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FERTILIZER TYPE AND ETHYLENE REMEDIATION AFFECT POSTHARVEST QUALITY TRAITS OF STORED TOMATO (*SOLANUM LYCOPERSICUM* L.) FRUITS

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ABSTRACT

Tomato fruits are highly perishable due to ethylene-mediated ripening. This study evaluated the effects of pre-harvest fertilizer applications of NPK 15-15-15, poultry manure, NPK-poultry manure composite, and unfertilized control with postharvest ethylene remediation treatments of 0.1, 0.3, 0.5 µL/L 1-MCP; 5% and 10% $KMnO_4$; 10 g and 20 g zeolite; and open-shelf storage, on some tomato quality traits. Fruits harvested at the breaker stage, across fertilizer treatments, subjected to the varying ethylene remediation agents, were assessed for firmness, total soluble solids, titratable acidity, lycopene and vitamin C, using a 4 × 8 factorial laid out in a completely randomized design with three replications. NPK 15-15-15 treatment produced significantly firmer fruits at harvest. Among remediation treatments, 0.3–0.5 µL/L 1-MCP and 5% $KMnO_4$ most effectively preserved firmness, titratable acidity and vitamin C during storage. Lycopene content was highest in open-shelf fruits and those treated with zeolite or 10% $KMnO_4$, though these fruits exhibited concurrent softening. Open-shelf storage consistently resulted in inferior quality across all parameters. NPK fertilizer application combined with 1-MCP or 5% $KMnO_4$ yielded optimal overall quality retention. The study concluded that integrating NPK fertilizer application with appropriate ethylene remediation, particularly 1-MCP or $KMnO_4$, synergistically enhances postharvest quality and shelf life of tomato fruits.

Keywords: *Solanum lycopersicum*; fertilizer type; Postharvest quality; ethylene modulation.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is among the most widely cultivated vegetable crops globally, valued for its culinary versatility and nutritional richness (Abubacar, 2006; Sattar, *et al.* 2024). Tomato fruits contain essential vitamins, minerals, and bioactive phytochemicals including lycopene, β-carotene and flavonoids, which are associated with reduced risks of cardiovascular disease and certain cancers (Ali *et al.,* 2020; Wang *et al.,* 2022). However, tomatoes are highly perishable, and their postharvest quality, particularly firmness and nutritional content deteriorates rapidly during ripening and storage, leading to significant economic losses (Piccolo *et al.,* 2024). Fruit ripening in tomato is a complex, genetically - programmed process primarily regulated by the plant hormone ethylene, which coordinates chlorophyll degradation, carotenoid accumulation (notably lycopene), and fruit texture softening (Bayoumi *et al.,* 2023; Loayza *et al.,* 2020). Loss of firmness during ripening is a major concern for postharvest shelf life and susceptibility to mechanical damage (Bayoumi *et al.,* 2023). Consequently, considerable research attention has focused on strategies to slow ripening and preserve fruit quality.

Conventional agricultural practices that rely on excessive chemical fertilizer application, beyond their negative environmental impacts, may not optimize fruit quality (Ţopa *et al.,* 2025). Recent research has increasingly focused on innovative preharvest and postharvest interventions. Strategic planning for postharvest quality begins at the farm level, yet the impact of preharvest factors is often underestimated. Nutrient management decisions during crop production significantly influence final produce quality (Kyriacou & Rouphael, 2023; Nxumalo *et al.,* 2022). Tomato fruit is especially susceptible to rapid spoilage under tropical ambient conditions due to its high moisture content, which drastically shortens shelf life (Oladosu *et al.,* 2021). This inherent perishability underscores the need for approaches to strengthen the tomato value chain at the postharvest stage.

Extending tomato postharvest life requires handling technologies that effectively mitigate ethylene accumulation in the storage environment. Recent advances focus on reducing or removing ethylene using ripening remediation substances (Onyeaka *et al.,* 2022; Wilson *et al.,* 2023). Integrating careful preharvest management such as precision fertilizer application with improved postharvest techniques is essential for maintaining fruit quality and prolonging storage life (Singh *et al.,* 2024). This study aimed to evaluate the influence of different fertilizer strategies and ethylene-modulating treatments on key quality parameters of tomato fruits; identifying sustainable practices that enhance both postharvest longevity and nutritional quality.

MATERIALS AND METHODS

Material and Sample Preparation

Two field experiments (Experiments 1 and 2) were conducted to determine the effects of fertilizer type on postharvest life and some quality traits of tomato fruits. Four fertilizer types were evaluated: NPK 15:15:15 (300 kg ha^{-1}), Poultry manure (10 t ha^{-1}), NPK 15:15:15 (150 kg ha^{-1}) + Poultry manure (5 t ha^{-1}) and Control (No fertilizer). Fresh tomato fruits harvested at breaker stage (to minimize perishability during storage) from the four fertilizer type treatments were selected for uniformity in size and freedom from visual defects or mechanical damage. The fruits were arranged at the Department of Horticulture Laboratory, Federal University of Agriculture, Abeokuta and were subjected to seven ripening remediation treatments: 0.1 µl/L 1-MCP concentration, 0.3 µl/L 1-MCP concentration, 0.5µl/L 1-MCP concentration, 5% conc. $KMnO_4$ solution, 10 % conc. $KMnO_4$ solution, 10g of Zeolite, 20 g of Zeolite and an Open shelf as control. The ripening remediation treatments cut across Ethylene Absorbers [Potassium permanganate ($KMnO_4$)], Ethylene Adsorber (Zeolite) and Ethylene inhibitor [1-Methylcyclopropene (1-MCP)].

The fruits were containerized in 28 perforated plastic containers (size of 659.75 cm^3) for all the ethylene remediation treatments. Each perforated plastic container had 500 g healthy tomato fruits for all the treatment combinations. The laboratory experiment was laid out in a 4 x 8 arrangement in a Completely Randomized Design (CRD), with three replications.

Parameters assessed

The following quality traits were observed;

Storability (days): The maximum storage period from harvest to loss of marketable quality was assessed by daily monitoring of spoilage incidence and extent across treatments. Estimates here were taken as shelf life.

Fruit firmness (kg/cm^2): This was determined using the hand pi model GY-series penetrometer (Yueqing Handpi Instruments).

Total Soluble Solids (TSS) content – Determination of TSS was done using a handheld refractometer (PAL-1, ATAGO Co., Ltd., Tokyo, Japan).

Titratable acidity (TA): This was measured using a fully automatic titrator (Model 855, Metrohm AG, Herisau, Switzerland), with 0.1 mol L^{-1} NaOH standard solution as the titrant, with values expressed as citric acid equivalents.

Lycopene content (mg/kg): This was measured using a multifunctional microplate reader (Synergy HTX, BioTek Instruments, Inc., Winooski, VT, USA).

Vitamin C content: This was determined using the Coomassie Brilliant Blue G-250 staining method and the molybdenum blue colorimetric method.

Statistical analysis

Data collected were subjected to analysis of variance (ANOVA) using PROC GLM in SAS version 9.3 (SAS, 2012). Treatment means were separated using Least Significant Difference (LSD) for set of means not more than six and Duncan's Multiple Range Test (DMRT) for set of means more than six, both at 5% probability level.

RESULTS AND DISCUSSION

Maximum storability period recorded across all treatments was 49 days that was attained for fruits produced from application of poultry manure and subjected to 0.5 µL/L 1 -MCP in Experiment 1 and those from NPK 15-15-15 fertilizer subjected to 5% $KMnO_4$ treatment in Experiment 2 (Table 1). The shortest storability periods (≤31 days) were consistently observed from fruits stored with 10 g of Zeolite and those from Open shelf, irrespective of fertilizer type.

It was observed that attainment of maximum storage potential is not dependent upon a specific fertilizer type, as both inorganic (NPK) and organic (poultry manure) fertilizer types were capable of supporting a 49-day storage period when paired with an appropriate ethylene remediation agent (Table 1).

EFFECT OF FERTILIZER TYPE ON PRE AND POST STORAGE FRUIT FIRMNESS

Fertilizer type significantly affected fruit pre-storage firmness in both experiments but a significant effect was observed only at the post-storage, in experiment 2 (Figure 1). At pre-storage, fruits from plots treated with NPK 15-15-15 were significantly firmer than those from all other fertilizer treatments in both experiments. After storage, fruits from all treated plots were firmer than those from the control plots in experiment 1. In experiment 2, fruits from plots treated with NPK 15-15-15 or the complementary fertilizer were significantly firmer than those from the other treatments. The observation that NPK 15-15-15 and complementary fertilizer treatments produced better fruit firmness in Experiment 2 post-storage is supported by earlier report of Raiesi *et al.,* (2024) who worked on the comparative studies on chemical and organic fertilizer application. The consistent superiority of NPK 15-15-15 treatment for firmness at harvest across both experiments suggests that balanced fertilizer application with adequate calcium is essential for producing fruits with essential textural quality. For postharvest firmness retention, NPK 15-15-15 treatment provided a readily available and balanced supply of nitrogen, phosphorus and potassium at crucial stages of fruit development, especially potassium that helps in regulating osmotic potential as well as maintaining cell turgor pressure which is essential for firmness as reported by Mercado-Hornos, *et al.,* (2025).

Table 1: Storability period of tomato fruits under different ethylene remediation treatments

		Storability period (Days)	
Fertilizer type	**Ethylene remediation agent**	**Exp. 1**	**Exp. 2**
NPK 15-15-15	0.1 μL/L 1-MCP	43a	37ab
	0.3 μL/L 1-MCP	48a	40a
	0.5 μL/L 1-MCP	46a	42a
	5% $KMnO_4$	45a	49a
	10% $KMnO_4$	40a	36ab
	10 g of Zeolite	28b	30b
	20 g of Zeolite	40a	36ab
	Open shelf	21bc	19c
Poultry manure	0.1 μL/L 1-MCP	39ab	42a
	0.3 μL/L 1-MCP	40a	43a
	0.5 μL/L 1-MCP	49a	40a
	5% $KMnO_4$	46a	46a
	10% $KMnO_4$	30b	37ab
	10 g of Zeolite	31ab	31ab
	20 g of Zeolite	30b	31ab
	Open shelf	19c	19c
NPK + Poultry manure	0.1 μL/L 1-MCP	37ab	31ab
	0.3 μL/L 1-MCP	46a	42a
	0.5 μL/L 1-MCP	37ab	36ab
	5% $KMnO_4$	42a	45a
	10% $KMnO_4$	42a	36ab
	10 g of Zeolite	27b	36ab
	20 g of Zeolite	40a	36ab
	Open shelf	19c	18c
Control	0.1 μL/L 1-MCP	31ab	40a
	0.3 μL/L 1-MCP	45a	45a
	0.5 μL/L 1-MCP	45a	39a
	5% $KMnO_4$	45a	43a
	10% $KMnO_4$	39a	37ab
	10 g of Zeolite	28b	34ab
	20 g of Zeolite	34ab	37ab
	Open shelf	19c	19c

Means followed by the same alphabet in the same column are not significantly different at 5% probability level of DMRT

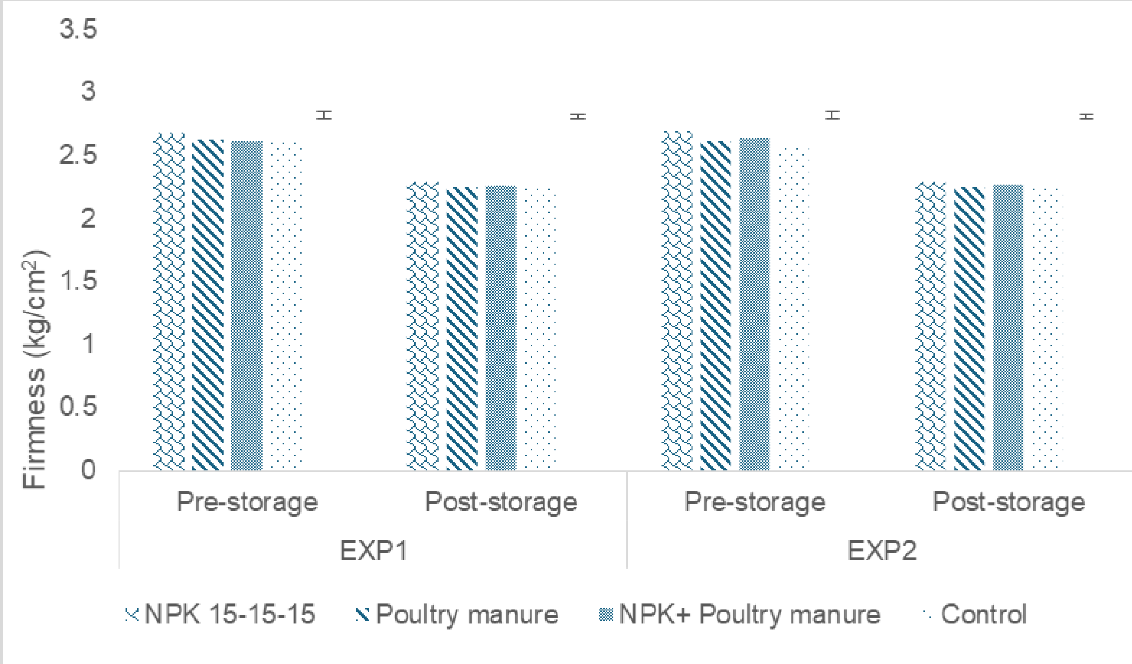


Figure 1: Effect of fertilizer type on firmness of tomato fruits

Effects of Ethylene Remediation Substance on Fruit Firmness

Ethylene remediation agents had a significant effect on tomato fruit firmness in both experiments (Figure 2). Ethylene remediation agents, especially 1-methylcyclopropene (1-MCP) and Potassium permanganate ($KMnO_4$), significantly influenced tomato fruit firmness retention during storage. In experiment 1, fruits exposed to 0.5 µL/L 1-MCP or kept in 5% $KMnO_4$ solution were significantly firmer than those stored on open shelves and were also comparatively firmer than fruits kept in the other remediation media. In experiment 2, fruits exposed to 0.1, 0.3, or 0.5 µL/L 1-MCP and those stored in 5% $KMnO_4$ solution performed similarly, and all were significantly firmer than fruits kept on open shelf (Figure 2). The consistent superiority of 0.5 µL/L 1-MCP and 5% $KMnO_4$ treatments in both experiments, along with the broader effectiveness of all 1-MCP concentrations in Experiment 2, reveals the major role of ethylene regulation in controlling the softening process that accompanies climacteric fruit ripening as reported by Zhang, *et al.* (2024) as it suppresses cell wall degrading enzymes that are usually induced by ethylene.

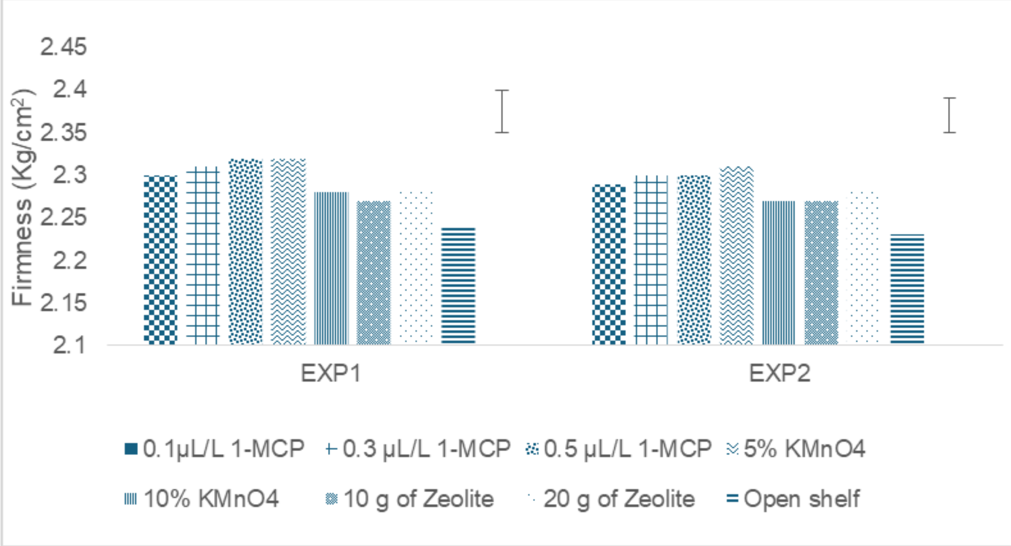


Figure 2: Effect of ethylene remediation substances on firmness of tomato fruits

Interaction of fertilizer type and ethylene remediation substance on post storage firmness of tomato fruits

The interaction between fertilizer type and ripening remediation substance significantly affected tomato fruit firmness (Table 2). In both experiments, fruits from plots treated with 300 kg ha-¹ NPK 15-15-15 combined with 0.1, 0.3, or 0.5 µL/L 1-MCP or 5% $KMnO_4$ solution were firmer than other treatment combinations. Fruits from plots that received 10 t ha-¹ poultry manure and those treated with 0.3 or 0.5 µL/L 1-MCP or 5% $KMnO_4$ solution also exhibited higher firmness. A similar trend was observed with fruits from complementary fertilizer and control plots. Fruits from the plots which were exposed to 0.3 or 0.5 µL/L 1-MCP or 5% $KMnO_4$ solution treatments were firmer compared to other ripening remediation treatments. The significant interaction between fertilizer type and ripening remediation substances on tomato fruit firmness shows the complementary roles of preharvest nutrition in establishing cell wall integrity, and postharvest ethylene management in suppressing softening-related gene expression. NPK 15-15-15 combined with all tested 1-MCP concentrations or 5% KMnO4 produced superior firmness retention (Table 2), demonstrating the synergy between balanced calcium nutrition and effective ethylene management (Al-Saif., *et al.,* 2024). Poultry manure required higher 1-MCP concentrations for optimal results, likely reflecting differences in fruit ripening kinetics. The general decline in firmness with storage time, despite optimal treatments emphasizes the expected advance of ripening processes and this agrees with the observation by Al-Saif, *et al.,* (2024). The magnitude of decline observed in this study was, however, considerably reduced by integrated nutrient and ethylene management methods (Table 2).

Table2: Interaction of fertilizer type and ethylene remediation treatments on firmness of tomato post storage

Fertilizer type	RRA	Firmness (kg/cm^2)	
		Exp. 1	Exp. 2
NPK 15-15-15	P1	2.41^{c}	2.34^{d-g}
	P2	2.30^{e-h}	2.39^{c-e}
	P3	2.35^{d-f}	2.36^{de}
	P4	2.41^{c}	2.49^{a}
	P5	2.35^{d-f}	2.34^{d-g}
	P6	2.11^{k-m}	2.14^{j-m}
	P7	2.23^{ghi}	2.27^{f-h}
	P8	2.21^{h}	2.12^{kl}
Poultry manure	P1	2.31^{e-g}	2.23^{g-i}
	P2	2.32^{ef}	2.24^{gh}
	P3	2.20^{hi}	2.25^{g}
	P4	2.28^{fg}	2.20^{hi}
	P5	2.32^{ef}	2.25^{g}
	P6	2.26^{f-i}	2.25^{g}
	P7	1.93^{p}	2.11^{k-m}
	P8	1.90^{p-s}	2.09^{l}
NPK + Poultry manure	P1	2.38^{c-f}	2.30^{e-h}
	P2	2.40^{cd}	2.31^{e-g}
	P3	2.40^{cd}	2.36^{de}
	P4	2.49^{a}	2.36^{de}
	P5	2.18^{i-l}	2.18^{i-l}
	P6	2.17^{j}	2.16^{jk}
	P7	2.25^{g}	2.24^{gh}
	P8	1.96^{op}	2.34^{d-g}
Control	P1	2.24^{gh}	2.30^{e-h}
	P2	2.38^{c-f}	2.39^{c-e}
	P3	2.31^{e-g}	2.38^{c-f}
	P4	2.38^{c-f}	2.36^{de}
	P5	2.33^{e}	2.28^{fg}
	P6	2.28^{fg}	2.22^{g-j}
	P7	2.29^{f}	2.26^{f-i}
	P8	1.97^{o}	1.98^{n-q}

R.R.A- Ethylene remediation agent, P1, 0.1 µL/L 1-MCP, P2- 0.3 µL/L 1-MCP, P3- 0.5 µL/L 1-MCP, P4- 5% $KMnO_4$, P5- 10% $KMnO_4$, P6- 10 g of Zeolite, P7- 20 g of Zeolite, P8-Open shelf

Means followed by the same alphabet in the same column are not significantly different at 5% probability level of DMRT

EFFECT OF FERTILIZER TYPE ON NUTRITIVE AND BIOCHEMICAL CONTENTS

Vitamin C Content

In Experiment 1, pre-storage vitamin C was significantly higher in fruits from complementary fertilizer plots, followed by those from 10 t ha-¹ poultry manure (Figure 3a). After storage, fruits from 300 kg ha-¹ NPK 15-15-15 plots had significantly higher vitamin C than other treatments. In Experiment 2, pre-storage vitamin C was highest in fruits from 10 t ha-¹ poultry manure, followed by complementary fertilizer. At the end of storage, fruits from complementary fertilizer plots contained the highest vitamin C content (Figure 3a).

The observation that complementary fertilizer and poultry manure treatments produced significantly higher pre-storage vitamin C compared to NPK and control treatments in both experiments aligns with Mahmud *et al.* (2024) who demonstrated that combined application of poultry manure (10 t ha-¹) with reduced chemical fertilizer rates significantly improved tomato fruit quality attributes, including vitamin C content, compared to sole chemical fertilizer applications. Similarly, Adekiya *et al.* (2022) reported that poultry manure application at 10 t ha-¹ produced the highest vitamin C content in tomato fruits compared to lower rates and control treatments, establishing it as an optimal rate for nutritional quality enhancement. The significantly higher vitamin C after storage in NPK-treated fruits in experiment 1, despite having lower pre-storage values than complementary fertilizer and poultry manure treatments could suggest that the mineral nutrient status of the treatment may have encouraged greater stability to ascorbic acid during postharvest handling. In Experiment 2, complementary fertilizer plots maintained the highest vitamin C content after storage (Figure 3a), indicating that the integrated nutrient approach provided both high initial accumulation and superior retention capacity. The enhanced retention of vitamin C in complementary fertilizer plots may be attributed to the activities of some antioxidant enzymes and availability of potassium, which stabilize cell membranes during storage as reported by Ramos-García *et al.*, (2020).

Lycopene Content

Fertilizer type significantly influenced lycopene content both before and after storage in both experiments (Figure 3b). In Experiment 1, pre-storage lycopene was highest in fruits from 300 kg ha-¹ NPK 15-15-15 plots, followed by complementary fertilizer, with control plots recording the lowest. After storage, lycopene content increased slightly across treatments, with control plots showing higher levels than fertilized plots. In Experiment 2, pre-storage lycopene was highest in fruits from 10 t ha^{-1} poultry manure plots, followed by 300 kg ha^{-1} NPK 15-15-15, while control plots again recorded the lowest. At post-storage, a similar pattern emerged, with control plots exhibiting higher lycopene than fertilized treatments (Figure 3b).

During postharvest storage, tomato fruits continue ripening processes, including the conversion of chloroplasts to chromoplasts and the associated accumulation of carotenoids, especially lycopene (Zakriya *et al.,* 2023). This explains the general increase in lycopene across all treatments after storage (Figure 3b). However, fruits from control plots showed progressive lycopene accumulation during storage higher than those from treated plots which showed lower lycopene due to delayed ripening. The difference in post-storage behavior between control and fertilizer type treatments may be related to the role of potassium in fruit maturation; this aligns with the report of Zdravković *et al.* (2007) who observed that plants treated with increased potassium had the lowest beta-carotene content, which they attributed to accelerated transformation of beta-carotene to lycopene during ripening.

Titratable Acidity (TTA)

In Experiment 1, fertilizer type did not significantly affect TTA before or after storage (Figure 3c). It was higher in fruits from complementary fertilizer plots, followed by those from 300 kg ha-¹ NPK 15-15-15, with the lowest observed in fruits from 10 t ha-¹ poultry manure treatment. A similar trend was observed in Experiment 2, where complementary fertilized plots recorded higher TTA in stored tomato fruits, followed by NPK and poultry manure treatments (Figure 3c).

This superior TTA observed in complementary fertilizer plots could be attributed to enhanced potassium availability and uptake as potassium plays a fundamental role in organic acid metabolism and translocation as reported by Wang *et al.* (2024). Studies have shown that while potassium fertilization alone may not significantly affect titratable acidity, its availability in combination with other nutrients from organic amendments may enhance organic acid synthesis.

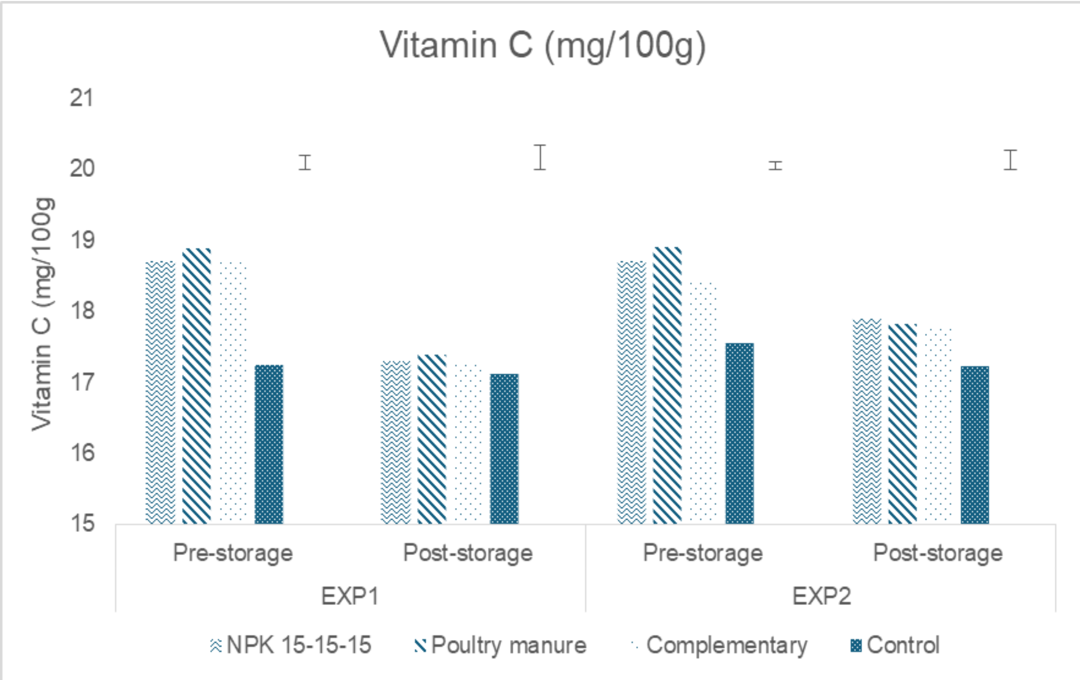
Total Soluble Solids (TSS)

Fertilizer type significantly affected TSS at pre storage in Experiment 1 (Figure 3d). Control plots recorded the highest TSS, followed by complementary fertilizer, while 10 t ha-¹ poultry manure recorded the lowest. For post-storage, TSS levels increased across treatments, with fruits from 300 kg ha -¹ NPK 15-15-15 plots having the highest TSS and control plots the lowest. In Experiment 2, fertilizer type had a significant effect on TSS both before and after storage. Pre-storage, fruits from 300 kg ha-¹ NPK 15-15-15 and complementary fertilizer plots recorded the highest TSS, while control plots recorded the lowest. At post-storage, TSS increased across all treatments, with fruits from NPK plots again showing the highest values and control plots the lowest (Figure 3d).

In Experiment 1, the higher pre-storage TSS content for fruits from control plots which were characterized by small fruit sizes is in concurrence with Yara, (2018) who reported the likelihood of more concentrated sugars in smaller fruits. Contrarily, in Experiment 2, NPK and complementary fertilizer treatments yielded the highest TSS, indicating that adequate nutrient availability could have enhanced photosynthetic capacity and sugar translocation, with potassium playing a key role in sugar metabolism as suggested by Wang *et al.* (2024).

Poultry manure treatments showed the lowest pre-storage TSS in Experiment 1, possibly due to slower nutrient release and delayed fruit maturation and this result agrees with Carricondo-Martínez *et al.* (2022), who observed that organic fertilization systems produced fruits with different ripening processes compared to mineral fertilization. For post-storage, TSS increased across all treatments during storage, indicating normal postharvest ripening processes such as starch degradation and water loss. NPK-treated fruits consistently achieved the highest post-storage TSS, suggesting greater sugar accumulation potential, possibly from higher initial starch reserves (Wang, *et al.,* 2024). Control fruits, despite having the highest pre-storage TSS in Experiment 1, recorded the lowest post-storage values (Figure 3d), indicating they may have been harvested at an advanced ripening stage with limited remaining reserves.

A



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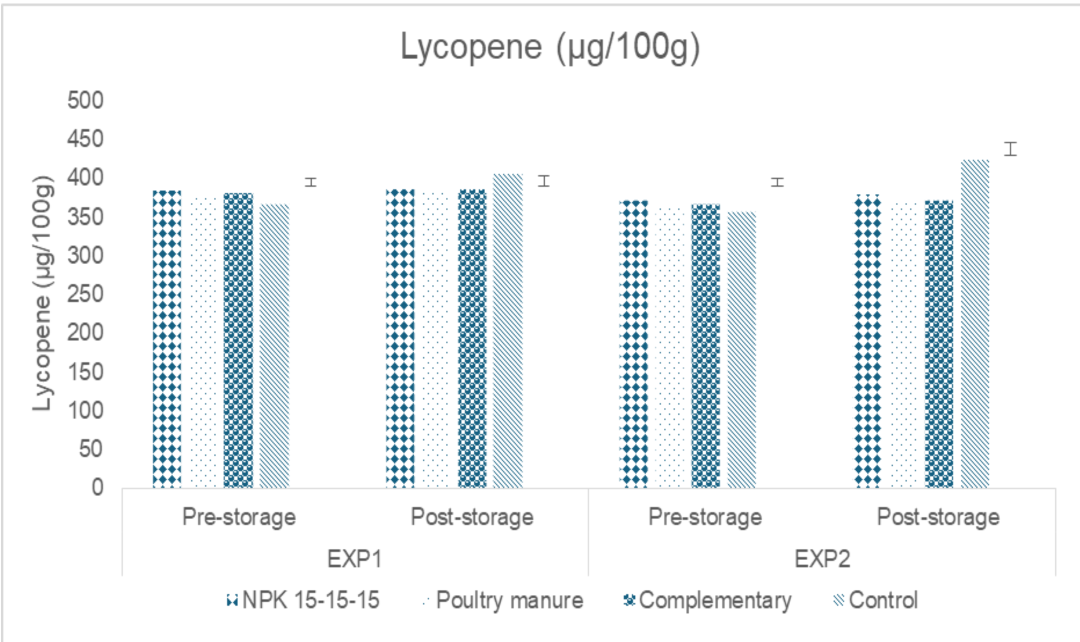

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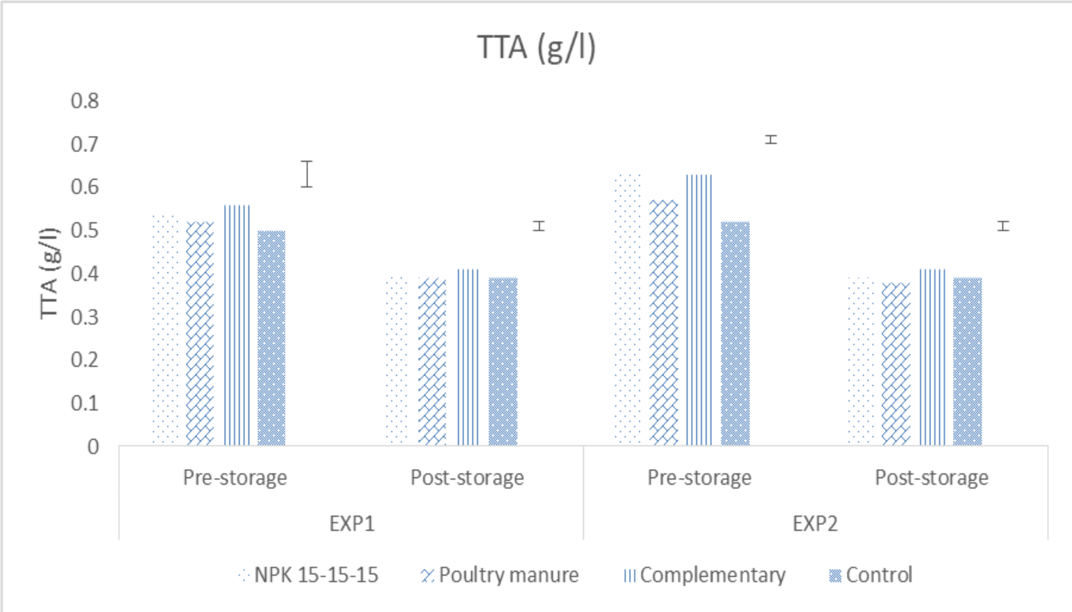

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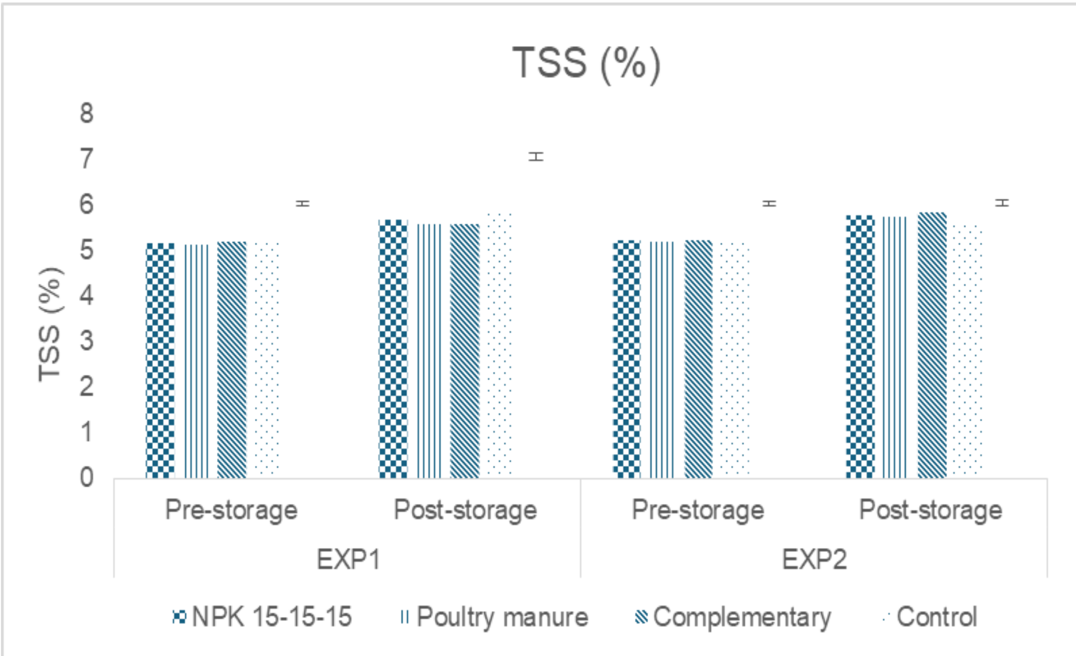


Figure 3: Effect of fertilizer type on pre and post storage on nutritive and biochemical contents of tomato fruits in Exp. 1 and Exp. 2: (a) Vitamin C; (b) Lycopene; (c) TTA; (d) TSS

EFFECT OF ETHYLENE REMEDIATION AGENTS ON NUTRITIVE AND BIOCHEMICAL CONTENTS

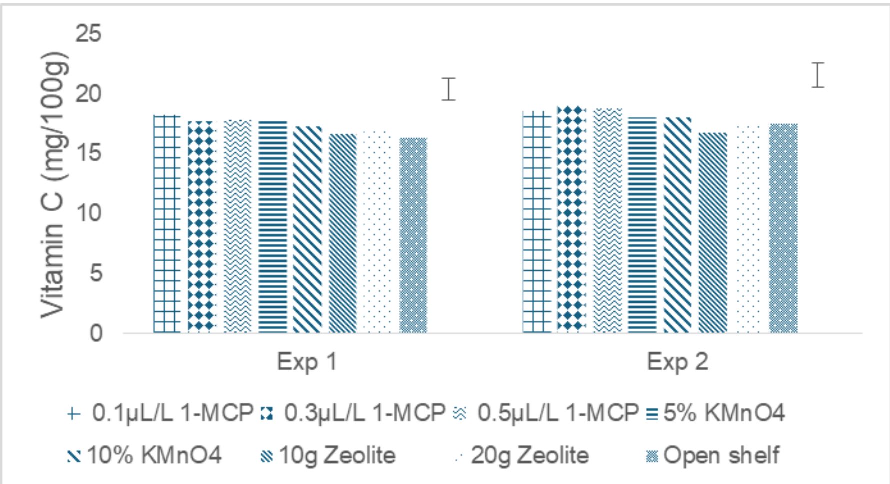
Ripening remediation treatments significantly affected vitamin C content in both experiments (Figure 4a). In Experiment 1, vitamin C content was highest in fruits treated with 0.1 µL/L and 0.5 µL/L 1-MCP, as well as those in the 5% $KMnO_4$ solution. In Experiment 2, fruits treated with 0.3 µL/L 1-MCP had the highest vitamin C content, followed by those exposed to 0.1 µL/L and 0.5 µL/L 1-MCP. Fruits stored in 5% and 10% $KMnO_4$ solutions also had high vitamin C levels. The preservation of vitamin C likely resulted from delayed ripening and reduced oxidative metabolism, as ascorbic acid degradation accelerated during advanced ripening stages. The superior performance of 0.3 and 0.5 µL/L 1-MCP and 5% $KMnO_4$ for vitamin C retention aligns with recommendations from the work of Wang *et al.* (2025) who identified these agents as effective ethylene scavengers for extending tomato shelf life while maintaining quality attributes (Figure 4a).

Ripening remediation treatments significantly influenced total titratable acidity (TTA) in both experiments (Figure 4b). In Experiment 1, TTA was highest in fruit treated with 0.3 µL/L and 0.5 µL/L 1-MCP, as well as those in a 5% $KMnO_4$ solution. Intermediate values were observed for fruit exposed to 0.1 µL/L 1-MCP and those in a 20 g zeolite medium. In Experiment 2, the highest TTA values were also observed in fruits treated with 0.3 µL/L and 0.5 µL/L 1-MCP, along with those in the 5% $KMnO_4$ solution. Across both experiments, fruit stored on open shelves exhibited the lowest TTA (Figure 4b). The consistently higher titratable acidity (TTA) observed in 0.3 and 0.5 µL/L 1-MCP treatments and 5% $KMnO_4$ in both experiments aligns with established understanding of the mode of action of and ethylene inhibition and scavenging mechanisms of the substances as reported by Maqbool *et al.* (2024). 1-Methylcyclopropene (1-MCP) functions as an ethylene receptor blocker, competitively binding to receptors and thereby suppressing ethylene-mediated ripening processes. This suppression delays the metabolic conversion of organic acids into sugars, preserving higher acidity levels as reported by Wang, *et al.* (2025). Similarly, Ozdemir, (2023) stated that potassium permanganate ($KMnO_4$) acts as an oxidative ethylene scavenger, chemically degrading ethylene into carbon dioxide and water and effectively reducing ethylene concentration in the storage environment. However, the lowest TTA values recorded for open-shelf fruit are consistent with unrestricted ethylene exposure, which accelerates ripening-associated acid catabolism. This finding corroborates with Aftab *et al.* (2025) who demonstrated that tomato fruits stored under ambient conditions experience progressive declines in titratable acidity alongside increases in pH and sugar-acid ratios. The intermediate TTA values observed with zeolite treatment reflect its physical adsorption mechanism, which, while effective at ethylene removal, may be less efficient than chemical oxidation or receptor blockade under the tested conditions (Figure 4b).

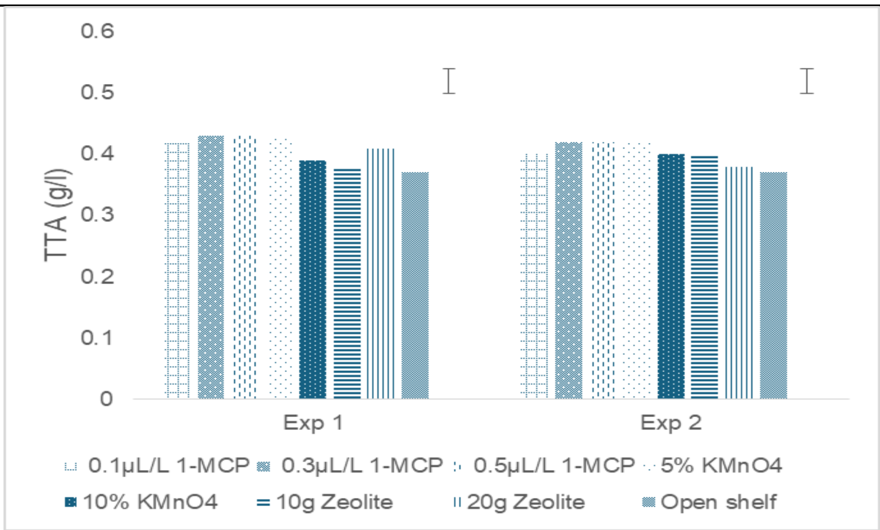
Lycopene content was also significantly affected by the ripening remediation treatments (Figure 4c). In Experiment 1, fruits treated with a 10% $KMnO_4$ solution, as well as those in 10 g and 20 g of zeolite medium, showed higher lycopene levels. Conversely, lower levels were recorded for fruits treated with 0.1, 0.3, and 0.5 µL/L 1-MCP and those in the 5% $KMnO_4$ solution. The highest lycopene content in this experiment was observed in fruits kept on open shelves. In Experiment 2, fruits treated with 0.1, 0.3, and 0.5 µL/L 1-MCP and those in 5% $KMnO_4$ solution had low lycopene content, while those stored in zeolite media had high levels. Again, fruits on open shelves recorded the highest lycopene content. The higher lycopene content in zeolite-treated fruits, compared with lower levels in 1-MCP and 5% $KMnO_4$ treatments, suggests that lycopene biosynthesis may be differentially regulated by ethylene signaling. Lycopene accumulation is an ethylene-dependent ripening process; therefore, effective suppression of ethylene action or removal would predictably delay or reduce lycopene synthesis. Pangaribuan (2017) reported that 1-MCP application to early-maturity tomatoes result in lower lycopene content compared to untreated controls, as ethylene blockade delays the ripening-associated carotenoid biosynthetic pathway. However, the inconsistent observation of high lycopene in open-shelf fruits simply reflects normal, unhindered ripening progression (Figure 4c).

Total soluble solids were significantly influenced by the ripening remediation treatments (Figure 4d). In both experiments, fruits kept on open shelves recorded the highest TSS. In Experiment 1, TSS content was lower in fruits exposed to 0.1 µL/L and 0.5 µL/L 1-MCP and those treated with 5% $KMnO_4$ solution compared to fruits stored in zeolite medium or on open shelves. In Experiment 2, fruit stored in 10 g and 20 g of zeolite medium exhibited higher TSS than those exposed to 1-MCP concentrations or stored in 5% and 10% $KMnO_4$ solutions. Application of ripening remediation treatments produced differential effects on quality attributes of tomato fruits, reflecting their different mechanisms of ethylene regulation (Figure 4d).
Total soluble solids (TSS) exhibited the most peculiar response pattern, with open-shelf fruits consistently recording the highest values. The lower TSS in 1-MCP and $KMnO_4$ treatments (Figure 4d) could be as result of their ability to delay the ripening process and prevent over-ripening of the fruit by maintaining its structural integrity and continue natural sugar development without breaking down sugars too quickly as suggested by Wang *et al.* (2025).

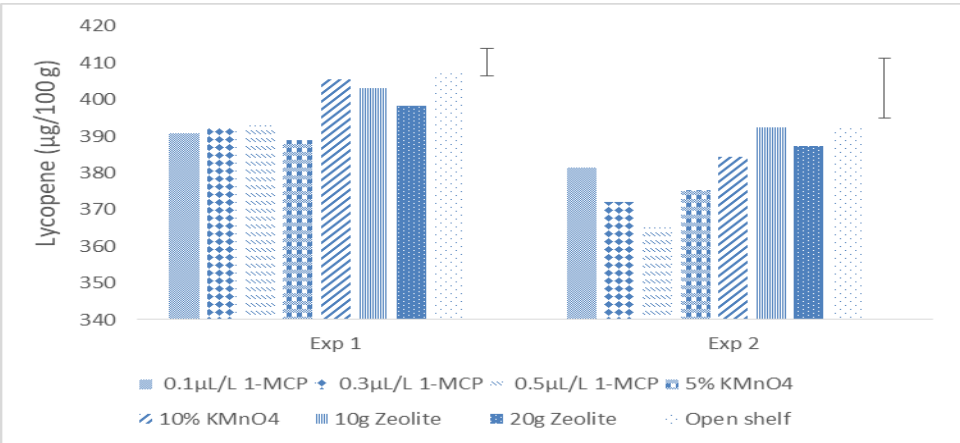
a



b



c



d

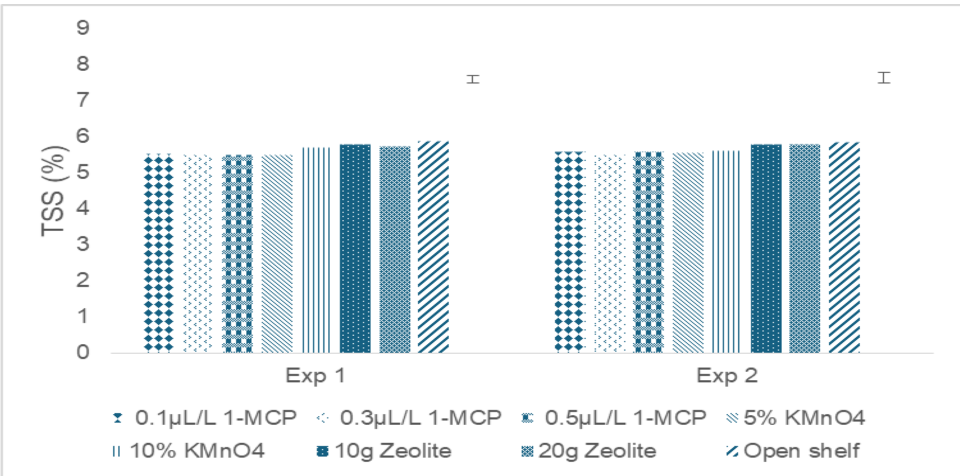


Figure 4: Effect of ethylene remediation substances on some nutritive contents of tomato fruits in Exp. 1 and Exp. 2: (a) Vitamin C; (b) TTA; (c) Lycopene; (d) TSS

Interaction of fertilizer type and ethylene remediation agents on some nutritive and biochemical traits of tomato fruits

Fertilizer type and ripening remediation treatments showed significant interactions across all parameters in both experiments (Table 3). Higher TTA was consistently associated with all 1-MCP concentrations (0.1, 0.3, 0.5 μL/L) and 5% $KMnO_4$ storage, regardless of fertilizer type, however, open-shelf storage consistently resulted in lower TTA. The consistent preservation of titratable acidity (TTA) with 1-MCP and $KMnO_4$ is supported by the report of Wang *et al.* (2024), who demonstrated that 1 -MCP delays ripening and senescence in tomato fruit through epigenetic regulation (DNA methylation), thereby maintaining organic acid levels. Onyeaka *et al.* (2022) also emphasized that ethylene management techniques, including both 1-MCP and ethylene scavengers like $KMnO_4$, effectively preserve acidity by suppressing ripening-associated metabolic shifts.

Higher lycopene was generally observed with fruits exposed to 0.3 μL/L 1-MCP, 10% $KMnO_4$, and 10 g zeolite irrespective of fertilizer type in Experiment 1 while 0.5 μL/L 1-MCP, 10 and 20 g zeolite, and 10% $KMnO_4$ recorded higher lycopene in experiment 2 (Table3). This is consistent with the work of Wilson *et al.* (2023), who reported that controlled atmosphere and ethylene inhibition strategies influence carotenoid biosynthesis, with optimal lycopene retention occurring at specific ethylene suppression levels. The variability between experiments reflects findings by Wang *et al.* (2023) that lycopene accumulation is highly sensitive to both pre-harvest nutritional status and postharvest storage conditions (Table 3).

Higher vitamin C content was consistently recorded across both experiments for all 1-MCP concentrations (0.1, 0.3, 0.5 μL/L) and 5% and 10% $KMnO_4$ storage and rarely 20 g zeolite in Experiment 2 (Table 4). However, open-shelf storage yielded the lowest values. Higher vitamin C retention with 1-MCP and $KMnO_4$ corroborates Nxumalo *et al.* (2022), who noted that combined pre- and postharvest interventions synergistically preserve ascorbic acid by reducing oxidative stress and delaying senescence. The superior performance of 5% and 10% $KMnO_4$ in this study aligns with its role as an effective ethylene oxidizer, as reviewed by Onyeaka *et al.* (2022).

Also, higher TSS was associated with fruits from NPK 300 kg/ha^{-1} fertilizer and stored with 10% $KMnO_4$ solution and 10–20 g zeolite media (Table 4). Lower TSS was recorded with 5% $KMnO_4$ and all 1-MCP concentrations across most fertilizer types. Higher TSS with NPK fertilizer and 10% $KMnO_4$/ zeolite, but lower with 1-MCP (Table 3) reflect the complex interplay between preharvest nutrition and postharvest ethylene management which was reported by Kyriacou and Rouphael (2023) who noted that mineral nutrition influences sugar accumulation. Wilson *et al.* (2023) also observed that ethylene inhibition can slow sugar metabolism, potentially explaining the lower TSS with 1-MCP in this study.

Combined applications of specific fertilizers especially NPK, with selected ripening remediation treatments such as 1-MCP at specific concentrations or $KMnO_4$, showed potential for enhancing postharvest quality, though optimal combinations varied by parameter. The significant interactions between fertilizer type and the postharvest postharvest ethylene remediation treatments are in line with findings of Kyriacou and Rouphael (2023), who emphasized that nutrient management during cultivation controls fruit metabolic status, thus influencing the effectiveness of consequent postharvest interventions. Also, Singh *et al.* (2024) reported that integrating pre-harvest nutrition with postharvest technologies jointly enhances tomato quality retention. The consistently inferior manifestations of quality traits under open-shelf storage emphasizes the critical importance of active postharvest interventions, as reported by Oladosu *et al.* (2021), who documented that under tropical ambient conditions, untreated tomato fruits undergo rapid quality deterioration due to high ethylene production and moisture loss.

Table 3: Interaction of fertilizer type and ethylene remediation agent on *Titratable Acidity* and Lycopene contents of tomato fruits

FERTILIZER TYPE	RRA	TTA (G/L)		LYCOPENE (µG/100G)	
		EXP. 1	EXP. 2	EXP. 1	EXP. 2
	0.1µL/L 1-MCP	0.41A	0.42A	389.26AB	391.38AB
	0.3µL/L 1-MCP	0.41A	0.42A	389.93AB	381.42AB
	0.5µL/L 1-MCP	0.41A	0.42A	389.98AB	378.93B
NPK 15-15-15	5% $KMNO_4$	0.44A	0.42A	358.67BC	388.94AB
	10% $KMNO_4$	0.36B	0.40A	379.10B	402.36A
	10G ZEOLITE	0.37B	0.38AB	381.89B	421.39A
	20G ZEOLITE	0.38AB	0.38AB	386.71AB	421.83A
	OPEN SHELF	0.35B	0.35B	412.73A	412.73A
	0.1µL/L 1-MCP	0.42A	0.42A	392.79AB	402.57A
	0.3µL/L 1-MCP	0.41A	0.42A	389.28AB	379.10B
	0.5µL/L 1-MCP	0.42A	0.41A	372.73B	408.49A
POULTRY MANURE	5% $KMNO_4$	0.40A	0.42A	389.63AB	399.71AB
	10% $KMNO_4$	0.37AB	0.39AB	413.71A	402.38A
	10G ZEOLITE	0.39AB	0.38AB	386.18AB	413.21A
	20G ZEOLITE	0.36B	0.39B	410.67A	403.18A
	OPEN SHELF	0.34B	0.34B	413.71A	412.78A
	0.1µL/L 1-MCP	0.41A	0.42A	382.51AB	390.73AB
	0.3µL/L 1-MCP	0.42A	0.42A	410.36A	392.11AB
	0.5µL/L 1-MCP	0.42A	0.42A	384.66AB	389.81AB
NPK + POULTRY	5% $KMNO_4$	0.42A	0.42A	387.48AB	371.45B
	10% $KMNO_4$	0.40A	0.40A	396.45AB	398.32AB
	10G ZEOLITE	0.37AB	0.38AB	413.56A	411.36A
	20G ZEOLITE	0.37AB	0.38AB	392.83AB	411.86A
	OPEN SHELF	0.35B	0.34B	369.91B	416.74A
	0.1µL/L 1-MCP	0.41A	0.42A	382.73AB	402.38A
	0.3µL/L 1-MCP	0.42A	0.42A	406.31A	367.33AB
	0.5µL/L 1-MCP	0.42A	0.42A	367.06B	401.38A
CONTROL	5% $KMNO_4$	0.43A	0.42A	389.46AB	366.16AB
	10% $KMNO_4$	0.39AB	0.40A	406.12A	416.79A
	10G ZEOLITE	0.38AB	0.39AB	402.73A	406.38A
	20G ZEOLITE	0.39AB	0.39AB	358.58B	408.31A
	OPEN SHELF	0.34B	0.35B	405.86BA	402,48A

RRA – ethylene remediation agent; Means followed by the same alphabets in the same columns are not significantly different at 5% probability are not significantly different at 5% probability level using DMRT.

Table 4: Interaction of fertilizer type and ethylene remediation agent on Vitamin C and *Total Soluble Solids* contents of tomato fruits

FERTILIZER TYPE	RRA	VITAMIN C (MG/100 G)		TSS (%)	
		EXP. 1	EXP. 2	EXP. 1	EXP. 2
NPK 15-15-15	0.1µL/L 1-MCP	20.67A	20.87A	5.79B	5.77B
	0.3µL/L 1-MCP	17.83AB	20.39A	5.76B	5.72B
	0.5µL/L 1-MCP	16.78B	20.36A	5.74B	5.72B
	5% $KMNO_4$	16.71B	20.11A	5.73B	5.74B
	10% $KMNO_4$	16.21B	19.22A	5.97A	5.82AB
	10G ZEOLITE	15.83	18.93AB	5.94A	5.99A
	20G ZEOLITE	16.38B	19.01A	5.97A	5.95A
	OPEN SHELF	15.21B	17.36AB	5.99A	5.99A
POULTRY MANURE	0.1µL/L 1-MCP	16.91B	20.01A	5.74B	5.79B
	0.3µL/L 1-MCP	17.01AB	19.86A	5.79B	5.76B
	0.5µL/L 1-MCP	18.12AB	17.10AB	5.76B	5.74B
	5% $KMNO_4$	20.38A	20.01A	5.76B	5.73B
	10% $KMNO_4$	16.08B	18.92AB	5.92A	5.97A
	10G ZEOLITE	16.78B	18.61AB	5.95A	5.94A
	20G ZEOLITE	17.86AB	17.89AB	5.91A	5.97A
	OPEN SHELF	16.11B	16.01B	5.99A	5.99A
NPK + POULTRY	0.1µL/L 1-MCP	18.01AB	17.93AB	5.77B	5.78B
	0.3µL/L 1-MCP	18.01AB	16.45B	5.72B	5.78B
	0.5µL/L 1-MCP	16.77B	18.86AB	5.72B	5.78B
	5% $KMNO_4$	18.39AB	16.93B	5.74B	5.74B
	10% $KMNO_4$	14.73BC	18.78AB	5.82AB	5.89AB
	10G ZEOLITE	15.48B	18.14AB	5.99A	5.92A
	20G ZEOLITE	16.77B	16.77B	5.95A	5.91A
	OPEN SHELF	16.92B	16.82B	5.99A	5.98A
CONTROL	0.1µL/L 1-MCP	16.72B	20.01A	5.78B	5.79B
	0.3µL/L 1-MCP	16.39B	19.83A	5.78B	5.76B
	0.5µL/L 1-MCP	17.62AB	16.45B	5.78B	5.74B
	5% $KMNO_4$	16.92B	19.89A	5.74B	5.73B
	10% $KMNO_4$	16.61B	17.81AB	5.89AB	5.97A
	10G ZEOLITE	16.18B	18.32AB	5.92A	5.94A
	20G ZEOLITE	16.82B	19.11A	5.91A	5.97A
	OPEN SHELF	16.21B	16.93B	5.98A	5.99A

RRA – Ethylene remediation agent; Means followed by the same alphabets in the same columns are not significantly different at 5% probability level using DMRT.

CONCLUSION

This study demonstrated that both preharvest fertilizer use and postharvest ethylene remediation strategies significantly influence the postharvest quality of tomato fruits. Appropriate fertilizer use, especially with NPK 15-15-15, produced fruits with better firmness at harvest and enhanced retention of textural quality during storage.

Among the ripening remediation treatments, 1-Methylcyclopropene (1-MCP) at concentrations of 0.3–0.5 μL/L and 5% Potassium permanganate ($KMnO_4$) consistently proved most effective in preserving fruit firmness, titratable acidity, and vitamin C content.

The comparable efficacy between higher 1-MCP concentrations and 5% $KMnO_4$ suggests that both approaches achieve significant ethylene signal reduction, though through fundamentally different mechanisms receptor inhibition versus chemical oxidation. Interaction between fertilizer type and remediation treatments revealed good synergistic effect. Open-shelf storage consistently resulted in the poorest quality outcomes across all parameters, emphasizing the necessity for active postharvest interventions, particularly in tropical ambient conditions.

RECOMMENDATIONS

For tomato production, fertilizer use, with emphasis on NPK 15-15-15, to establish baseline fruit quality with enhanced firmness and nutritional content at harvest should be encouraged. Adoption of combined approaches where fertility management is paired with postharvest ethylene management should be encouraged to maximize synergistic benefits on fruit quality retention.

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