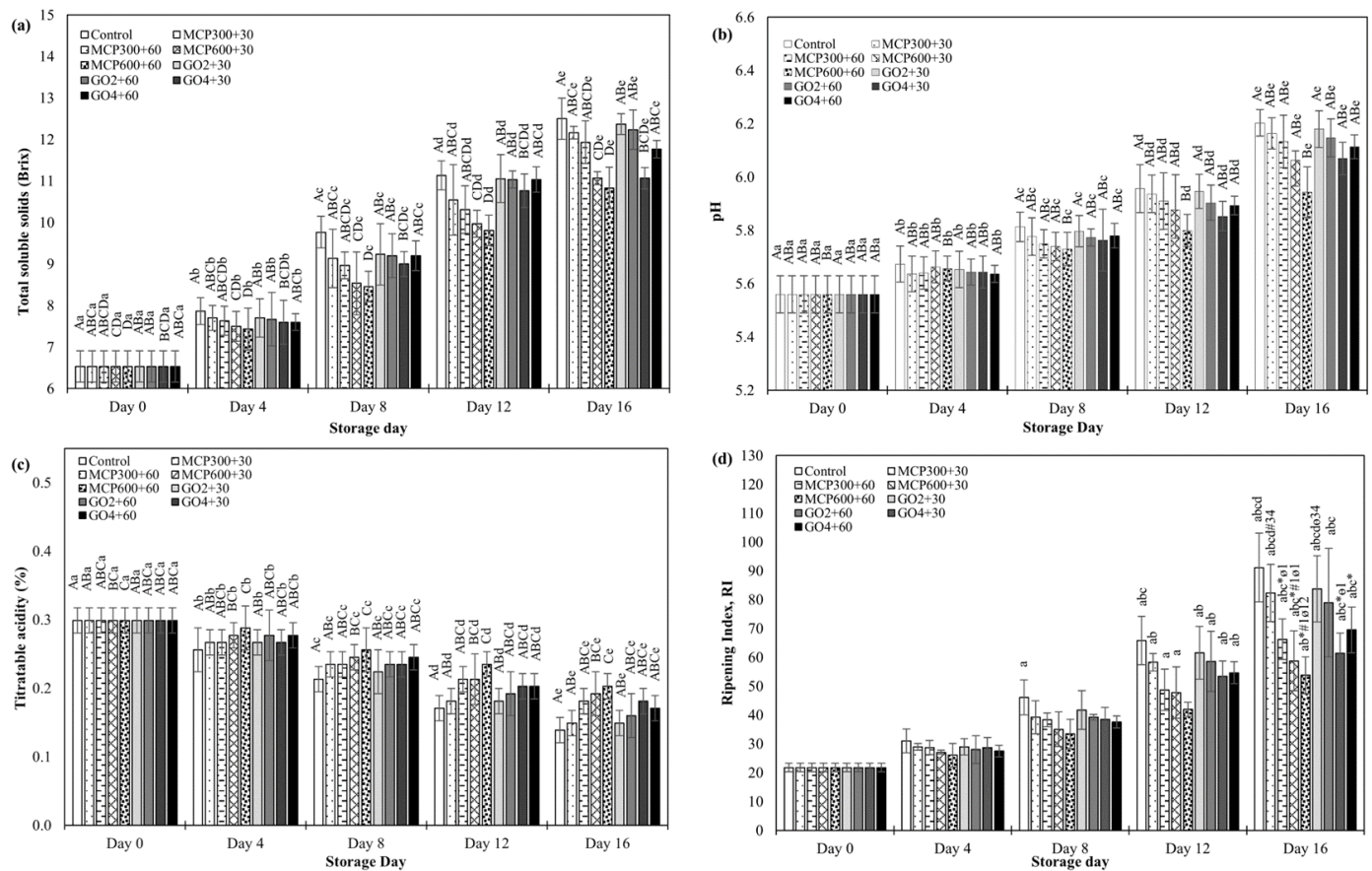


Figure 5. The changes in (a) total soluble solids content, TSS, (b) pH, (c) titratable acidity, TA and (d) ripening index, TSS/TA in papaya for each treatment over 16 DOS at 4 °C. Data are presented as mean±SD and significant differences among fruits are denoted by different letters using Tukey's test ($p < 0.05$). The letters a-d indicate the significance with respect to days 0-12, respectively. The symbols “*”, “#”, “ø” and “ø” designated significance with respect to control, among 1-MCP treatments, among GO treatments, and between 1-MCP and GO treatments, respectively. The #1-4 indicated significance versus MCP300+30, MCP300+60, MCP600+30 and MCP600+60, respectively, whereas ø1-4 and ø1-4 indicates significance versus GO2+30, GO2+60, GO4+30 and GO4+60 respectively. The error bars represented the standard deviation of the means of triplicate measurements.

storage (CS). Our study revealed that the treatment with 600 mg/L of 1-MCP for a brief exposure of 30 mins significantly reduced CI symptoms in papaya by 1.89-fold. This suggests that 1-MCP efficiently delays the onset of CI, resulting in milder symptoms. Papayas treated with 600 mg/L of 1-MCP and 4 ml v/v geranium oil (GO) exhibited less severe CI symptoms, such as reduced skin pits, sunken spots, and whitish spots (Figure 1b). Notably, the higher concentration treatment showed more promising results in reducing CI in papaya compared to the lower concentration treatment. This observation could be attributed to the diffusion/effusion rate, where the higher concentration gradient served as the main driving force for diffusion, facilitating particle diffusion, including uptake and sorption (Dauny *et al.*, 2003; Sun, 2004). Furthermore, the diffusion rate is influenced by the molecular mass of diffusing particles, with lighter particles exhibiting higher diffusivity/effusivity, as proposed by Graham's Law. Comparatively, the 1-MCP treatment could act 4.4 times faster in diffusivity/effusivity than GO, corresponding to being 4.4 times lighter in molecular weight. A similar study comparing 1-MCP and CO₂ gas treatment on

alleviating CI in peaches demonstrated that the action of 1-MCP on fruit quality and storability was reduced due to the lower diffusivity of the heavier 1-MCP gas (Tilahun *et al.*, 2022).

The initiation of ripening in climacteric fruit leads to an increase in the respiration rate (RR) and accelerates metabolic changes, such as the accumulation of secondary metabolites and softening of fruit structure (Wang *et al.*, 2022). In our study, only the 1-MCP treatments proved effective in reducing RR in papaya (Figure 2) and were competent in delaying the climacteric respiration pattern. The suppression of fruit RR is linked to the antagonistic action of 1-MCP against ethylene via irreversible binding to ethylene receptors. A minimal dose of 1-MCP is required to disrupt ethylene biosynthesis, given its 10 times higher affinity than ethylene (Sisler and Serek, 1997). As storage progressed, the increase in RR for the 1-MCP treatment might be related to fruit maturation, which could interfere with 1-MCP active responses, including diminishing the production of degradative enzymes (Ohashi *et al.*, 2016). The effectiveness of 1-MCP in reducing RR has also

been documented for papaya cv. Rainbow (Manenoi *et al.*, 2007) and cv. Solo (Ohashi *et al.*, 2016). The selective permeability of the EO coating could regulate gaseous exchange and water transmission, assisting in slowing down fruit RR, metabolic activity, and enzyme activity (Janjarasskul and Krochta, 2010). Consequently, ripening is delayed, and the breakdown of cell wall material is further reduced.

During storage, a natural loss in fruit weight occurs. If the water loss is below 3%, the fruit is considered marketable, but it loses marketability if the loss exceeds 5% (Ansah *et al.*, 2018). In our study, the 1-MCP-treated papaya showed reduced weight loss compared to the control (Figure 3). The reduction in WL in 1-MCP might be associated with suppressed RR and a reduced transpiration rate resulting from slowed metabolic activity. The reduced RR results in a decrease in heat generated from respiration, which, in turn, lowers the vapour pressure difference between the fruit surface and the surrounding environment, leading to a decrease in the transpiration rate (Sastry and Buffington, 1983). The effective dose of 1-MCP in delaying ripening and metabolic activity varied among commodities. In this study, all 1-MCP treatments, except for MCP300+30, showed no significant difference in WL. This suggests that 300 mg/L 1-MCP with an hour of vaporization is sufficient in reducing WL. Our study aligns with a study on jujube, where three different doses of 1-MCP (312.5 nL/L, 625 nL/L, and 1000 nL/L) showed no significant reduction in jujube WL (Ozturk *et al.*, 2021). However, jujube firmness was affected. Similarly, a study on papaya cv. Eksotika also reported that different doses of 1-MCP showed no significant impact on fruit WL (Ding and Ng, 2008). In comparing the effects between GO treatments and the control, GO-treated fruits showed a much-reduced loss in weight. However, no significant difference was observed between GO treatments except GO2+30. This suggests that the hydrophobicity of GO could provide an excellent barrier to prevent moisture loss through water transfer (Yousuf *et al.*, 2021).

Fruit firmness and peel colour are critical quality attributes affecting consumers' perceptions, acceptance, and purchase behaviour. From the findings, 1-MCP treatments demonstrated a prominent effect in preserving fruit rigidity, particularly through high-dosage applications (Figure 4a). The preservation of fruit rigidity is highly related to the ability of 1-MCP to delay the ripening process, especially with higher dosage treatment. The ability of 1-MCP to preserve fruit rigidity is likely credited to the decreased turnover rate of ethylene receptors. During storage, the free-released 1-MCP from desorption readily binds with regenerated or newly synthesized ethylene-binding sites (Golding *et al.*,

1998). The higher dose application might cause an oversaturation of ethylene-binding sites, thereby retarding ethylene biosynthesis and inhibiting ethylene-induced ripening. Our study is in agreement with the study on the 'Cox' apple, which reported that a higher dose of 1-MCP is better in preserving fruit rigidity (Dauny and Joyce, 2002). The preservation of fruit rigidity by 1-MCP is also related to the reduction of cell wall-degrading enzyme activity, such as a pectinolytic enzyme, thus preventing the active transformation of insoluble pectin into soluble pectin (Yoshioka *et al.*, 2011). In our study, among GO treatments, GO4+30 showed the best in preserving fruit firmness. A similar study using citrus oil (mandarin, lemon, and orange) also proved effective in preserving strawberry fruit's rigidity (Shehata *et al.*, 2020). On the contrary, the application of sage oil on tomato fruit at the breaker stage showed firmer fruits with lower concentrations (50 µL/L) as compared to higher concentrations, as the higher concentration might provoke ethylene emission (500 µL/L) (Chrysargyris *et al.*, 2021). Hence, our findings suggest that a high oil dosage and a shorter exposure are necessary to maintain fruit firmness, likely due to larger fruit size and to avoid oversaturation of EO, which may induce ethylene emission.

Over storage, fruit colour turning is associated with chlorophyll degradation and the transformation of green pigments into other colour-turning pigments. During ripening, the biosynthesis of carotenoids is initiated, and carotenoid pigments become visible, accompanied by chlorophyll degradation (Hashim *et al.*, 2012). In this study, 1-MCP and GO4+30 have been observed to be better at delaying colour turning in papaya (Figure 4). Similar findings were reported when applying 1-MCP to delay colour changes in Solo papaya cv. 'Gold' and 'Rainbow' (Manenoi *et al.*, 2007). Comparatively, GO treatment showed significant changes in lightness and yellowness compared to the control. This suggests that GO treatment could prevent the degradation of carotenoids and related compounds in the fruit, thereby preserving the colour (Santoro *et al.*, 2018). However, the underlying mechanism related to colour changes needs further study.

The total soluble solids (TSS), titratable acidity (TA), and pH value are essential parameters attributed to the fruit's aroma, flavour, and taste. The main sugars found in papaya are sucrose, glucose, and fructose, which gradually increase during the ripening process. In our findings, the highest increase in TSS in the control might be related to the highest moisture loss and sugar accumulation (Etemadipoor *et al.*, 2020). As storage progresses, the TSS content in fruit increases, correlated with the disassembly of cell walls to provide carbon (a

source of sugar synthesis) (Schweiggert *et al.*, 2011). In addition, the decomposition of organic matter into sugars, acids, and minerals during respiration also contributes to the increase in TSS content (Yin *et al.*, 2019). Hence, the reduction in respiratory and metabolic activity was the major cause of having no sharp increment of TSS content in 1-MCP treated fruits compared to the control. Our result is consistent with another study on papaya cv. 'Daqing No.7' (Shen *et al.*, 2017). The author reported that 18 hours of fumigation of 1-MCP, at a concentration of 1 $\mu\text{L/L}$ fumigation, could minimize the increase of TSS content in papaya. The lower sugar content reported in GO-treated fruits might be attributed to the moisture retained by coatings and reduced metabolic activity in fruit (Etemadipoor *et al.*, 2020). In comparing the GO doses' effect, it is inferred that higher dose treatment favours the uptake and adhesion rate of volatile compounds on fruit peels.

The pH value in fruits changes with fruit maturity and ripeness degree. The increase in pH value during storage correlates with fruit ripening as the amount of hydrogen ions from organic acid decreases. Moreover, the changes in pH value are associated with fruit firmness. A higher pH value will induce the release of calcium ions from pectin polymers to soften the fruit pulp (McFeeters and Fleming, 1991). In our findings, only MCP600+60 protected the fruits from a tremendous increase in pH value (Figure 5b). Hence, this might be best explained by the effectiveness of MCP600+60 in slowing down the fruit's metabolic activity and delaying the breakdown of organic acids.

Organic acids in fruits play a role as intermediate metabolites being consumed in various physiological reactions. The reduction in TA content in fruits is paralleled by the increase in pH and TSS content. Over storage, the TA content diminishes, most probably due to the degradation of organic acids involved in respiration and ripening to support the fruit's metabolic activity. In our findings, the TA content in 1-MCP and GO treatments was higher than in the control, even though no significant difference was reported except MCP600+60 (Figure 5c). Hence, it could be best explained that MCP600+60 slows fruit metabolic actions and reduces organic acid degradation. These findings are in agreement with the study on utilizing 1-MCP in maintaining TA content in papaya cv. Eksotika (Ding and Ng, 2008) and cv. 'Pococi' (Zerpa-Catanho *et al.*, 2017). Similar results were also reported in the utilization of lemon and cinnamon oil in maintaining TA in apple cv. 'Granny Smith' (Malekipoor *et al.*, 2022). The TSS/TA ratio depicts the fruit's flavour quality and sweetness. Hence, a good blend of TSS/TA is important for the fruit's aroma and taste. The rise in the TSS/TA

ratio was observed with the increase in fruit ripening degree. In our findings, a lower rise in the TSS/TA ratio was observed in 1-MCP and GO4 treatment, in which both lowered the increase of TSS and rendered the decrease of TA.

4. Conclusion

In conclusion, our study highlights the effectiveness of 1-MCP and geranium oil (GO) treatments in preserving the quality of papaya during cold storage. The 600 mg/L 1-MCP treatment, even with a brief 30-minute exposure, significantly reduced chilling injury symptoms, demonstrating its efficacy in delaying the onset of chilling injury and resulting in milder symptoms. Papayas treated with 600 mg/L 1-MCP and 4% v/v GO exhibited fewer chilling injury symptoms, such as skin pits and sunken spots, emphasizing the potential of these treatments in enhancing fruit quality. The respiration rate in papaya was effectively reduced by 1-MCP treatments, particularly at higher doses, contributing to delayed climacteric patterns. Moreover, 1-MCP treatments demonstrated superior performance in maintaining fruit weight and firmness compared to GO treatments. The hydrophobic nature of GO, especially in GO4+30, showed promise in reducing fruit weight loss. Both 1-MCP and GO treatments influenced the colour preservation of papaya, with 1-MCP, particularly at higher doses, demonstrating better outcomes. Additionally, the influence of these treatments on key parameters such as TSS, TA, pH, and the TSS/TA ratio underscores their potential to enhance flavour quality. Overall, our findings suggest that 1-MCP is consistently effective across various parameters, making it a promising postharvest treatment for papaya quality preservation.

Conflicts of interest

The authors declare no conflict of interest.

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