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RESEARCH ARTICLE

Evaluating the potential of 1-MCP card technology for extending shelf life and maintaining quality of tomato during ambient storage

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ABSTRACT

Tomato (*Solanum lycopersicum* L.) is a highly perishable climacteric fruit with a short shelf life under ambient conditions, leading to substantial qualitative and quantitative postharvest losses along the supply chain. The present study evaluated the effectiveness of 1-methylcyclopropene (1-MCP) card technology in extending shelf life and maintaining postharvest quality of tomato fruit during ambient storage. Freshly harvested tomatoes at the turning stage were treated with a 1-MCP card, while untreated fruits served as the control. The experiment was conducted using a completely randomized design with two treatments and three replications, with 1 kg of fruit per replication. Fruits were stored under ambient conditions and evaluated at 3-day intervals over an 18-day storage period. The application of the 1-MCP card significantly delayed ripening and senescence processes, resulting in reduced physiological weight loss, lower ethylene production and respiration rates, and improved retention of fruit firmness compared with control fruits. Treated tomatoes exhibited superior visual quality, higher marketability, reduced disease incidence, and better sensory attributes throughout storage. In addition, 1-MCP card treatment effectively preserved biochemical and nutritional quality, including higher retention of total soluble solids, titratable acidity, ascorbic acid, phenolic compounds, carotenoids, and antioxidant activity. Enhanced activities of antioxidant enzymes (superoxide dismutase, catalase, and peroxidase) and reduced browning-related enzymatic activity were also observed in treated fruits. Overall, the results demonstrate that 1-MCP card technology is an effective and practical postharvest tool for extending shelf life and maintaining the quality of tomato fruit under ambient storage conditions, particularly in regions with limited cold-chain infrastructure.

Key words: Postharvest physiology, ethylene inhibition, climacteric fruit, shelf-life extension, ambient storage, fruit ripening, respiration rate, ethylene production.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.), a member of the Solanaceae family, is one of the most widely cultivated and consumed vegetable crops worldwide. Originating from the western coastal plains of South America, particularly Ecuador and Chile, tomato is extensively utilized in fresh and processed forms, including sauces, salads, pickles, and ketchup (Paul and Pandey, 2013). The crop holds substantial economic importance, contributing significantly to global and regional trade. Pakistan earned approximately 128.4 million USD from fruit and vegetable exports during 2004–05, with tomato being a major contributor to these earnings (Tahir et al., 2012). Globally, tomato export volume increased from 3.6 million metric tons in 2000 to 6.1 million metric tons in 2007 (FAO STAT, 2007). Asia accounts for nearly 62% of global tomato production, followed by the Americas, Europe, and Africa (FAO STAT, 2019).

Beyond its economic value, tomato is recognized for its high nutritional and functional attributes. It is a rich source of vitamins, minerals, phenolic compounds, cardiovascular diseases, cancer, and other chronic disorders (Chen et al., 2001). Despite their nutritional importance, high postharvest losses significantly limit tomato availability, particularly in developing countries, where losses in fruits and vegetables can range from 25 to 40% or even higher (Yoon et al., 2024).

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flavonoids, carotenoids (including lycopene, β-carotene, and xanthophylls), and other bioactive phytochemicals (Giovannucci, 2002). Tomatoes also contain glutathione, an antioxidant known to reduce heavy metal accumulation in the human body, and have been associated with protective effects against

Tomato is a climacteric fruit exhibiting a ripening pattern similar to apple, banana, mango, papaya, pear, and peach (Sun et al., 2015). Elevated temperatures accelerate respiration and ethylene production, leading to rapid ripening and quality deterioration (Lakshan et al., 2024). Under typical storage conditions, tomatoes have a relatively short shelf life of 2–3 weeks at 12 °C and 68% relative humidity. Ripening is a complex physiological process involving metabolic changes such as pigment biosynthesis, volatile compound formation, and cell wall softening. Since tomatoes exhibit high respiration rates after harvest, slowing physiological and biochemical processes remains a key strategy for extending shelf life (Alexander and Grierson, 2002).

Ethylene plays a central regulatory role in tomato ripening by activating ethylene receptor sites that trigger gene expression associated with maturation and senescence (Hoeberichts et al., 2002). Additionally, tomato fruits are highly susceptible to postharvest fungal diseases, particularly *Botrytis cinerea* and *Alternaria alternata*, which cause gray mold and black mold, respectively (Su and Gubler, 2012). Although synthetic fungicides are commonly used to control postharvest diseases, increasing concerns regarding pathogen resistance, environmental impact, and human health have intensified the search for safer alternatives. Several postharvest technologies, including controlled atmosphere storage, modified atmosphere packaging, hot water treatments, edible coatings, and ethylene inhibition strategies, have been explored to reduce losses and extend tomato shelf life (Zapata et al., 2008; Loayza et al., 2010; López-Valenzuela et al., 2011; Fagundes et al., 2015; Taye et al., 2019).

Among ethylene inhibitors, 1-methylcyclopropene (1-MCP) has emerged as a highly effective compound due to its strong affinity for ethylene receptors, where it binds approximately ten times more strongly than ethylene itself (Taye et al., 2019). By blocking ethylene perception, 1-MCP delays ripening-related processes such as softening, color development, respiration, and ethylene production. However, early commercial adoption of 1-MCP was limited by variability in fruit response, which is influenced by factors such as concentration, exposure duration, maturity stage, and temperature (Paul et al., 2010; Serek et al., 1994). Previous studies have reported variable efficacy of gaseous and aqueous 1-MCP applications in tomato, with concentrations ranging from 0.03 to 100 µL L^{-1} and differing exposure times (Opiyo and Ying, 2005). Alternative formulations, such as AFxRd-300, have demonstrated promising results under conditions where airtight treatment facilities are unavailable (Choi and Huber, 2008).

In this context, the present study aimed to evaluate the effectiveness of a novel 1-MCP card technology in extending the shelf life and maintaining the quality of tomato fruits under ambient storage conditions. The overarching goal of this work was to reduce postharvest losses and contribute to more sustainable fresh produce supply chains.

MATERIALS AND METHODS

Plant Material and Experimental Design

Tomato fruits (*Solanum lycopersicum* L.) cv. Sahil were harvested at the breaker stage from a hydroponic production system at Muhammad Nawaz Sharif University of Agriculture, Multan, Pakistan. Immediately after harvest, fruits were transported to the postharvest laboratory, washed with tap water, air-dried for 30 min under ambient conditions, and sorted to ensure uniformity in size and color and freedom from visible defects, mechanical injury, or disease symptoms.

The experiment was conducted using a completely randomized design (CRD) with two treatments: T_1 (Control): fruits wrapped in Guddhi paper without a 1-MCP card, and T_2 (1-MCP card): fruits packed with a 1-MCP card and wrapped in Guddhi paper.

Each treatment consisted of three replications, with 1 kg of fruit per replication. Fruits were stored under ambient conditions (25 ± 2 °C and 65–70% relative humidity) for 18 days, and analyses were conducted at 3-day intervals (0, 3, 6, 9, 12, 15, and 18 days).

Description of 1-MCP Card Treatment

The 1-methylcyclopropene (1-MCP) card is a solid-phase ethylene inhibitor designed to release 1-MCP gradually within sealed packaging environments. For the treated samples, one 1-MCP card was placed inside each fruit package before sealing with Guddhi paper, allowing continuous exposure of fruits to 1-MCP throughout storage. Control fruits were packed in the same manner but without the card. This packaging-based approach was selected to simulate practical commercial handling conditions where airtight treatment chambers are not available.

Physical Quality Attributes

Physiological weight loss (%) was determined using a digital balance and expressed as the percentage reduction in fruit weight relative to the initial weight, following the method described by Ali et al. (2016). Fruit firmness was measured at two equatorial positions per fruit using a penetrometer and expressed in Newtons (N) (Razzaq et al., 2014). Fruit peel color parameters (L*, a*, and b*) were recorded using a colorimeter at three equidistant points on the fruit surface. Visual quality was assessed by a trained panel of five judges using a 1–9 hedonic scale, where 1 indicated poor and inedible fruit and 9 indicated excellent and fresh appearance (Nasef, 2018). The marketability index (%) was calculated based

on the percentage of fruits free from visible blemishes, decay, shriveling, or other quality defects (Hasan et al., 2020). Disease incidence was visually evaluated using a 1–5 rating scale, as described by Amin et al. (2007), where higher scores indicated greater disease severity.

Physiological Measurements

Ethylene production was measured by placing one fruit from each replication into an airtight container for 1 h at ambient temperature. Ethylene concentration was determined using an ethylene analyzer (ICA-56, International Controlled Atmosphere Ltd., UK) and expressed as μmol C_2H_4 kg^{-1} h^{-1} (Razzaq et al., 2015).

Respiration rate was determined as CO_2 production using a CO_2 analyzer (Vaisala MI-70, Vaisala Inc., Finland) and expressed as mmol CO_2 kg^{-1} h^{-1} (Razzaq et al., 2015).

Sensory Evaluation

Sensory attributes including color, taste, texture, flavor, and overall acceptability were evaluated using a 1–9 hedonic scale by a panel of five trained judges, following the method of Peryam and Pilgrim (1957). Mean sensory scores were calculated for each treatment at each sampling interval.

Biochemical Analyses

Total soluble solids (TSS) were measured using a hand refractometer and expressed as °Brix (Bhatt et al., 2001).

Titratable acidity (TA) was determined by titration with 0.1 N NaOH and expressed as percentage citric acid, following the procedure described by Sadler and Murphy (2010).

Ascorbic acid content was determined using the AOAC (2000) method and expressed as mg 100 g^{-1} fresh weight.

Phytochemical and Antioxidant Analyses

Total phenolic content was determined from tomato peel and pulp extracts using the Folin–Ciocalteu method and expressed as mg gallic acid equivalents per 100 g fresh weight (Ainsworth and Gillespie, 2007). Antioxidant activity was assessed using the DPPH radical scavenging assay and expressed as percentage inhibition (Ali et al., 2016). Anthocyanin content was determined spectrophotometrically and expressed as absorbance change per gram fresh weight. Total carotenoid content was estimated according to the method described by Nagata and Yamashita (1992).

Antioxidant Enzyme Assays

Enzyme extracts were prepared from tomato peel and pulp tissues using phosphate buffer (pH 7.0–7.8). Activities of superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and polyphenol oxidase (PPO) were determined spectrophotometrically following standard protocols, and enzyme activities were expressed on a fresh weight basis.

Statistical Analysis

All data were subjected to analysis of variance (ANOVA) using a completely randomized design. Treatment means were compared at $P \leq 0.05$, and results are presented as means ± standard error (SE).

RESULTS AND DISCUSSION

Effect of 1-MCP card on fruit color development

Fruit color is a critical quality attribute influencing consumer acceptance and marketability of tomato fruit. Significant effects ($P \leq 0.05$) of storage duration, treatment, and their interaction were observed on color attributes (L*, a*, and b*) throughout ambient storage. Regardless of treatment, progressive color changes were observed from the turning stage to full ripening; however, these changes were markedly delayed in fruits treated with the 1-MCP card. The lightness value (L*) declined gradually during storage in both treatments, indicating ripening-associated darkening of fruit surface. Nevertheless, 1-MCP–treated fruits retained significantly higher L* values compared to control fruits, particularly during the early and mid-storage periods (Fig. 1a). Similarly, the a* value, representing redness development, increased with storage time; however, the increase was substantially inhibited in 1-MCP–treated fruits, demonstrating delayed lycopene accumulation and color development (Fig. 1b). The b* value also declined progressively, with treated fruits showing significantly slower changes compared to control fruits (Fig. 1c). The delayed color development observed in 1-MCP–treated fruits can be attributed to inhibition of ethylene perception, which suppresses ethylene-mediated activation of carotenoid biosynthesis pathways. Similar inhibitory effects of 1-MCP on tomato fruit color development have been reported previously (Opiyo and Ying, 2005). These findings confirm that 1-MCP card technology effectively delays ripening-related color changes under ambient storage conditions.

Effect of 1-MCP card on fruit firmness and weight loss

Fruit firmness and physiological weight loss are key indicators of postharvest quality deterioration. Both parameters were significantly influenced ($P \leq 0.05$) by storage duration, treatment, and their interaction during ambient storage. Fruit firmness decreased progressively in both treatments as storage advanced; however, 1-MCP–treated fruits retained significantly higher firmness compared to control fruits throughout the storage period (Fig. 2a). Control fruits exhibited rapid softening, particularly during the later stages of storage, whereas firmness loss was markedly reduced in fruits treated with the 1-MCP card. The maintenance of firmness in treated fruits is likely associated with delayed cell wall degradation and reduced ethylene-mediated enzymatic activity responsible for softening. Similarly, fruit weight loss increased linearly with storage time in both treatments; however, 1-MCP–

treated fruits exhibited significantly lower weight loss than control fruits (Fig. 2b). After 18 days of ambient storage, weight loss in treated fruits was approximately 1.27-fold lower than that of control fruits. Reduced weight loss in 1-MCP–treated fruits may be attributed to improved membrane integrity and reduced transpiration and respiration rates, as previously suggested by Guillén et al. (2007). These results demonstrate that application of 1-MCP card technology effectively preserves textural integrity and reduces moisture loss, thereby extending the postharvest life of tomato fruit under ambient conditions.

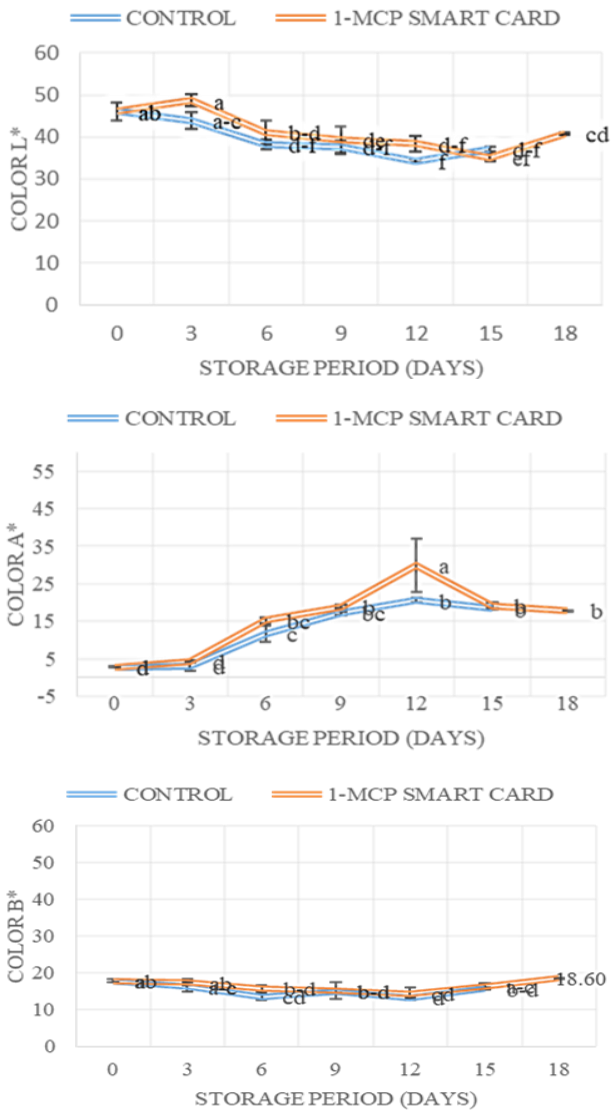

Fig. 1: Effect of postharvest application of 1-MCP card technology on fruit color attributes of tomato during ambient storage: (A) L*, (B) a*, and (C) b*. Values represent means ± standard error (SE) of three replications (n=3).

Effect of 1-MCP card on decay incidence and marketability

Fruit decay incidence increased progressively with storage duration in both treatments; however, 1-MCP card treatment significantly (P≤0.05) reduced decay development compared to control fruits throughout the ambient storage period. Control fruits exhibited higher decay severity, particularly after day 12, whereas treated fruits maintained comparatively lower decay levels (Fig. 3).

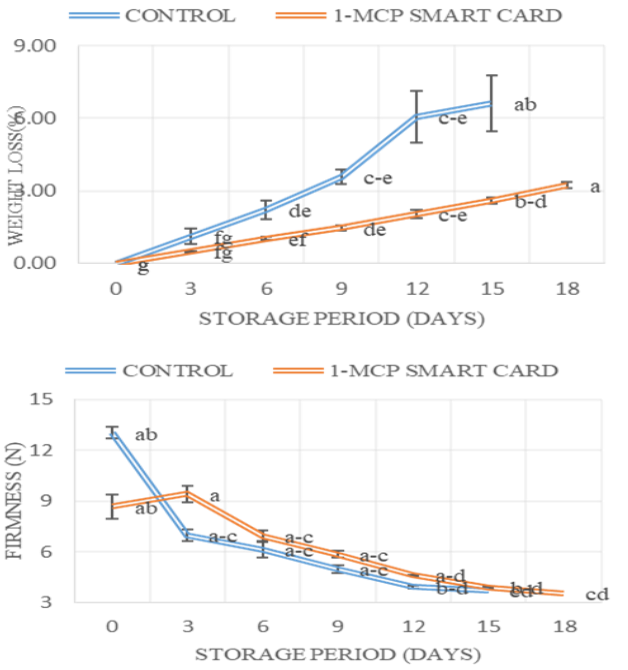

Fig. 2: Effect of postharvest application of 1-MCP card technology on (A) physiological weight loss (%) and (B) fruit firmness (N) of tomato during ambient storage. Values represent means ± standard error (SE) of three replications (n=3).

The reduced decay incidence in 1-MCP–treated fruits may be associated with delayed senescence, reduced ethylene production, and lower respiration rates, which collectively limit tissue breakdown and pathogen colonization. Postharvest decay in tomato fruit is commonly caused by pathogens such as *Alternaria* spp. and *Botrytis cinerea*, which readily infect senescing tissues (Mubarok et al., 2024). The inhibition of ethylene action by 1-MCP likely slowed fruit softening and reduced microcrack formation, thereby limiting pathogen entry and disease progression.

These findings are consistent with previous reports demonstrating reduced decay incidence in 1-MCP–treated tomato fruits under ambient storage conditions (Guillén et al., 2007). Overall, the application of 1-MCP card technology significantly improved fruit marketability by minimizing decay and extending shelf life.

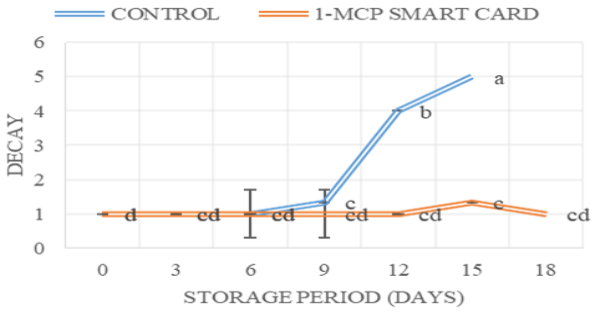

Fig. 3: Effect of postharvest application of 1-MCP card technology on decay incidence of tomato fruit during ambient storage. Values represent means ± standard error (SE) of three replications (n=3).

Effect of 1-MCP card on ethylene production and respiration rate

Ethylene production and respiration rate are central physiological processes regulating ripening and senescence in climacteric fruits such as tomato. In the present study, storage duration, treatment, and their interaction significantly affected (P≤0.05) both ethylene evolution and respiration rate during ambient storage. Ethylene production increased progressively with advancement of storage time in both treatments; however, fruits treated with the 1-MCP card consistently exhibited significantly lower ethylene production compared to control fruits throughout the storage period (Fig. 4a). Control fruits showed a pronounced rise in ethylene evolution at the later stages of storage, coinciding with accelerated ripening, whereas 1-MCP–treated fruits maintained suppressed ethylene levels, indicating effective inhibition of ethylene perception and action.

Similarly, respiration rate increased with storage duration in both treatments; however, control fruits exhibited significantly higher CO_2 production than 1-MCP–treated fruits (Fig. 4b). The application of the 1-MCP card markedly reduced respiration rate, particularly during mid-storage, reflecting delayed metabolic activity and slower progression of ripening. Lower respiration rates in treated fruits suggest reduced substrate utilization and energy turnover, contributing to extended shelf life. The suppression of ethylene production and respiration in 1-MCP treated fruits can be attributed to the strong binding affinity of 1-MCP to ethylene receptors, which blocks ethylene signal transduction and delays activation of ripening-related metabolic pathways. Similar reductions in ethylene evolution and respiration rate following 1-MCP treatment have been reported in tomato and other climacteric fruits (Guillén et al., 2007; Malik et al., 2021). These results confirm that 1-MCP card technology effectively modulates key physiological processes associated with ripening, thereby contributing to improved postharvest quality and extended shelf life under ambient conditions.

Effect of 1-MCP card on sensory quality attributes

Sensory quality attributes, including visual quality, aroma, flavor, and taste, were significantly affected (P≤0.05) by storage duration, treatment, and their interaction during ambient storage. Sensory scores declined progressively in both treatments with increasing storage time; however, fruits treated with the 1-MCP card consistently maintained higher sensory scores compared to control fruits (Fig. 5). Both treated and untreated fruits exhibited minimal sensory changes up to 6 days of storage, after which a rapid decline was observed, particularly in control fruits. The superior sensory quality of 1-MCP–treated tomatoes during mid and late storage stages can be attributed to delayed ethylene-mediated ripening and reduced metabolic activity, resulting in improved retention of freshness, flavor, and overall acceptability. Similar improvements in sensory attributes following 1-MCP application have been reported previously in tomato and other climacteric fruits (Dek et al., 2018).

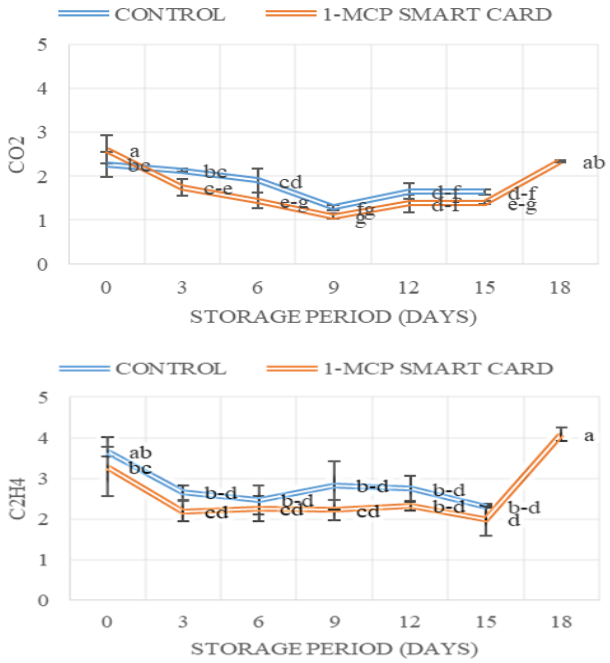

Fig. 4: Effect of postharvest application of 1-MCP card technology on **(A)** respiration rate (CO_2 production) and **(B)** ethylene production of tomato fruit during ambient storage. Values represent means ± standard error (SE) of three replications (n=3).

Effect of 1-MCP card on biochemical quality attributes

Biochemical quality attributes, including total soluble solids (TSS), titratable acidity (TA), SSC:TA ratio, and ascorbic acid content, were significantly influenced (P≤0.05) by storage duration, treatment, and their interaction during ambient storage. Total soluble solids gradually declined in both treatments with increasing storage time; however, fruits treated with the 1-MCP card maintained significantly higher TSS values compared to control fruits, particularly during later stages of storage (Fig. 6A). The slower decline in TSS in treated fruits indicates delayed metabolic conversion of sugars associated with ripening. Similarly, titratable acidity decreased progressively during storage in both treatments, but the reduction was significantly less pronounced in 1-MCP–treated fruits (Fig. 6B), suggesting improved retention of organic acids. As a result of changes in TSS and TA, the SSC:TA ratio increased with storage duration in both treatments, with higher values observed in control fruits due to faster acid degradation (Fig. 6C). In contrast, the moderated increase in SSC:TA ratio in 1-MCP–treated fruits reflects delayed ripening and better flavor balance during storage. Ascorbic acid content declined steadily during ambient storage irrespective of treatment; however, fruits treated with the 1-MCP card exhibited significantly lower losses compared to control fruits (Fig. 6D). The retention of ascorbic acid in treated fruits

may be attributed to reduced oxidative degradation and delayed senescence. Similar trends in biochemical quality preservation following 1-MCP application have been reported in tomato and other climacteric fruits (Sabir et al., 2012; Mir et al., 2004). Overall, these results demonstrate that 1-MCP card technology effectively preserves key biochemical attributes of tomato fruit by delaying ripening-associated metabolic changes under ambient storage conditions.

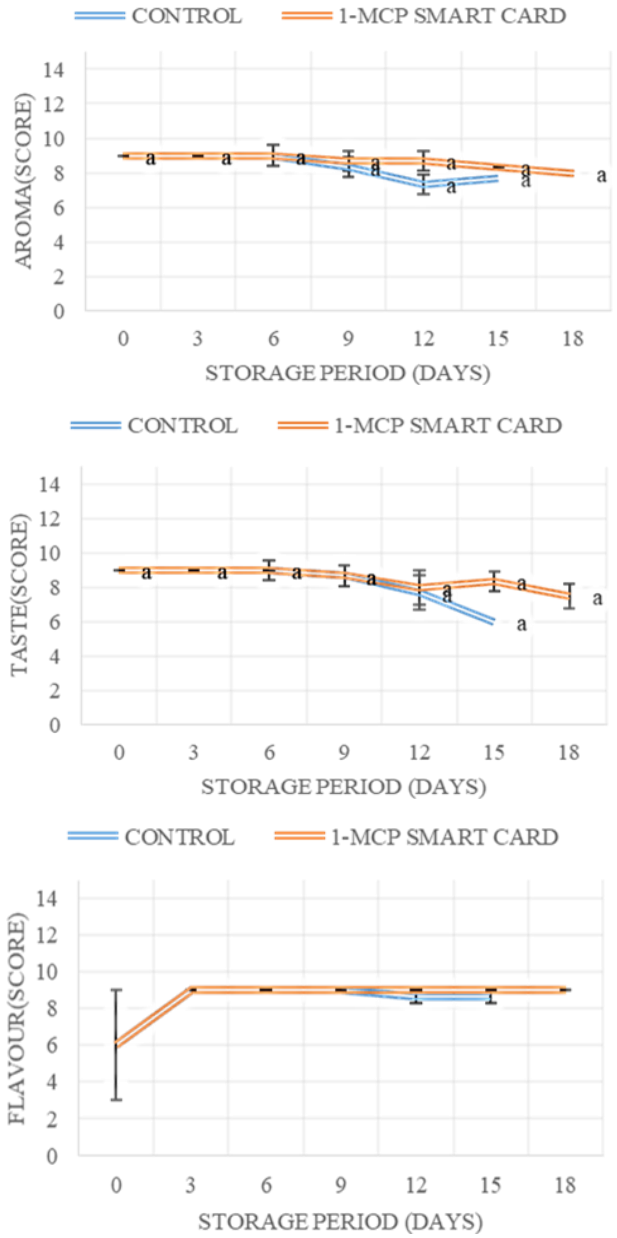

Fig. 5: Effect of postharvest application of 1-MCP card technology on sensory quality attributes of tomato fruit during ambient storage: (A) aroma score, (B) taste score, and (C) overall acceptability score. Values represent means ± standard error (SE) of three replications (n=3).

Effect of 1-MCP card on phytochemical attributes and antioxidant activity

Phytochemical attributes, including total phenolic content (TPC) and antioxidant activity (DPPH), were significantly affected (P≤0.05) by storage duration, treatment, and their interaction during ambient storage. Total phenolic content declined progressively in both peel and pulp tissues with the advancement of storage time; however, fruits treated with the 1-MCP card retained significantly higher TPC compared to control fruits throughout the storage period (Fig. 7A). The reduced loss of phenolic compounds in treated fruits indicates delayed senescence and better preservation of secondary metabolites associated with nutritional quality. Similarly, antioxidant activity, as determined by the DPPH assay, decreased with storage duration in both treatments; however, 1-MCP–treated fruits exhibited significantly higher antioxidant activity compared to control fruits, particularly during later stages of storage (Fig. 7B). The higher antioxidant capacity observed in treated fruits is closely associated with improved retention of phenolic compounds and ascorbic acid, which play a central role in scavenging reactive oxygen species.

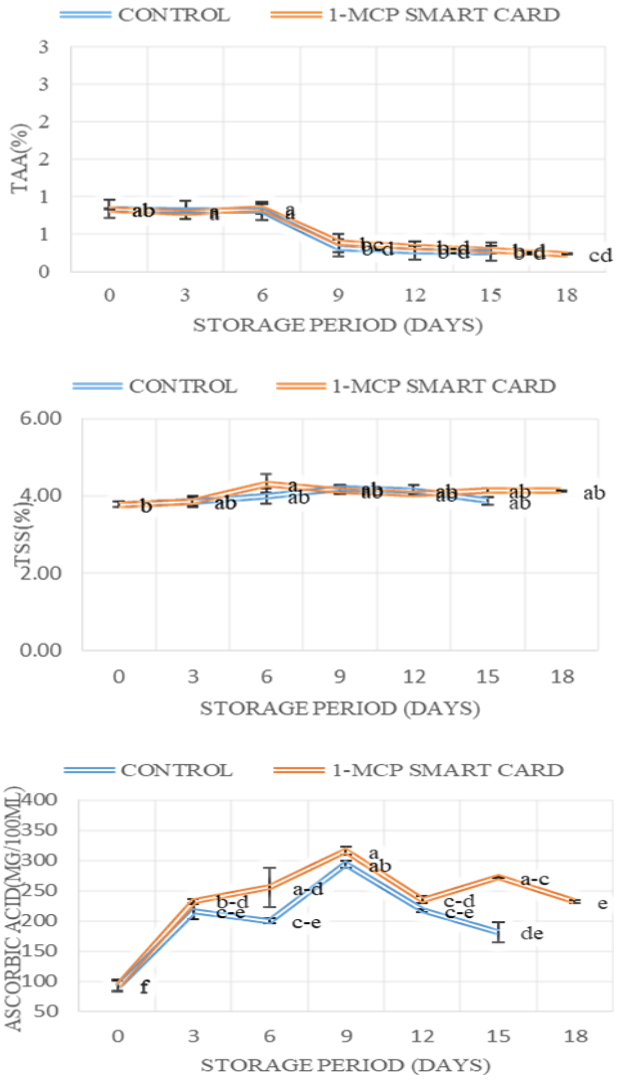

Fig. 6: Effect of postharvest application of 1-MCP card technology on biochemical quality attributes of tomato fruit during ambient storage: (A) titratable acidity (%), (B) total soluble solids (TSS, °Brix), and (C) ascorbic acid content (mg 100 g^{-1} fresh weight). Values represent means ± standard error (SE) of three replications (n=3).

The decline in phenolic content and antioxidant activity during storage is commonly attributed to oxidative degradation and increased activity of browning-related enzymes during ripening. The application of the 1-MCP card likely delayed these processes by inhibiting ethylene-mediated metabolic pathways and reducing oxidative stress. Similar trends in phytochemical preservation following 1-MCP treatment have been reported previously in tomato and other horticultural crops (Park et al., 2016). Overall, these findings indicate that 1-MCP card technology effectively preserves phytochemical composition and antioxidant capacity of tomato fruits during ambient storage.

Effect of 1-MCP card on antioxidant enzyme activities

Antioxidant enzyme activities, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and polyphenol oxidase (PPO), were significantly influenced ($P \leq 0.05$) by storage duration, treatment, and their interaction during ambient storage. The activity of SOD increased progressively with storage time in both treatments; however, fruits treated with the 1-MCP card exhibited significantly higher SOD activity compared to control fruits, particularly during the later stages of storage (Fig. 8A). Enhanced SOD activity in treated fruits indicates improved scavenging of superoxide radicals and reduced oxidative stress during ripening. Similarly, CAT and POD activities were significantly higher in 1-MCP–treated fruits compared to control fruits throughout the storage period (Fig. 8B, C). The elevated activities of these enzymes suggest enhanced detoxification of hydrogen peroxide, thereby protecting cellular components from oxidative damage and delaying senescence. The peak activity of CAT observed in treated fruits during mid-storage further highlights the role of 1-MCP in strengthening the antioxidant defense system. In contrast, PPO activity increased markedly in control fruits with advancement of storage time, whereas fruits treated with the 1-MCP card exhibited significantly lower PPO activity (Fig. 8D). Since PPO is closely associated with enzymatic browning and quality deterioration, its suppression in treated fruits indicates delayed tissue degradation and improved maintenance of visual and nutritional quality.

The enhanced antioxidant enzyme activities (SOD, CAT, POD) and reduced PPO activity observed in 1-MCP–treated fruits may be attributed to inhibition of ethylene-mediated oxidative metabolism and delayed ripening. Similar modulation of antioxidant enzyme systems following 1-MCP application has been reported previously in tomato and other climacteric fruits (Min et al., 2018). These results demonstrate that 1-MCP card technology effectively mitigates oxidative stress and contributes to extended shelf life and quality preservation of tomato fruits under ambient storage conditions.

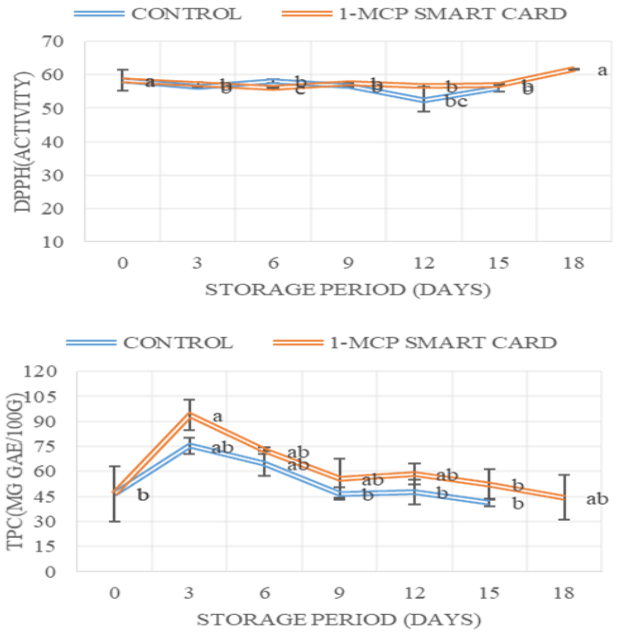

Fig. 7: Effect of postharvest application of 1-MCP card technology on phytochemical attributes and antioxidant activity of tomato fruit during ambient storage: **(A)** antioxidant activity determined by DPPH assay (%) and **(B)** total phenolic content (TPC, mg gallic acid equivalents per 100 g fresh weight). Values represent means ± standard error (SE) of three replications (n=3).

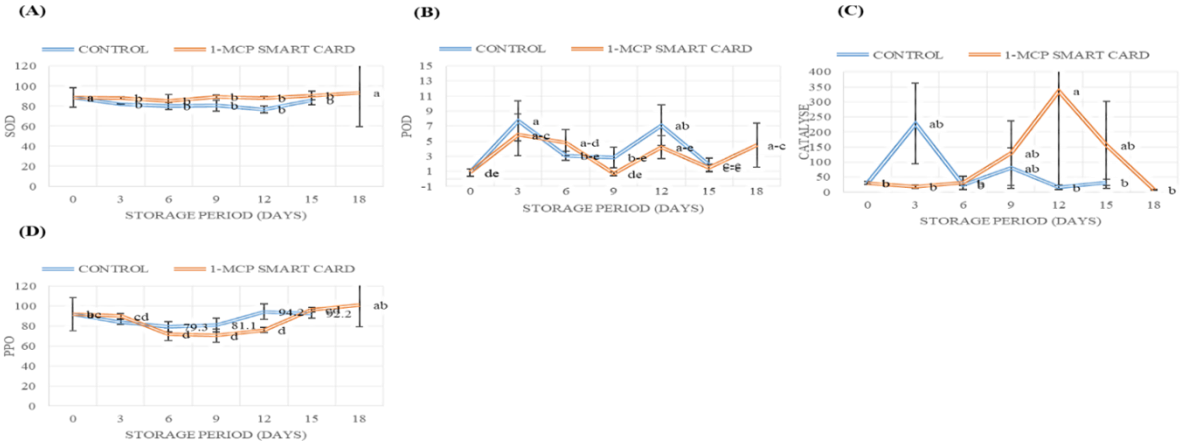

Fig. 8: Effect of postharvest application of 1-MCP card technology on antioxidant enzyme activities of tomato fruit during ambient storage: **(A)** superoxide dismutase (SOD), **(B)** peroxidase (POD), **(C)** catalase (CAT), and **(D)** polyphenol oxidase (PPO). Values represent means ± standard error (SE) of three replications (n=3).

Conclusions

The present study demonstrates that application of 1-MCP card technology is an effective and practical approach for extending shelf life and maintaining postharvest quality of tomato fruit under ambient storage conditions. Treatment with the 1-MCP card significantly delayed ripening-related changes by suppressing ethylene production and respiration rate, thereby preserving fruit firmness, reducing weight loss, minimizing decay incidence, and maintaining higher marketability. Furthermore, 1-MCP card–treated fruits exhibited improved retention of sensory quality, biochemical attributes, phytochemical composition, and antioxidant capacity, accompanied by enhanced activities of antioxidant enzymes and reduced browning-related enzymatic activity. These findings indicate that 1-MCP card technology effectively mitigates oxidative stress and slows senescence processes associated with tomato fruit ripening. Overall, the results highlight the potential of 1-MCP card technology as a simple, cost-effective, and commercially viable postharvest strategy to reduce losses and improve quality of tomatoes during ambient storage, particularly in regions with limited cold-chain infrastructure.

DECLARATION

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Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement: This study was conducted in accordance with institutional guidelines for fruit research. No human or animal subjects were involved

Author's Contribution: Muhammad Anees Arif conducted the experiments, performed data analysis, and wrote the original manuscript. Aman Ullah designed and supervised the study and contributed to manuscript revision. Murium Sultan and Salma Rehmat contributed to manuscript review, editing, and language improvement. All authors read and approved the final manuscript.

Generative AI Statement: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

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