

International Journal of Plant & Soil Science

Volume 38, Issue 11, Page 321-329, 2026; Article no.IJPSS.169459
ISSN: 2320-7035

Harnessing Arbuscular Mycorrhizal Fungi, Biochar and Kale Amendment to Enhance Fruit Quality and Extend the Shelf Life of Greenhouse Tomatoes

Titus Kiplagat Bawen [a*], Chiveu C. Josiah [a], Chebet K. Daniel [a] and Pixley K. Kipsumbai [b]

[a] Department of Crop and Soil Sciences, School of Agriculture and Biotechnology, University of Eldoret, P.O. Box 1125 - 30100, Eldoret, Kenya.
[b] Department of Biological Sciences, School of Science, University of Eldoret, P.O. Box 1125-30100, Eldoret, Kenya.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i116426

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/169459

Original Research Article

Received: 09/09/2026
Accepted: 03/11/2026
Published: 14/11/2026

Abstract

Tomato (*Solanum lycopersicum* L.) is considered one of the most profitable and popular vegetable crops grown in the world. The current study evaluated the individual and combined effects of AMF, biochar, and kale amendments on the physicochemical quality and shelf life of tomatoes. The experiment was conducted in a completely randomised design (CRD) for both greenhouse and laboratory experiments, each replicated four times. Evaluation of physicochemical properties was carried out on the day of harvest and shelf life was assessed for 30 days of storage at intervals of 3 days. The collected data were subjected to analysis of variance (ANOVA), and mean separations were performed using Duncan's Multiple Range Test (DMRT) at the 5% level of significance. Compared to the control, tomatoes from plants treated with AMF, biochar, and kale showed significantly higher levels of total soluble solids (TSS) and sugar-to-acid ratio (TSS/TA). The highest total soluble solid content (5.87 °Brix) was recorded for the treatment combination of AMF and kale. In contrast, the highest sugar-to-acid ratio (12.91%) was recorded for the combination of

**Corresponding Email(s): titus.bawen@uoeld.ac.ke;*

Contact Email(s): titus.bawen@uoeld.ac.ke;

Cite as: *Bawen, T. K., Josiah, C. C., Daniel, C. K., & Kipsumbai, P. K. (2026). Harnessing Arbuscular Mycorrhizal Fungi, Biochar and Kale Amendment to Enhance Fruit Quality and Extend the Shelf Life of Greenhouse Tomatoes. International Journal of Plant & Soil Science, 38(11), 321–329. https://doi.org/10.9734/ijpss/2026/v38i116426*

the AMF, biochar, and kale treatments. In terms of shelf life extension, the application of AMF, biochar, and kale amendments reduced weight loss and shrinkage indices of fruits during storage compared with those of the control. The maximum weight loss (18.39%) and shrinkage index were recorded in tomato fruits from the control treatment. In contrast, the lowest values were recorded in tomato fruits from the treatment with AMF, biochar, and kale amendment, at 9.15% and 25.4%, respectively. The findings of this study showed that pre-harvest application of AMF, biochar and kale has potential to enhance the physicochemical properties and storage quality of tomatoes.

Keywords: Arbuscular mycorrhiza fungi; biochar; TSS; TA; TSS/TA; shelf life.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is considered one of the most profitable vegetable crops grown in the world (Rashmi *et al.*, 2025). Kenya is ranked among the leading producers of tomatoes with an annual production of 482,951.50 metric tonnes in 2024 (Agriculture and Food Authority [AFA], 2025). In Kenya, tomatoes are among the most important exotic vegetables, contributing to approximately KES 23,485.39 million, which accounts for 29.5% of the value of exotic vegetables (AFA, 2024). Nutritionally, tomatoes are rich in vitamins A, B and C, as well as minerals such as iron, potassium, calcium, and zinc, which are beneficial for human health (Ali *et al*., 2021). Tomatoes are also rich in phytochemicals such as lycopene, which gives them their natural colour and has been linked to health benefits, including the prevention of heart disease, a reduced risk of cardiovascular conditions, and various types of cancer (Bukirwa *et al*., 2026; Kumar *et al*., 2026). Tomatoes, being of paramount interest, can be utilized in various forms, including fresh fruit, raw salads and several other products, including as an ingredient in many recipes or processed forms such as purées, tomato sauce and ketchup (Amr & Raie, 2022). In Kenya, tomato farming is economically important, and production has increased in response to growing demand in recent years. Tomatoes play a crucial role in guaranteeing food and nutrition security within sustainable food systems, which seek to improve the living standards of Kenyans. The tomato sector supports livelihoods, particularly for smallholder farmers, through employment and household income generation. In Kenya, tomato production has primarily been practised in open fields, accounting for 95% of the total production, while greenhouses accounting for 5%. However, due to climate change and rising demand, there has been a gradual shift towards adopting modern technologies, such as greenhouse farming, to enhance tomato production and meet the growing demand (Sanzua, 2021). The increase in production and consumption has led to higher consumer demand for higher-quality products (Owino *et al*., 2025). Despite the increase in production, tomatoes are highly perishable due to their softness, high respiration rates, and sensitivity to fungal rots, which limit their postharvest shelf life. The perishable nature of tomatoes poses a significant challenge in maintaining their quality and extending shelf life, making it difficult to achieve optimal consumer quality and food security. These losses stem from various factors such as inadequate preharvest techniques, improper handling, poor infrastructure and limited management capacity along the supply chain (Bukirwa *et al*., 2026). Tomato fruit quality is determined by colour, flavour, texture and nutritional characteristics. Consumer preferences are largely influenced by flavour and taste, which depend on the levels of soluble solids, sugar, and organic acids (Guo *et al*., 2026). Additionally, texture and flavour are important quality attributes of fresh market tomatoes, whereas soluble solids, titratable acidity and colour are major quality components of processing tomatoes (Machado *et al*., 2025). Tomato quality has attracted considerable attention due to increasing consumer demand for tasty, nutritious and safe food, driven by growing health and environmental awareness. One of the crucial agricultural practices that influence tomato quality before and after harvest is fertilisation (Al-Saif *et al*., 2024). The quality of tomato fruits after harvest largely depends on their quality at harvest. Therefore, improving preharvest practices to produce higher-quality tomato fruits at harvest is important. In a separate field study, preharvest mulching treatments were associated with differences in total soluble solids and titratable acidity in tomato fruits (Kumar *et al*., 2026).

Conventional approaches, such as synthetic fertilisers and chemical preservatives, have been used to improve tomato quality and shelf life. However, the intensive and continuous use of chemical inputs has increased to levels that threaten the environment and human health. Furthermore, extensive use of chemical fertilisers has given rise to a series of problems, including declines in soil fertility and crop quality (Hu *et al*., 2022; Sun *et al*., 2026). In response to consumers' concerns about the harmful effects of chemical residues on human health, environmental pollution, and regulatory restrictions on the use of synthetic chemicals, alternative, sustainable and environmentally friendly practices have received increasing attention. Among the environmentally friendly management practices that have attracted considerable attention are the use of biochar as a soil amendment, the use of arbuscular mycorrhizal fungi, and Brassica biofumigation. In tomato, biofertilizer treatments incorporating arbuscular mycorrhizal fungi (AMF) have been evaluated alongside other nutrient inputs, with differences reported in plant growth, yield and fruit-quality characteristics (Smitha & Markose, 2026). Experimental evidence also indicates that biochar and AMF can interact in phosphorus acquisition by tomato plants (Figueira-Galán *et al*., 2023). Greenhouse experiments have additionally examined AMF inoculation under differing nitrogen and phosphorus supply conditions and reported variation in tomato fruit-quality attributes (Ullah *et al*., 2025). With regard to postharvest outcomes, a biochar study reported lower tomato fruit weight loss and longer shelf life than in the untreated control (Adekiya *et al*., 2025). Although studies have reported positive effects of AMF, biochar and kale amendments on agronomic performance and disease suppression, research on their effects on the physicochemical quality and shelf life of tomatoes remains limited. Therefore, to comprehensively understand their effects on the physicochemical quality of tomatoes and shelf life, the current study aimed to address the existing gap by evaluating the individual and combined effects of AMF, biochar, and kale amendment, as a potential alternative to synthetic chemicals, for improving the physicochemical properties and shelf life of tomatoes.

2. Materials and Methods

2.1 Study Location

The study was conducted in the greenhouse and postharvest laboratory of the Department of Crop and Soil Sciences, University of Eldoret, at a latitude of 0°34' N and a longitude of 35°18' E, Kenya.

2.2 Preparation of Soil Substrate

The soil used in the study was collected from the university farm, air-dried, and then sieved through a 5 mm mesh. Soil sieving was intended to facilitate uniform mixing and remove any plant debris, fine roots, and biological residues. To improve soil texture, the sieved material was mixed with manure and sand at a 3:2:1 (soil:manure:sand) ratio. The soil mixture was then placed into plastic pots measuring 35 cm in height and 35 cm in diameter.

2.3 Seedling Establishment

Certified seeds of the tomato variety Prostar F1 were purchased and raised in seedling trays prefilled with sterilized coco-peat, vermiculite, and peat moss in a 5:3:1 ratio. Coco-peat was first soaked overnight to remove excess salts and other compounds and was then mixed with vermiculite and peat moss. Watering was done every two days until the seedlings germinated. Easygrow starter fertiliser containing NPK at a ratio of 18:20:21 + TE was applied at a rate of 2 g per litre once a week for three weeks, after which the plants were ready for transplanting. Before transplanting, the seedlings were hardened off by reducing the watering frequency and exposing them to sunlight.

2.4 Experimental Design and Layout

The greenhouse and postharvest experiments were conducted using a completely randomised design (CRD) with eight treatments and four replicates per treatment. The treatments were Control, arbuscular mycorrhizal fungi, Biochar, Kale, AMF x Biochar, AMF x Kale, Biochar x Kale, and AMF x Biochar x Kale.

2.4.1 Incorporation of Kale

A commercial kale variety, Ahadi F1, was used for the kale treatment. Three-week-old kale seedlings, var. Ahadi F1, were purchased and transplanted into the university farm. The seedlings were maintained until harvest, at the vegetative growth stage (60 days after transplanting). The kale leaves were harvested, finely chopped with a sharp knife, and immediately incorporated into the soil to a depth of about 10 cm from the top of the pot. The quantity of kale incorporated into the soil was 200 g of fresh weight per pot. A small amount of water was sprinkled to facilitate the release of isothiocyanates (ITCs). The pots were covered with a transparent polythene sheet for two weeks to limit the escape of gases during kale tissue biodegradation.

2.4.2 Biochar Application

For the biochar treatment, biochar obtained from Seedballs Kenya Limited was mixed with soil in the respective pots at a rate of 120 g/pot. For the biochar and kale treatment combination, pathogen-infested soil was first mixed with biochar at a rate of 120 g/pot, and then amended with macerated kale. The pots were then covered with a transparent polythene sheet for two weeks.

2.4.3 AMF Inoculation

AMF inoculation was applied during seedling transplantation, when 50 g of AMF inoculum was added to the planting hole, 5 cm below the soil surface, in the prepared soil (Chebet *et al*., 2021). The AMF inoculum was thoroughly mixed with the planting soil to ensure even distribution.

The control received no additional amendment.

2.4.4 Crop Establishment and Management

One healthy and vigorous tomato seedling was transplanted into each plastic pot measuring 35 cm in height and 35 cm in diameter, which was filled with 6 kg of sieved soil containing the prepared treatments. The pots were arranged 60 cm apart, with 45 cm between rows. Plants were staked with sisal twine when plants reached 30 cm in height, which was tied to a binding-wire trellis. Pruning was performed to maintain one stem per plant, and any lateral shoots were promptly removed as they emerged. Plants were watered every morning and evening, and soil moisture levels were monitored using a soil moisture meter (FIELDSCOUT® TDR 150 Soil Moisture Meter, Spectrum Technologies, Inc.). Weeds were removed manually from the pots, and pests were managed using an integrated pest management approach.

2.5 Physicochemical Analysis

Tomato fruits were hand-harvested at red maturity, and fruits from each treatment were placed in labelled khaki bags before being taken to the Department of Crop and Soil Sciences postharvest laboratory. In the laboratory, the harvested tomato fruits were cleaned with tap water to remove surface dust and then air-dried at room temperature. Eight undamaged tomato fruits per treatment were randomly selected according to size and colour. The colour of the tomato fruits was determined using the RHS Color Chart (Sixth Edition, 2015). Four of the selected tomato fruits were used to measure quality parameters immediately, and the remaining four were used to assess storage quality. The measured quality parameters were total soluble solids (TSS), titratable acidity (TA), and sugar-to-acid ratio (TSS: TA). The shelf life of tomato fruits, as influenced by preharvest application of AMF, biochar, and kale, was determined by monitoring and recording weight loss and shrinkage index from day 0 to day 30 at 3-day intervals.

2.5.1 Total Soluble Solids (°Brix)

The total soluble solids (TSS) content was determined using a portable refractometer (Model: ATC, GRIFFCHEM™, China) with a range of 0-30 °Brix. The refractometer was first standardised by adding a drop of sterile distilled water to the prism, with a TSS reading of 0 °Brix, after which the water was wiped off the prism. Two drops of tomato juice from each treatment were placed on the refractometer prism, and the reading was recorded and expressed as °Brix. Between treatments, refractometer standardization was repeated before each sample reading.

2.5.2 Titratable Acidity (Citric Acid %)

Titratable acidity (TA) was determined by titration, as described by Gharezi *et al*. (2012). Fifty grams of tomato pulp was homogenized with 30 mL of distilled water using a kitchen blender (Model: SGP22). The homogenised samples from each treatment were filtered through Whatman® filter paper, and the supernatant was transferred into a 100 mL conical flask, with the final volume made up to the mark with distilled water. Ten millilitres (10 mL) of the filtered supernatant was taken from each treatment and transferred into a conical flask. Three drops of 1% phenolphthalein indicator were added, and the solution was mixed. The titratable acidity (TA) of the tomato juice was determined by titrating the contents in the conical flask against 0.1 N sodium hydroxide (NaOH) solution until the appearance of a permanent pale pink color (Kumar *et al*., 2013). The final volume of NaOH solution used for titration was recorded, and the percentage titratable acidity was calculated using the following equation:

$$\% \text{ Acid} = \frac{\text{Titre Value x Normality of NaOH x m.eq.wt. of acid}}{\text{Volume of Sample}} X\ 100$$

2.5.3 Weight Loss (%)

The tomato fruits from each treatment were weighed on the first day of storage to obtain the initial weight using a digital weighing balance (Model: TP-B2000) with an accuracy of 0.1 g. The weight loss of the tomato samples was assessed every three days over 30 days. Fruit weight loss was calculated from the weight at the beginning of each measurement period using the formula described by Dhami *et al*. (2023).

$$\text{Weight loss (\%)} = \frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}} \text{X } 100$$

2.5.4 Shrinkage Index %

The shrinkage index was assessed by observing visible changes in the skin of stored tomatoes. It was calculated from changes in the average dimensions (length and breadth) of tomato fruits at three-day intervals over 30 days, using a digital Vernier caliper. The results were expressed as the shrinkage index as a percentage relative to the initial diameter, using the formula below.

$$\text{Shrinkage Index} = \frac{D0 - D1}{D0} \text{X } 100$$

where D0 = average length and breadth on day zero and D1 = average length and breadth on the respective day of storage.

2.6 Data Analysis

The data collected were subjected to analysis of variance (ANOVA) at a 5% level of significance using GenStat statistical software, version 16.0, VSN International Ltd. Mean separation was conducted using the Duncan's multiple range test (DMRT) at the 5% level of significance.

3. Results

3.1 Effects of AMF, Biochar and Kale Amendment on the Total Soluble Solids (TSS)

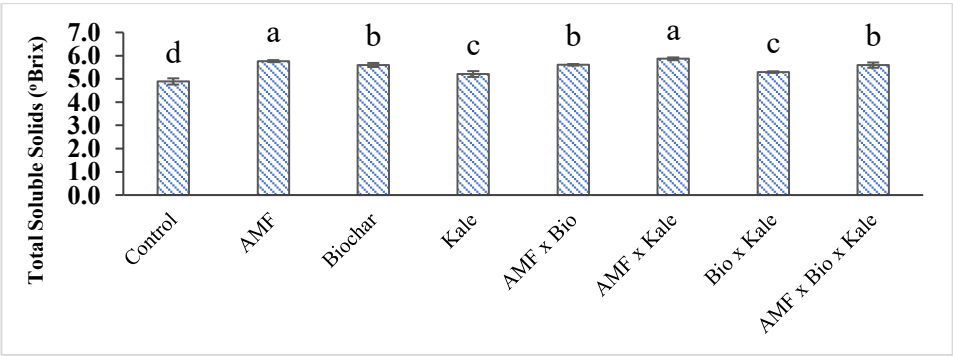


Fig. 1. Preharvest treatment's effect on the Total Soluble Solids of tomato fruit

Means followed by different letters differ significantly across treatments at 5% level of significance (DMRT, P = .05). Error bars signify the standard deviation

The total soluble solids (TSS) were significantly influenced by the application of AMF, biochar, and kale biofumigation (P =.05). Compared with the control, the total soluble solids content increased significantly in tomato fruits with the individual and combined applications of AMF, biochar, and kale. Among the treatments, the combination of AMF and kale produced the highest TSS value in tomato fruits (5.87 °Brix), which was not significantly different from that of tomato fruits from plants inoculated with AMF alone (5.77 °Brix). On the other hand, the lowest TSS value was recorded for tomato fruits from the control treatment (4.89°Brix).

3.2 Effects of AMF, Biochar and Kale Amendment on the Titratable Acidity (TA)

The application of AMF, biochar, and kale amendments significantly affected the titratable acidity of tomato fruits (P = .05). Compared with the control, the titratable acidity content decreased significantly in tomato fruits with the individual and combined applications of AMF, biochar, and kale. The highest titratable acidity was recorded in tomato fruits from the control treatment (0.60%) whereas tomato fruits from the individual or combined application of AMF, biochar and kale had lower titratable acidity, with the combined application of AMF, biochar, and kale amendment having a titratable acidity of 0.43%, the lowest among all treatments.

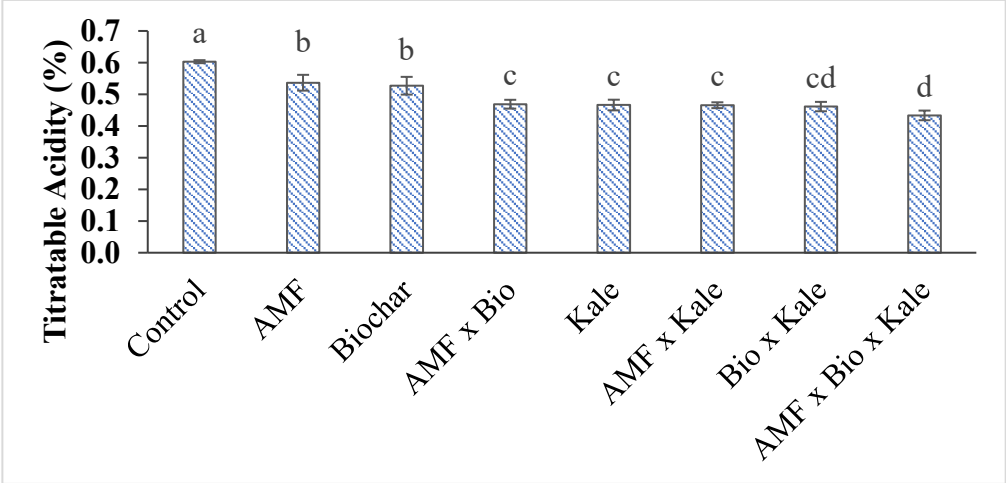


Fig. 2. Pre-harvest treatment's effect on Titratable Acidity of tomato fruit

Means followed by different letters differ significantly across treatments at 5% level of significance (DMRT, P = .05). Error bars signify the standard deviation

3.3 Effects of AMF, Biochar and Kale Amendment on the Sugar Acid Ratio

The application of AMF, biochar, and kale amendments significantly affected the sugar-to-acid ratio in tomato fruits compared with the control (P = .05). The highest sugar-to-acid ratio was observed in tomato fruits from the combined application of AMF, biochar, and kale (12.91%), followed by the combination of AMF and kale amendment (12.61%). On the other hand, the lowest sugar-to-acid ratio was recorded in tomato fruits from the control treatment (8.11%).

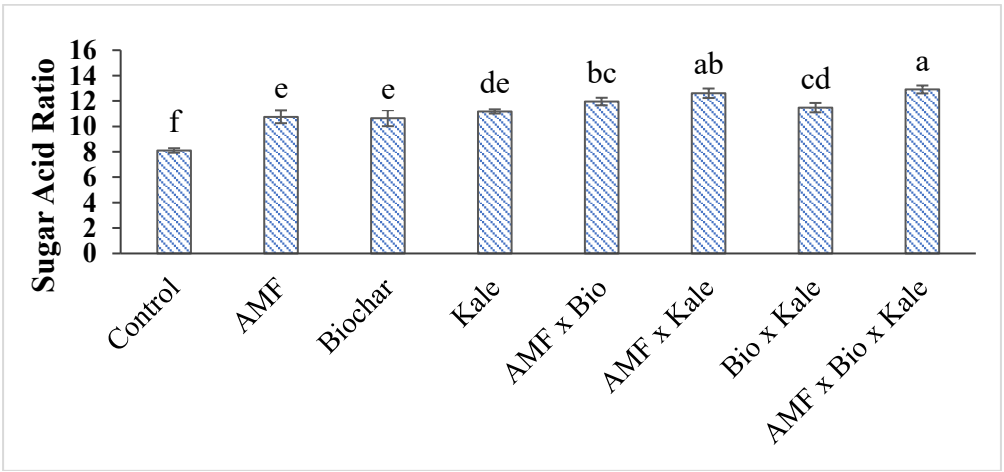


Fig. 3. Pre-harvest treatment's effect on the Sugar to Acid Ratio of tomato fruit

Means followed by different letters differ significantly across treatments at 5% level of significance (DMRT, P = .05). Error bars signify the standard deviation

3.4 Physiological Loss in Weight (PLW %)

The application of AMF, biochar, and kale amendments significantly affected the percentage weight loss of tomato fruits after 30 days of storage at room temperature (P = .05). Generally, the percentage weight loss in tomato fruits increased gradually as the storage period increased, regardless of treatment. During the first three days of storage, all treatments significantly affected the percentage weight loss of tomato fruits. However, from day 6 onward, the percentage weight loss of tomato fruits from the control increased more rapidly than that of tomato fruits from the other treatments. Compared with the control, the percentage weight loss of tomato fruits from the individual or combined applications of AMF, biochar, and kale amendment was lower (Fig. 4). Throughout the storage period, the percentage weight loss was lowest in tomato fruits from the triple application of AMF, biochar and kale. In contrast, the highest percent weight loss was recorded for tomato fruits in the control treatment. At the end of the storage period, the highest percent weight loss (18.39%) was recorded for tomato fruits in the control treatment. The lowest percent weight loss was recorded in tomato fruits from the triple application of AMF, biochar, and kale (9.15%), which was the lowest among all treatments.

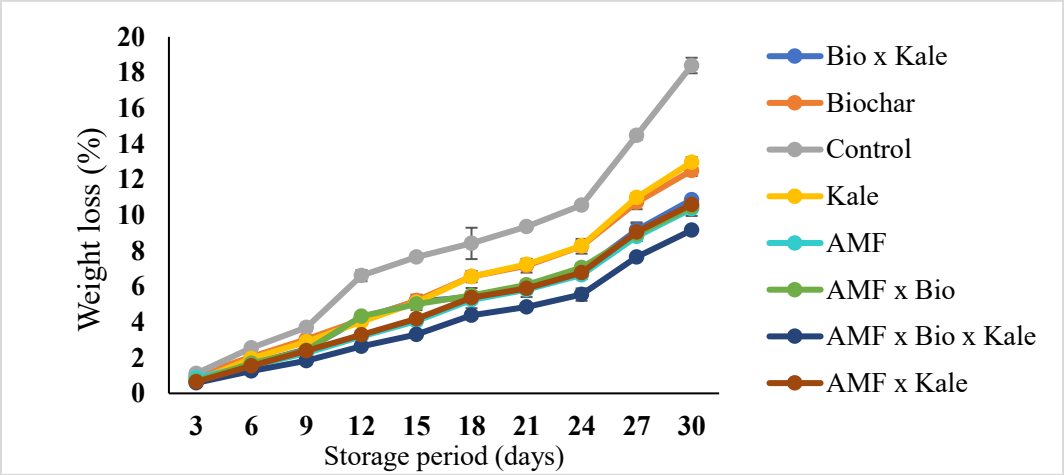


Fig. 4. Preharvest treatment effect on the weight loss of tomato fruit

3.5 Shrinkage Index

The shrinkage index of harvested tomato fruits was monitored for 30 days at ambient temperature. A significant difference was observed among treatments in their effects on the tomato shrinkage index (P = .05). The shrinkage index increased as the storage period increased, irrespective of treatment. During the first six days of storage, shrinkage indices increased slowly, regardless of the treatment. However, as storage progressed, tomatoes from the control treatment showed the highest shrinkage index, whereas those from the triple application of AMF, biochar, and kale showed the lowest. At the end of the storage period, tomato fruits from the control treatment recorded the highest shrinkage index (32.68%), whereas the lowest shrinkage index was recorded in tomato fruits from the triple application of AMF, biochar and kale (25.4%) (Fig. 5).

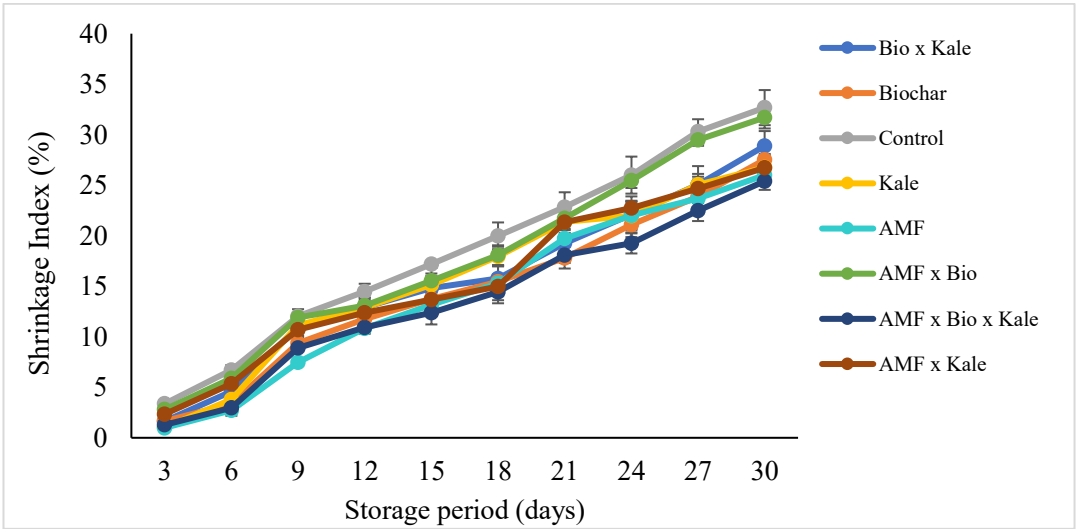


Fig. 5. Preharvest treatment effect on shrinkage indices of tomato fruit

4. Discussion

The total soluble solids (TSS), titratable acidity (TA), and sugar-acid ratio (TSS: TA) in tomato fruits are key indicators for assessing fruit quality. The findings of this study suggest that the application of AMF, biochar and kale significantly increased total soluble solids content, which includes dissolved solids such as sucrose and fructose and indicates fruit sweetness. Similarly, the positive effect of mycorrhiza on total soluble solids is consistent with previous research (Chafai *et al*., 2023; Ullah *et al*., 2023). The increase in total soluble solids may be due to AMF's ability to explore a large volume of soil via its extraradical mycelium and efficiently transfer nutrients from the soil to the plant, thereby enhancing the overall nutritional status of the plant. Furthermore, as reported by Cordeiro *et al.* (2019), AMF may improve fruit quality by boosting the photosynthetic rate and facilitating the translocation of sucrose and organic acids to fruits, thereby increasing sucrose concentration. The increased total soluble solids content observed with biochar treatments is consistent with findings from Lei *et al*. (2024) and Zhao *et al*. (2024), who reported higher soluble solids in tomatoes grown in biochar-amended soils. Overall, the increase in total soluble solids following the application of AMF, biochar and kale amendments could be attributed to improved nutrient and water uptake. Biochar can enhance soil water retention due to its high water-holding capacity, while AMF can improve nutrient and water uptake through its association with plant roots. Under conditions of ample nutrient supply, plants tend to produce more sugars through increased photosynthesis, resulting in higher carbohydrate and sugar levels during fruit ripening.

Regarding titratable acidity, the control treatment showed the highest values, whereas the treatments with AMF, biochar, and kale amendment all exhibited decreases in acidity. The higher titratable acidity in the control might have been due to nutrient deficiency, which hindered plant growth and development, possibly reducing energy capture and inhibiting sugar production, thereby affecting fruit acidity. However, in this study, the results indicated that the AMF, biochar, and kale amendments significantly reduced titratable acidity. Less acidic tomatoes may be preferred by consumers who favour milder flavours.

The balance between acidity and sweetness is important for flavour and significantly influences consumer preference for tomatoes, especially in salads. In the present study, the application of AMF, biochar, and kale amendments favoured sugar accumulation relative to organic acids, resulting in an increased sugar-to-acid ratio. This may reflect lower organic acid levels in relation to the measured total soluble solids. The increased sugar-to-acid ratio may be associated with nutrient availability and the observed differences in fruit quality relative to the control.

Tomato fruits are highly perishable and are susceptible to postharvest losses, resulting in a shorter shelf life. Weight loss in fruits is one of the most important indicators of quality maintenance during postharvest storage. Fruit weight loss is associated with respiration, transpiration through the peel and other physiological changes. In the present study, the application of AMF, biochar and kale amendments improved the storage quality of tomato fruits by reducing weight loss and shrinkage indices. During storage, the weight loss and shrinkage indices gradually increased in tomato fruits from the control treatment; however, the application of AMF, biochar, and kale amendment appeared to slow these changes. Lower weight loss and shrinkage indices were recorded in tomato fruits treated with AMF, biochar, and kale amendment throughout the storage period.

Additionally, a lower shrinkage index was recorded in tomato fruits following the application of AMF, biochar, and kale amendment. The observed improvement in tomato shelf life under the combined application of AMF, biochar, and kale amendment may reflect interactions among these treatments. Arbuscular mycorrhizal fungi may increase the content of biologically active substances in fruits, thereby extending storage life before spoilage (Alam *et al*., 2023). This aligns with findings from Anah and Eze (2022), who reported that bell pepper fruits from plants inoculated with arbuscular mycorrhiza had a longer shelf life than those from non-inoculated plants. Additionally, AMF inoculation has been reported to increase the concentration of essential nutrients, especially phosphorus, potassium, zinc, and calcium (Sellitto *et al*., 2019). Calcium is crucial for maintaining membrane stability and cell wall integrity, both of which are vital for extending fruit shelf life. Studies by Alam *et al*. (2023) and Carillo *et al*. (2020) reported that AMF-inoculated tomato plants exhibited higher calcium levels, resulting in better fruit firmness, lower moisture loss, and possibly longer shelf life. As calcium contributes to cell membrane stability, a low calcium concentration reduces membrane integrity. The integrated application of AMF, biochar, and kale amendments reduced weight loss and the shrinkage index throughout the storage period. These observations suggest that the triple application of AMF, biochar, and kale can reduce tomato shrinkage and weight loss, and may help maintain tomato quality during storage.

5. Conclusions

The study found that preharvest applications of arbuscular mycorrhizal fungi (AMF), biochar and kale amendments were associated with differences in tomato physicochemical characteristics and physical condition during storage. Compared with untreated fruits, tomatoes obtained from amended plants generally showed higher total soluble solids, lower titratable acidity and higher sugar-to-acid ratios. The combination of AMF and kale produced the highest recorded total soluble solids content (5.87 °Brix), while the three-amendment combination produced the highest sugar-to-acid ratio (12.91). During 30 days of storage at room temperature, all treatments showed increasing weight loss and shrinkage, but fruits from the combined AMF, biochar and kale treatment had the lowest values at the final assessment. Specifically, weight loss and shrinkage index were 9.15% and 25.4%, respectively, for the triple treatment, compared with 18.39% and 32.68% in the control. These findings suggest that the combined preharvest treatment may help maintain selected quality attributes of tomato fruits during ambient storage. Its practical performance should be interpreted within the specific cultivar, greenhouse conditions and observation period examined in this study.

6. Limitations

This study was conducted using a single tomato cultivar under greenhouse conditions and evaluated fruit quality during one 30-day storage period at room temperature. Consequently, the results may not represent responses under other cultivation systems, cultivars

or storage environments. Postharvest performance was assessed mainly through weight loss and shrinkage index, while a separate spoilage-based shelf-life endpoint was not reported. Therefore, the observed reductions in physical deterioration should not be interpreted as a directly measured extension in the number of marketable storage days.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

Adekiya, A. O., Ogunbode, T. O., Esan, V. I., Adedokun, O., Olatubi, I. V., & Ayegboyin, M. H. (2025). Short-term effects of biochar on soil chemical properties, growth, yield, quality, and shelf life of tomato. *Scientific Reports, 15*, Article 24965. https://doi.org/10.1038/s41598-025-10411-5

Agriculture and Food Authority. (2024). *AFA yearbook of statistics 2024*. Agriculture and Food Authority.

Agriculture and Food Authority. (2025). *AFA yearbook of statistics 2025*. Agriculture and Food Authority.

Alam, M. Z., Choudhury, T. R., & Mridha, M. A. U. (2023). Arbuscular mycorrhizal fungi enhance biomass growth, mineral content, and antioxidant activity in tomato plants under drought stress. *Journal of Food Quality, 2023*, Article 2581608. https://doi.org/10.1155/2023/2581608

Ali, M. Y., Sina, A. A. I., Khandker, S. S., Neesa, L., Tanvir, E. M., Kabir, A., Khalil, M. I., & Gan, S. H. (2021). Nutritional composition and bioactive compounds in tomatoes and their impact on human health and disease: A review. *Foods, 10*(1), Article 45. https://doi.org/10.3390/foods10010045

Al-Saif, A. M., Ahmed, M. E. M., Taha, M. A., Sharma, A., El-Sheshtawy, A.-N. A., Abouelsaad, I. A., El-Serafy, R. S., & Mahdy, R. M. (2024). Preharvest applications improve the postharvest storage and quality of tomato fruits by enhancing the nutritional value and antioxidant system. *Horticulturae, 10*(12), Article 1248. https://doi.org/10.3390/horticulturae10121248

Amr, A., & Raie, W. Y. (2022). Tomato components and quality parameters: A review. *Jordan Journal of Agricultural Sciences, 18*(3), 199–220. https://doi.org/10.35516/jjas.v18i3.444

Anah, C. O., & Eze, E. U. (2022). Shelf life and visual fruit quality of bell pepper fruits exposed to arbuscular mycorrhizal fungi in Owerri. *International Journal of Scientific Engineering and Applied Science, 8*(2), 1–8.

Bukirwa, N. C., Ngigi, M., & Gitau, R. K. (2026). Exploring smallholder farmers' awareness and perceptions of post-harvest tomato losses, Kirinyaga County, Kenya: A thematic analysis. *Agricultural Sciences, 17*(8), 781–799. https://doi.org/10.4236/as.2026.178045

Carillo, P., Kyratzis, A., Kyriacou, M. C., Dell'Aversana, E., Fusco, G. M., Corrado, G., & Rouphael, Y. (2020). Biostimulatory action of arbuscular mycorrhizal fungi enhances productivity, functional and sensory quality in 'Piennolo del Vesuvio' cherry tomato landraces. *Agronomy, 10*(6), Article 911. https://doi.org/10.3390/agronomy10060911

Chafai, W., Haddioui, K., Serghini-Caid, H., Labazi, H., AlZain, M. N., Noman, O., Parvez, M. K., Addi, M., & Khalid, A. (2023). Impact of arbuscular mycorrhizal fungal strains isolated from soil on the growth, yield, and fruit quality of tomato plants under different fertilization regimens. *Horticulturae, 9*(9), Article 973. https://doi.org/10.3390/horticulturae9090973

Chebet, D. K., Wanzala, F. K., & Wamocho, L. S. (2021). Effect of arbuscular mycorrhiza fungi on the growth, nutrient uptake, root infectivity and soil colonisation of rough lemon (*Citrus jambhiri*) seedlings. *International Journal of Agronomy and Agricultural Research, 18*(2), 25–31.

Cordeiro, E. C. N., Resende, J. T. V. de, Córdova, K. R. V., Nascimento, D. A., Saggin Júnior, O. J., Zeist, A. R., & Favaro, R. (2019). Arbuscular mycorrhizal fungi action on the quality of strawberry fruits. *Horticultura Brasileira, 37*(4), 437–444. https://doi.org/10.1590/S0102-053620190412

Dhami, J. C., Katuwal, D. R., Awasthi, K. R., & Dhami, K. S. (2023). Effect of different post-harvest treatments on quality and shelf life of tomato (*Lycopersicon esculentum* Mill.) fruits during storage. *Nepalese Horticulture, 17*(1), 41–48. https://doi.org/10.3126/nh.v17i1.60631

Figueira-Galán, D., Heupel, S., Duelli, G., Morgano, M. T., Stapf, D., & Requena, N. (2023). Exploring the synergistic effects of biochar and arbuscular mycorrhizal fungi on phosphorus acquisition in tomato plants by using gene expression analyses. *Science of the Total Environment, 884*, Article 163506. https://doi.org/10.1016/j.scitotenv.2023.163506

Gharezi, M., Joshi, N., & Sadeghian, E. (2012). Effect of post harvest treatment on stored cherry tomatoes. *Journal of Nutrition & Food Sciences, 2*(8), Article 157. https://doi.org/10.4172/2155-9600.1000157

Guo, X., Zhou, S., Li, Y., Li, L., & Han, Z. (2026). The dissection of tomato flavor and key nutrients: Chemical composition, biological function and molecular regulation. *Journal of the Science of Food and Agriculture*. Advance online publication. https://doi.org/10.1002/jsfa.70750

Hu, G.-Q., Ma, X.-X., Li, X.-H., & Wang, H. (2022). Evaluation of organic substitution based on vegetable yield and soil fertility. *Environmental Pollutants and Bioavailability, 34*(1), 162–170. https://doi.org/10.1080/26395940.2022.2064335

Kumar, A., Kumar, V., Trivedi, H., Pandey, S., Ojha, J., & Singh, S. (2026). Influence of organic and inorganic mulches on fruit quality attributes of tomato (*Solanum lycopersicum* L.) cv. Azad T-6. *Plant Cell Biotechnology and Molecular Biology, 27*(7–8), 255–262. https://doi.org/10.56557/pcbmb/2026/v27i7-810789

Kumar, A., Vikanksha, & Singh, J. (2026). Nutritional value and health benefits of solanaceous crops. In M. K. Dubey, K. Verma, K. Ahmed, & S. Dubey (Eds.), *Artificial intelligence and sustainable agriculture for Solanaceae crops* (pp. 25–43). CRC Press. https://doi.org/10.1201/9781003647423-2

Kumar, R., Srivastava, K., Singh, R. K., & Kumar, V. (2013). Heterosis for quality attributes in tomato (*Lycopersicon esculentum* Mill.). *Vegetos, 26*(1), 101–106. https://doi.org/10.5958/j.2229-4473.26.1.015

Lei, Y., Xu, L., Wang, M., Sun, S., Yang, Y., & Xu, C. (2024). Effects of biochar application on tomato yield and fruit quality: A meta-analysis. *Sustainability, 16*(15), Article 6397. https://doi.org/10.3390/su16156397

Machado, T. de A., Fernandes, H. C., Guimarães, C. M., Megguer, C. A., Costa, W. P. da, Santos, F. L., & Santos, N. T. (2025). Physicochemical attributes of tomatoes after different forms of harvesting and transportation for industrial processing. *PLOS ONE, 20*(4), Article e0319668. https://doi.org/10.1371/journal.pone.0319668

Owino, W., Kahenya, P., Wafula, E., & Otieno, G. (2025). Food loss and waste reduction in specific fruit and vegetable value chains in Eastern Africa. *Foods, 14*(22), Article 3938. https://doi.org/10.3390/foods14223938

Rashmi, V. M., Sharma, P., Kaur, M., Sharma, A., Kumar, N., Dwivedi, A., & Sanadya, S. K. (2025). Genetic diversity and population structure of tomato (*Solanum lycopersicum* L.) genotypes. *Genetika, 57*(1), 37–52. https://doi.org/10.2298/GENSR2501037R

Sanzua, L. J. (2021). *Evaluating performance of greenhouse technology in the hot humid coastal region of Kenya* (Doctoral dissertation, Pwani University). Pwani University Institutional Repository.

Sellitto, V. M., Golubkina, N. A., Pietrantonio, L., Cozzolino, E., Cuciniello, A., Cenvinzo, V., Florin, I., & Caruso, G. (2019). Tomato yield, quality, mineral composition and antioxidants as affected by beneficial microorganisms under soil salinity induced by balanced nutrient solutions. *Agriculture, 9*(5), Article 110. https://doi.org/10.3390/agriculture9050110

Smitha, K. O., & Markose, B. (2026). Efficacy of biofertilizers on growth, quality and yield of tomato [*Solanum lycopersicum* (L.) cv. Anagha]. *Journal of Scientific Research and Reports, 32*(1), 462–472. https://doi.org/10.9734/jsrr/2026/v32i13912

Sun, G., Deng, Z., Zhao, R., Zhao, F., Wang, T., Li, Y., Song, Y., Deng, S., Du, K., Lyu, C., Tang, D., & Wang, J. (2026). Effects of biochar combined with organic fertilizer on soil properties and the yield and quality of sweet potato. *Horticulturae, 12*(2), Article 235. https://doi.org/10.3390/horticulturae12020235

Ullah, F., Ullah, H., Ishfaq, M., Gul, S. L., Kumar, T., & Li, Z. (2023). Improvement of nutritional quality of tomato fruit with *Funneliformis mosseae* inoculation under greenhouse conditions. *Horticulturae, 9*(4), Article 448. https://doi.org/10.3390/horticulturae9040448

Ullah, F., Zaman, F., Ishfaq, M., Ullah, H., Wang, C., Li, Z., & Geilfus, C.-M. (2025). Sustainable greenhouse tomato production: Benefits of inoculation with arbuscular mycorrhizal fungi under low nitrogen and phosphorus conditions. *Plant-Environment Interactions, 6*(6), Article e70058. https://doi.org/10.1002/pei3.70058

Zhao, W., Wu, K., Wu, Y., Yu, H., Cao, W., & Ma, H. (2024). Effects of biochar amendment on greenhouse tomato quality, nutrient uptake and use efficiency under various irrigation and fertilization regimes. *Scientia Horticulturae, 337*, Article 113441. https://doi.org/10.1016/j.scienta.2024.113441

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2026): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:
The peer review history for this paper can be accessed here: https://pr.sdiarticle5.com/review-history/169459