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Combined application of hot water treatment and 1-methylcyclopropene enhances postharvest quality of 'Solo' Papaya (*Carica papaya* L.)

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Abstract Results of this study revealed that fruits treated with the combined application (T2) of hot water treatment (HWT) at 50 °C for 10 minutes coupled with 1-methylcyclopropene (1-MCP) through gas exposure at 1.50 ppm for 12 hours exhibited delayed peel color change, superior firmness retention, and consistently higher visual quality ratings throughout 15 days of storage. Untreated fruits (T1) ripened faster and had higher total soluble solids (TSS), while T2-treated fruits maintained comparable organoleptic attributes in terms of taste, aroma, and overall acceptability. HWT alone (T6) is effective in suppressing anthracnose incidence and severity which supports its role in postharvest disease management. However, neither HWT nor 1-MCP alone, nor their combination, completely eliminated disease development which indicates the need for supplementary interventions. These findings support the potential of integrated, non-chemical postharvest strategies for enhancing quality and extending the marketability of tropical fruits like papaya.

Keywords: Aqueous dipping, Gas exposure, Papaya disease, Ripening changes, Shriveling

Introduction

Papaya (*Carica papaya* L.) is a succulent, sweet fruit recognized worldwide and is considered one of the most important fruit crops in the Philippines due to its significant economic and export potential (Daagema *et al.*, 2020). Among the popular cultivars grown in the country is the 'Solo' variety (Randle and Tennant, 2021), which holds high economic value because of its productivity, uniform shape and size, excellent taste, and other desirable fruit quality attributes (Yebes, 2015). Developing countries contribute to over 90% of global papaya production, establishing a dominant presence in both fresh and processed products on the international market (Palei *et al.,* 2018). Although papaya contains significant nutritional content, particularly rich in vitamins and

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minerals, papaya consumption remains comparatively low compared to other high-valued fruits attributed to several factors including limited awareness of its diverse uses and health benefits (Daagema *et al.*, 2020).

Despite its national and international market potential, it has not emerged as a major traded fruit due to its highly perishable nature (Altendorf, 2017). Papayas are highly susceptible to postharvest losses, including mechanical damage, rapid flesh softening, decay, physiological disorders, pest infestation, especially if subjected to inadequate temperature management (Singh *et al.*, 2024). In addition, papaya fruit is classified as climacteric which exhibits an increase in respiration and ethylene production during ripening (Fabi and do Prado, 2019). Excessive ethylene action can shorten the postharvest period of fruits, potentially reducing their shelf life. Ethylene is a plant hormone that regulates several plant growth and developmental processes, including seed germination, flower and leaf senescence, and responses to biotic or abiotic stresses, as well as fruit ripening (Iqbal *et al.*, 2017).

Physiologically, papaya is a highly perishable fruit which manifests rapid softening and susceptibility to physical and mechanical diseases especially after harvest and when exposed to ethylene stress (Zerpa-Catanho *et al.*, 2017; Loh *et al.*, 2024). The shelf-life of papaya is typically between 7 to 9 days after harvest, necessitating effective storage practices to prevent postharvest quality deterioration (Dari, 2017). Typically, a tropical fruit, including papaya, ripens rapidly at room temperature which consequently manifests softening and color changes (Rahman, 2020).

Henceforth, postharvest treatments are used to minimize the loss of fresh papayas as well as to maintain quality, and increase the shelf life (Dari, 2017). These strategies include chemical, physical and gaseous treatments. Among the gaseous treatments accepted for fresh produce is 1-MCP or 1-methylcyclopropene (Paul and Pandey, 2017). 1-MCP is a novel compound used as an effective postharvest technology widely utilized in maintaining postharvest quality of horticultural commodities like fruits and vegetables. The action of 1-MCP gas is mediated through the inhibition of an ethylene-induced respiration process by interacting with the receptor and competing against the ethylene for binding in the receptor sites (Hu *et al.*, 2017; Satekge and Magwaza 2022). In papaya, application of 1-MCP delays ethylene production rate and retains green color of the peel during storage, thereby maintaining quality and appearance as if they were harvested freshly (Trevisan *et al.*, 2013). On the other hand, 1-MCP varies its effect on fruits depending on whether it is applied in aqueous immersion or gaseous form, influencing its interaction with the fruit to regulate ethylene sensitivity and extend shelf life while maintaining postharvest quality (Escribano *et al.*, 2017; Pongprasert and Srilaong, 2014). Commercial 1-MCP is typically in powder form, where 1-MCP gas is released through its aqueous dissolution in a sealed container or chamber where fruits are placed (Manigo and Limbaga, 2019).

On some fruits such as pear (Escribano *et al.*, 2017), and banana (Pongprasert and Srilaong, 2014), immersion in aqueous 1-MCP solution consistently demonstrated greater effectiveness in delaying ripening compared to gaseous 1-MCP. A concentration of 300 ng kg-1 of 1-MCP applied for either 30 or 60 seconds effectively inhibited softening and slowed skin color change of papaya for a period lasting up to 12 days (Báez-Sañudo *et al.*, 2017). The application of 1-MCP in aqueous form is more convenient, requiring no sealed room or chamber for application (Escribano *et al.*, 2017). However, the limited information regarding the effect of aqueous 1-MCP on fruit postharvest quality and the absence of comparative studies between application methods hinder its widespread adoption in the fruit industry (Satekge and Magwaza, 2022).

Several researchers reported another effective postharvest treatment, a non-chemical approach called the Hot Water Treatment or HWT (Ndlela *et al.,* 2021). Hot water treatment has been proven as a promising method of preserving postharvest quality of fruits such as mitigating the peel and pulp chilling injury (CI) in papaya cv. 'Frangi' (Shadmani *et al.*, 2015), and inhibition of anthracnose and stem-end rot incidence when applied to *Carica papaya* cv. 'Sunrise' (Li *et al.*, 2013). In the hot water treatment study by Benjamin *et al.* (2018), 'Solo' papaya dipped at 49°C for about 90 minutes, followed by storage at 15°C, showed lower weight loss, retained fruit hardness, improved organoleptic attributes, and extended shelf life up to 20 days.

1-MCP and HWT treatments have been scientifically demonstrated to extend the shelf life of fruits, including papaya. However, their individual applications sometimes face limitations, as their efficacy may occasionally be lower compared to chemical fungicide treatments. Generally, in developing a postharvest protocol, attaining such high levels of decay control is difficult with a single biological or physical control method, and the use of an integrated rather than a single approach is advocated (Kitinoja, 2011). The combined use of 1-MCP and HWT had been studied by Ngamchuachit *et al.* (2014) in mango, a climacteric fruit similar to papaya. They identified the optimal 1-MCP treatment to slow ripening of whole 'Keitt' mangos, either alone or in combination with HWT prior to or post 1-MCP treatment. On the other hand, storage temperature for 'Karaj' persimmon was observed together with HWT and 1-MCP treatments on its postharvest quality. The results showed that at 1°C storage, the firmness of control fruits reduced, and their coloration retarded. The existence of these symptoms in persimmon, which are chilling symptoms, showed that 'Karaj' persimmon is sensitive to chilling, but using treatments of 1-MCP and to some extent hot water at 50°C for 15 minutes effectively reduced these symptoms and maintained fruit quality (Rasouli and Khademi, 2017).

Given the inherent high perishability of papaya and its sensitivity to both exogenous and endogenous ethylene production during fruit ripening, along with exposure to various abiotic and biotic stresses, there is a pressing need for effective strategies to extend the shelf life of this fruit and mitigate ethylene-related issues. Hence, this study was undertaken to address postharvest losses of papaya by employing 1-MCP and HWT applications, with the objective of extending its shelf life while simultaneously preserving the postharvest quality attributes of 'Solo' papaya.

Materials and methods

The study was conducted at the Food Technology Laboratory of the University of Southeastern Philippines (USeP), Tagum-Mabini Campus, Apokon, Tagum City, Davao del Norte, Philippines. Analysis of chemical components was done at the Chemistry Laboratory of the campus. 'Solo' papaya variety was used to evaluate the effects of HWT and 1-MCP application. The study was carried out in a Completely Randomized Design (CRD) with three replications and 25 samples in each replicate. Treatments are as follows: T1=control/no treatment; T2=HWT [at 50°C for 10 mins] +1-MCP Gas Exposure [GE; at 1.50 ppm for 12 hours]; T3=1-MCP GE alone; T4=HWT+1-MCP Aqueous Dipping [AD; at 50 $ng \cdot kg^{-1}$ 1-MCP for 30 seconds]; T5=1-MCP AD alone; and T6=HWT alone.

Matured fruits of 'Solo' papaya variety used in the experiments were harvested from the papaya farm in Sitio Lumogon Pangian, Calinan, Davao City, Philippines. The harvested fruits were transported to the experimental site. Papaya fruits were harvested at peel color index 2 or breaker stage showing a slight overall loss of green color with some signs of yellow color. Uniformity in shape and size, and fruits without deformity and any sign of disease were also considered. Right after selection, fruits were brought to USeP Laboratory, washed with tap water, and immediately placed on a clean table and allowed to dry at room temperature.

Fruit treatment

HWT was done by dipping the fruit in hot water, following the protocol of USeP Tagum-Mabini Campus Hot water facility. Papaya fruits were placed in an automatic control table sorter for sorting to ensure uniformity of the size and shape. Sorted fruits were washed and were placed in stacking crates. The stacking crates containing the papaya fruits were dipped in hot water at 50 °C for 10 minutes. After dipping, the fruits were dried through forced convection air drying. Dried fruits were brought to the laboratory for storage or further treatment.

For fruits treated with 1-MCP through as exposure, papaya fruits were placed in an airtight chamber following the 1-MCP gas exposure method as utilized by Manigo and Limbaga (2019) The formulation of the product (powder) contains 0.43% 1-MCP (active ingredient: 2 g/kg $^{-1}$, Panpan brand, Rohm and Hass, China). For 1-MCP aqueous dipping method, fruit were dipped in 50 ng·kg-1 of 1-MCP solution for 30 seconds following the method of Báez-Sañudo *et al.* (2017). Papaya fruits were dried for 30 min at room temperature then stored or further treated. For treatments combined with other applications, HWT was done prior to 1-MCP gas exposure or aqueous dipping, prior to storage for data gathering.

Data gathered

The fruits were observed from the day they treated until day 15 with a 3 days interval from day 0. For ripening changes, peel color index (PCI) was assessed through visual evaluation using the standard scale utilized by Blas *et al.* (2010). PCI 1 denotes mature green (all green peel color); 2 means the fruit has slight loss of green with signs of yellow color; 3 signifies 30% ripe (green yellow stage, more yellow than green); 4 indicates 80% ripe (yellow with green tips); and 5 represents 100% ripe (all yellow). For sensory firmness, the hardness of unpeeled papaya fruit samples was obtained quantitatively using a portable fruit hardness tester with 5-mm diameter flat-tipped cylindrical probe (GY-3 model). Penetrometer plunger was pressed perpendicular against the sample enough only to sink the whole pointed part of the plunger in order to get its firmness and in terms of resistance to deformation. The fruits were punctured at 3 points in the middle portion cheeks of papaya fruit and the data were converted in Newton (N). The total soluble solids (TSS), total titratable acidity (TTA) and pH of all fruit samples at PCI 4 were measured. The TSS was determined using a hand-held refractometer with a range of 0 to 30° Brix and resolutions of 0.2. The brix reading was used to determine TSS by placing 1 to 2 drops of the filtered papaya juice on the prism of the refractometer in each sample reading. TTA was determined by titrimetric method with 0.1N sodium hydroxide in the presence of phenolphthalein indicator which changed pink and then the titrate volume of NaOH was recorded. The pH value was measured using a digital pH meter. On the other hand, the sensory attributes such as pulp color, taste, aroma, texture and overall acceptability at PCI 4 was measured using a 9-point hedonic scale as utilized by Mishra *et al.* in 2015 [like extremely (9), like very much (8), like moderately (7), like slightly (6), neither like or dislike (5), dislike slightly (4), dislike moderately (3), dislike very much (2), and dislike extremely (1)]. Fruit samples were cubed and were assessed by a panel of 25 evaluators.

The visual quality rating (VQR) of fruit was assessed following the rating scale used by Gunathilake *et al.* in 2018 with slight modification [excellent, field fresh (9, 8); good, defects minor (7, 6); fair, defects moderate (5, 4); poor, defects serious, Limit saleability (3, 2); and non-edible under usual condition (1)]. For weight loss (%) was determined by dividing weight difference to initial weight from initial weight of papaya sample at regular 3 days' intervals using a digital weighing scale. The equation was used to calculate is: Weigh loss = [(weight difference to initial weight)/(initial weight of the sample or weight at day 0)] x 100. For the degree of shriveling of papaya samples, a 1–4 index used by Abeywickrama *et al.* (2012) as no shriveling (1), slight shriveling (2), moderate shriveling (3), and severe shriveling (4)]. Postharvest disease (Anthracnose) was measured using the disease severity scale formulated by Kahawattage *et al.,* (2023) as 0-5% fruit surface showing symptoms (0), 6-10% fruit surface showing symptoms (1), 11-25% fruit surface showing symptoms (2), 26-50% of fruit surface show symptoms (3), and more than 50% of fruit surface shows symptoms (4). The disease incidence was determined in terms of percent disease incidence and abundance following the equation used by Hamim *et al.* (2014): % Disease incidence= (number of diseased fruits affected by particular disease)/(total number of fruits) x 100. The data were analysed using the Analysis of Variance (ANOVA) appropriate for Completely Randomized Design (CRD). The significant difference among treatment means was further analysed using Tukey's Honest Significant Difference (HSD) Test at 5% and 1% levels of significance.

Results

The quality attributes of 'Solo' papaya treated with 1-MCP and HWT are illustrated in Figure 1. Fruits were stored at ambient room temperature, and data were collected over a 15-day period with 3-day intervals. By day 6, significant differences in fruit physical characteristics specially on color were observed as shown in Figure 2. Fruits treated with 1-MCP alone through gas exposure, as well as those treated with the combination of 1-MCP and HWT, exhibited a notably stronger retention of their green peel color compared to other treatments. The combined treatment of 1-MCP via gas exposure (GE) and HWT (T2) delayed color change starting from day 3 up to day 15 of storage, outperforming the individual treatments. Papayas treated with 1-MCP (GE) or aqueous dipping

(AD) alone, as well as HWT alone, showed faster peel yellowing compared to the combined treatment. The gas exposure method of 1-MCP was more effective than aqueous dipping in slowing down peel yellowing. This suggests that the combination of HWT and 1-MCP (GE) significantly prolongs the shelf life of papaya by delaying color change. Similarly, the combined application of 1-MCP and HWT consistently delayed the softening of papayas throughout storage. Fruits treated with HWT alone (T6) or untreated fruits (T1) exhibited earlier and faster softening. The synergistic effect of HWT and 1-MCP was essential in maintaining fruit firmness over time.

In terms of weight loss, the combination of 1-MCP (GE) and HWT (T2) effectively delayed weight loss, while untreated fruits (T1) incurred the highest weight loss. Neither 1-MCP nor HWT alone was as effective in preventing weight loss as their combined application. Additionally, the combined treatment (T2) effectively inhibited shriveling from day 6 to day 15, while untreated fruits (T1) showed the highest degree of shriveling, highlighting the limitations of using 1-MCP or HWT individually. The visual quality rating (VQR) of papayas was also significantly enhanced by the combined treatment of 1-MCP and HWT. Fruits treated with HWT and 1-MCP gas exposure (T2) consistently achieved better VQR on days 3, 6, 12, and 15. In contrast, untreated fruits (T1) displayed the lowest ratings throughout storage. The combination of HWT and 1-MCP gas exposure was more effective than using HWT with spray methods in maintaining the visual appeal of the fruits.

The total soluble solids (TSS), titratable acidity (TTA), and pH were measured to assess fruit quality. Statistical analysis revealed significant differences in TSS among treatments, with untreated fruits (T1) exhibiting the highest TSS, followed by HWT-treated fruits (T6). This may be attributed to the faster ripening of untreated fruits. However, no significant differences were observed for TTA and pH among the treatments. Moreover, sensory evaluation also showed significant differences across treatments for organoleptic attributes such as pulp color, taste, aroma, texture, and overall acceptability. Untreated fruits (T1) had the highest scores for these attributes, correlating with their advanced ripeness and higher TSS. Fruits treated with 1-MCP gas exposure (T3) scored the lowest for color and overall acceptability, while HWT combined with 1-MCP spray (T4) received the lowest ratings for taste and aroma. The combination of HWT and 1-MCP (T2) showed trade-offs, with lower texture scores compared to untreated fruits.

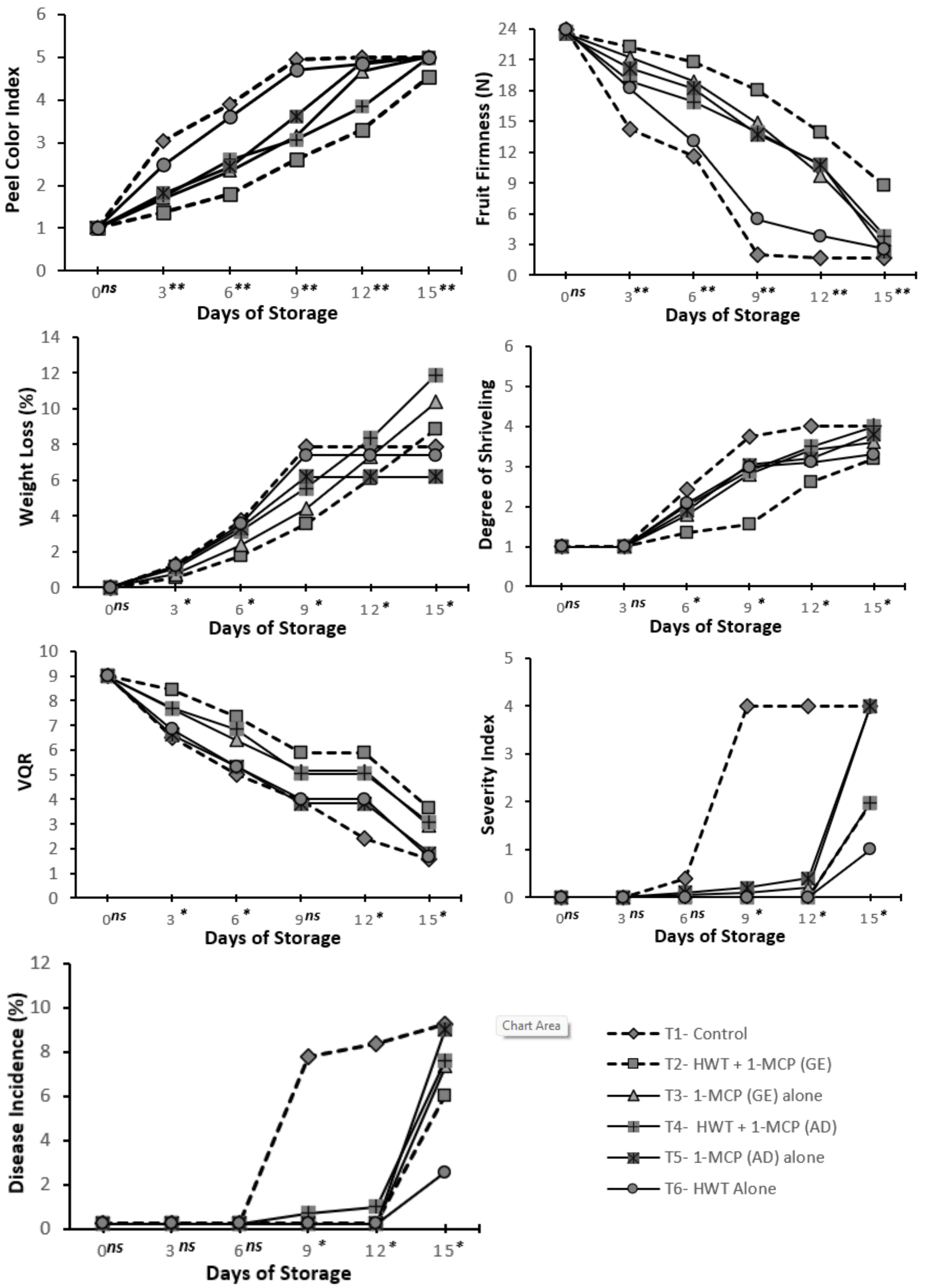

Figure 1. Postharvest quality of 'Solo' papaya is influenced by 1-MCP and HWT
Note: * means significant at 5% level of significance ($p \leq 0.05$) while ** denotes highly significant at 1% level ($p \leq 0.01$).

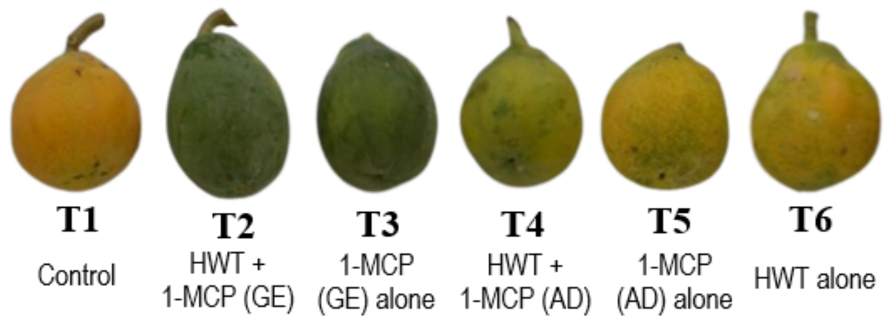

Figure 2. Appearance of 'Solo' papaya at Day 6 of storage as influenced by 1-MCP and HWT

Table 1. Changes on the Chemical and Sensory Properties of 'Solo' Papaya at PCI 4 as influenced by 1-MCP and HWT applied singly and in combination

Treatments	**Chemical Properties**			**Organoleptic Attributes**				
	TSS **	TTA ns	pH ns	Pulp Color **	Taste **	Aroma **	Texture **	Overall Acc. **
T1: Control	8.13 a	0.84	6.87	7.74 a	8.62 a	9.08 a	7.50 a	8.18 a
T2: HWT + 1-MCP (GE)	7.15 d	0.72	6.83	6.64 abc	6.40 c	7.90 bc	4.50 d	7.08 ab
T3: 1-MCP (GE) alone	7.45 c	0.82	6.77	6.34 c	6.50 c	8.10 bc	4.90 d	6.78 a
T4: HWT + 1-MCP (AD)	7.20 d	0.72	6.97	6.56 bc	5.30 d	7.50 c	6.14 c	6.98 ab
T5: 1-MCP (AD) alone	7.33 c	0.73	6.9	6.54 c	6.30 c	8.50 ab	6.40 bc	6.98 ab
T6: HWT alone	7.93 b	0.77	7.07	7.72 ab	7.50 b	8.50 ab	7.10 ab	8.14 a
CV (%)	0.54	6.93	1.93	5.78	4.23	3.84	4.47	5.60

Note: Means with the same letter do not differ significantly at 0.05 level using HSD; **ns** denotes not significant; * denotes significant; ** denotes highly significant.

Anthracnose disease was also monitored to assess its impact on the quality of papaya fruit. Disease severity reflected the extent of damage, while disease incidence indicated the frequency of affected fruits. As shown in Figure 2, untreated fruits (T1) had the highest disease incidence on days 9, 12, and 15. In contrast, fruits treated with HWT alone (T6) exhibited the lowest disease incidence during these periods. The combination of 1-MCP and HWT also helped to reduce the disease incidence, though HWT alone was particularly effective in controlling anthracnose.

Discussion

The postharvest quality of papaya is crucial for maintaining its market value, and various treatments have been explored to enhance this quality. In this study, the effects of 1-MCP and HWT on these quality attributes were investigated, providing valuable insights into optimizing postharvest handling for better marketability. The peel color of papayas is a critical indicator of ripeness and quality, and strongly influences consumer purchase decisions (Prasad *et al.*, 2018). The findings of this study demonstrated that 1-MCP-treated fruits retained their green color longer compared to control or untreated fruits, which exhibited rapid degreening due to ethylene activity. This finding aligns with previous research showing that chlorophyll degradation is mediated by ethylene and associated enzymatic activities (Wang *et al.*, 2015; Charoenchongsuk *et al.*, 2015). 1-MCP molecules bind to ethylene receptors in the fruit, thereby inhibiting ripening-related changes, including alterations in peel color (Ohashi *et al.*, 2016; Hu *et al.*, 2017; Satekge and Magwaza, 2022). Furthermore, HWT enhanced both the skin and pulp color of the fruits, contributing to extended shelf life. Specifically, heat treatment at 49°C for 90 minutes also improved the skin and pulp color of papaya, prolonging its shelf life to 20 days (Benjamin *et al.*, 2018).

Firmness is another critical quality parameter, and in this study, untreated papaya fruits stored at ambient temperatures exhibited a gradual decline in firmness, reaching unacceptable levels (≤20 N) by the third day. In contrast, 1-MCP-treated fruits retained superior firmness throughout ripening, indicating that this treatment effectively reduces the activity of pectinolytic enzymes due to diminished ethylene exposure (Ohashi *et al.*, 2016), thereby prolonging the desirable textural characteristics of the fruit. The solubility of pectin and the depolymerization of matrix polysaccharides are essential factors contributing to fruit softening (Wang *et al.*, 2018). However, it is important to note that while 1-MCP can delay softening, typical ripening-related changes may still occur, potentially affecting overall quality. Although 1-MCP treatments successfully postpone softening, Ohashi *et al.* (2016) observed that ethylene competition inhibited the usual softening processes in papayas, leading to undesired firmness despite noticeable changes in peel and flesh color and other signs of deterioration. Additionally, Ngamchuachit *et al.* (2014) investigated the effects of combining 1-MCP and HWT on mangoes, revealing that heat treatments could accelerate fruit softening. This study illustrates that while 1-MCP is effective in delaying softening by inhibiting ethylene action, HWT may counteract this effect, potentially hasten the ripening and softening of papaya fruits. Therefore, the interaction between 1-MCP and HWT treatments on fruit softening requires careful consideration to optimize papaya postharvest strategies.

Moreover, weight loss, a significant determinant of postharvest quality, is primarily driven by transpiration and respiration. In this study, both 1-MCP and HWT treatments effectively minimized weight loss in papayas, correlating with enhanced shelf life. Research supports the notion that these treatments not only reduce weight loss but also preserve overall quality, as excessive weight loss can lead to market rejection. Zhang *et al.* (2020) demonstrate that 1-MCP effectively reduces water loss in tropical fruits by inhibiting ethylene perception, which slows the ripening process and decreases transpiration rates. This inhibition helps maintain the fruit's moisture content and overall quality during storage, thereby minimizing weight loss. Wu *et al.* (2023) further corroborate these findings, showing that 1-MCP enhances cuticle wax biosynthesis, thereby strengthening the fruit's natural barrier to moisture loss and improving postharvest quality retention. Moreover, treatments with 1-MCP have been shown to effectively reduce weight loss in other fruits including bananas (Saeed and Abu -Gouk, 2013). Kaka *et al.* (2018) confirmed moreover, that a 50 °C HWT for 10 minutes results in the lowest weight loss values observed.

Shriveling, often resulting from water loss and transpiration, negatively impacts the quality and marketability of fresh produce. Results show that 1-MCP treatment effectively reduces shriveling, especially when compared to untreated fruits. Bayogan *et al.* (2018) reported that 1-MCP mitigates shriveling by minimizing weight loss, a key factor linked to shriveling in pummelo fruits. Under low relative humidity, fruits with higher weight loss exhibit more shriveling (Majomot *et al.,* 2019). Additionally, HWT was found to preserve cell integrity and reduce shriveling. Yimyong *et al.* (2011) noted that untreated fruits showed significant wrinkling at room temperature, while HWT-treated fruits displayed less shriveling due to enhanced cell stability and increased heat shock protein levels, which protect against protein breakdown (Majomot *et al.*, 2019).

Consumer perception of fruit defects is crucial, as visual quality directly affects purchasing behavior (Jaeger *et al.*, 2016). Previous report suggests that visual quality was significantly higher in 1-MCP-treated fruits, which maintained good visual ratings for up to ten days (Trivedi, 2012). This extended period of marketable quality is vital, especially considering the significant food waste associated with rapid deterioration of fresh produce. Consumers are more likely to purchase fruits that meet high visual standards, emphasizing the importance of effective postharvest treatments. Kiran *et al.* (2024) further proved that HWT at 50°C for 40 minutes effectively preserves the visual quality of export Alphonso mangoes by reducing weight loss, maintaining firmness, and retaining the saffron-like yellow color during storage, making it a suitable chemical-free postharvest quarantine treatment.

Chemical attributes such as total soluble solids (TSS), titratable acidity (TTA), and pH are critical for determining the taste and overall acceptability of fruits. In this study, TSS levels increased over time in both treatments, enhancing the sweetness and flavor profile of the papayas. Previous research by Ohashi *et al.* (2016) indicated that while 1-MCP inhibited ethylene perception, it did not hinder sugar accumulation during ripening. Additionally, Zhang *et al.* (2012) found that 1-MCP-treated jujube fruits exhibited higher TSS due to reduced respiration rates, though the results can vary depending on the fruit and storage conditions. Notably, TTA remained consistent across treatments, suggesting that while sweetness was enhanced, acidity levels did not change significantly, which is essential for consumer satisfaction. Sensory attributes, including taste, texture, and aroma, are crucial in influencing consumer preferences. Although 1-MCP did not demonstrate a pronounced effect on taste, it preserved sensory attributes over time, ensuring the fruits remained appealing to consumers. Furthermore, the treatments helped mitigate negative impacts on organoleptic properties, although caution is necessary with HWT, as excessive heat could adversely affect taste. Martins *et al.* (2010) reported that different temperatures did not significantly affect quality parameters like TSS and TTA, while Chávez-Sánchez *et al.* (2013) observed no detrimental effects on biochemical attributes from HWT. TTA remained stable across treatments, with 1-MCP showing no significant effect on papaya acidity (Bron *et al.,* 2006), which may be influenced by the naturally low acidity of papaya. Moreover, HWT was noted to decrease acidity over time; Benjamin *et al.* (2018) confirmed that heat treatments did not influence pH.

Anthracnose disease poses a substantial challenge in the postharvest handling of papayas. It was reported by Laurel *et al.* (2021) that the causal organisms of papaya anthracnose in the Philippines, as confirmed by morphological assessment and phylogenetic analysis, are *Colletotrichum brevisporum* and *Colletotrichum truncatum.* Studies revealed that HWT, when applied shortly after harvest, significantly mitigates disease severity, particularly anthracnose, which is a primary postharvest concern for papayas (Abeywickrama *et al.,* 2012). The results of this present study demonstrate that untreated fruits exhibited high disease severity over time, while HWT effectively reduced the incidence and severity of anthracnose, highlighting its role in postharvest disease management. Furthermore, while 1-MCP effectively delayed ripening processes by inhibiting ethylene action (Ohashi *et al.,* 2016; Hu *et al.,* 2017), it did not significantly reduce disease incidence in our study, contrasting with findings that report its efficacy in prolonging shelf life for other fruits. Persimmons treated with 1-MCP exhibited a lower fruit decay rate while showing increased levels of lignin and total phenolics, along with enhanced activities of key enzymes such as PAL, PPO, POD, CHI, and GLU, contributing to improved fruit defense and quality (Zeng *et al.* 2021). The lack of significant effect from 1-MCP on disease severity in papayas may be attributed to the specific nature of anthracnose, which can infect fruit during growth and remain dormant (Xueping *et al.,* 2013). HWT, at a temperature of 50°C for 10 minutes, has been shown to effectively delay the development of anthracnose without compromising fruit integrity, as confirmed by previous studies (Mirshekari *et al.,* 2012).

The combined application of HWT at 50 °C for 10 minutes and 1-MCP gas exposure proved to be an effective strategy for prolonging the shelf life and maintaining the postharvest quality of 'Solo' papaya. This integrated approach delayed ripening, minimized weight loss, reduced shriveling, and preserved firmness and visual appeal. While HWT showed efficacy in suppressing anthracnose, 1-MCP was more effective in regulating ethylene-driven changes. However, neither treatment alone nor in combination completely prevented disease incidence, suggesting that additional interventions may be needed. These findings support the potential of integrated, non-chemical postharvest strategies for tropical fruit preservation.

Conflicts of interest

The authors affirm that there are no financial, academic, or personal conflicts of interest that could have affected the research or its publication.

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