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Tomato crop resilience via grafting by improving the yield stability and nutritional quality under drought conditions

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Introduction: Water scarcity is a major abiotic stress that restricts tomato (*Solanum lycopersicum* L.) productivity and fruit quality, especially in arid and semi-arid regions. Grafting, by combining desirable traits from different genotypes, has emerged as a promising agronomic technique to enhance crop performance under stress. This study aims to investigate the comparative effects of drought stress on grafted and non-grafted tomato plants, focusing on fruit yield and nutritional quality.

Methods: Experimental trials were conducted in both controlled and drought-stressed environments. Tomato scions were grafted onto vigorous, drought-tolerant rootstocks and compared with non-grafted controls under identical irrigation regimes. Key parameters measured included total fruit yield, marketable yield, average fruit weight, and nutritional quality attributes such as lycopene content, vitamin C, total soluble solids (TSS), and titratable acidity.

Results: Grafted tomato plants exhibited superior performance compared to non-grafted controls under both conditions. Grafted plants consistently produced higher total and marketable yields, as well as greater average fruit weight. Nutritional quality was also enhanced in grafted tomatoes, which showed significantly higher concentrations of lycopene, vitamin C, TSS, and titratable acidity. In contrast, drought-stressed non-grafted plants experienced reductions in both yield and nutritional quality, including smaller fruit size and lower levels of bioactive compounds.

Discussion: The findings underscore the effectiveness of grafting as a sustainable strategy to mitigate drought stress in tomato cultivation. Enhanced yield and improved nutritional profiles in grafted plants indicate potential benefits for flavor, antioxidant capacity, and consumer acceptance. However, the study's limitations include the absence of a standard commercial rootstock for direct comparison and the lack of stress imposition at uniform intervals. Future research should address rootstock-scion compatibility and evaluate long-term field performance to optimize grafting for commercial tomato production in water-limited environments.

KEYWORDS

drought, grafting, phytonutrients, postharvest, resilience, rootstock, tomato

Introduction

Tomato grafting is a common practice to enhance its resilience such as studies from Zia et al. (2021) observed higher relative water content, delayed wilting, and improved osmotic adjustment under drought stress. In another study mitigation and negative impacts of drought was reviewed, and consolidated that grafting can be widely adopted in vegetable production as a sustainable agronomic practice (Lee et al., 2010). Furthermore, grafting enhances tolerance to temperature extremes and improves vegetative growth parameters such as plant height, stem thickness, leaf area, and number of fruits per plant, thereby contributing to greater yield stability (Lee and Oda, 2003; López-Hinojosa et al., 2021). In terms of disease resistance, grafting onto resistant rootstocks has proven highly effective against soil-borne pathogens such as *Fusarium oxysporum*, *Verticillium dahliae*, and *Ralstonia solanacearum* (Louws et al., 2010). At the molecular level, transcriptomic and proteomic studies have revealed that grafting modulates key stress-responsive genes and proteins involved in hormone signaling, antioxidant defense, and transport processes, contributing to enhanced physiological homeostasis (Razi and Muneer, 2023; Hassan M. M. et al., 2021).

Grafting involves combining a high-yielding scion with a rootstock possessing superior tolerance traits, allowing the scion to benefit from enhanced water and nutrient uptake, improved root vigor, and increased resistance to abiotic stresses such as drought and salinity (Schwarz et al., 2010; Colla et al., 2010a; Kawaguchi, 2008). Several studies report that grafted tomato plants maintain higher stomatal conductance, chlorophyll content, and relative water content under water-deficit conditions, resulting in better growth and yield stability compared to non-grafted plants (Djidonou et al., 2013; Savvas et al., 2010). Yield improvements in grafted tomatoes under drought stress have been attributed to the vigorous root system of tolerant rootstocks, which facilitate more efficient water uptake and maintain nutrient absorption even under limited irrigation (Ruiz et al., 2020). For example, rootstocks like *Maxifort*, “Beaufort”, and wild relatives such as *Solanum habrochaites* and *S. pimpinellifolium* have shown potential to enhance tomato drought tolerance (Colla et al., 2010a; Schwarz et al., 2010). However, the performance of grafted plants can be highly dependent on the compatibility and interaction between rootstock and scion genotypes, highlighting the need for careful selection of grafting partners (Rouphael et al., 2012).

In addition to yield, grafting can influence fruit nutritional quality under drought stress (Harini et al., 2019). Studies have demonstrated that grafted tomatoes often retain or improve important quality parameters, such as total soluble solids (TSS), lycopene content, vitamin C concentration, and antioxidant activity, compared to non-grafted plants grown under similar stress conditions (Soteriou and Kyriacou, 2015; Turhan et al., 2011; Wang et al., 2015). These improvements are believed to result from rootstock-induced modulation of plant metabolism and stress signaling pathways, which help preserve fruit quality despite water limitation (Rouphael et al., 2010). Nonetheless, variations in fruit quality response have been observed depending on environmental conditions, rootstock-scion combinations, and the severity and duration of drought stress (Kyriacou et al., 2017).

Despite the recognized benefits of grafting, several research gaps persist. There is a lack of comprehensive studies that simultaneously assess both yield and detailed nutritional quality traits of grafted and non-grafted tomatoes under drought stressed conditions. Selecting appropriate rootstock and scion combinations, together with enhancing our comprehension of the physiological and molecular interactions in grafted plants, is essential for augmenting drought tolerance in crops (Mahapatra et al., 2025a). Moreover, most research has focused on short-term physiological and morphological responses, with limited understanding of the yield and fruit quality under grafting-induced drought tolerance. Additionally, the variability in rootstock and scion genotypes across different agroecological zones has not been sufficiently explored to develop region-specific recommendations.

To address these gaps, this study aims to investigate the comparative impacts of grafted vs. non-grafted tomato cultivars on fruit output and their nutritional value under regulated drought stress environments. The objective of this study is to discover rootstock-scion pairings that enhance yield and quality in water-scarce conditions and to further gain an understanding of grafting as a successful approach for improving tomato resilience to drought.

Plant material and treatments

Seedling preparation and plant grafting

In this experiment, two tomato genotypes (*Solanum lycopersicum*), Shivam and Arka Samrat, were selected based on their growth characteristics and their prevalence in local farming areas of Tamil Nadu and Karnataka, respectively. The selection of the genotypes is presented in our previous work (Mahapatra et al., 2025b). While using locally available cultivars as rootstocks was cost-conscious decision and better suited to local soil and climate conditions, as well as more popular among growers than commercial rootstocks. The Shivam seeds were obtained from a locally certified government seed vendor, Rajamanickam Seed Shop, while the Arka Samrat seeds were procured from the Indian Institute of Horticultural Research (IIHR), Bengaluru, India. The seeds of both genotypes were surface-sterilized by soaking in 1% sodium hypochlorite solution, followed by rinsing three to four times with distilled water. The sterilized seeds were then sown in germination trays (Portrays) filled with a mixture of red soil, sand, and vermicompost in equal proportions (1:1:1). The trays were placed in a greenhouse at the School of Agriculture Innovation and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore, India. The greenhouse environment was controlled with a photoperiod of 12 h of light and 12 h of darkness, a maximum temperature between 25 and 30 °C, and relative humidity in the range of 60 to 80%. The trays were regularly monitored, and thinning was performed as required to ensure healthy seedling growth. After 25 days, when the seedlings had reached an appropriate vegetative stage, grafting was carried out.

Two grafting combinations were performed using the following rootstock and scion pairs: (I) Shivam as rootstock with Arka Samrat as scion, and (II) Arka Samrat as rootstock with Shivam as scion.

Since the scion plays a crucial role in graft compatibility and drought stress resistance (Mahapatra et al., 2025a,b), the genotypes Shivam and Arka Samrat were selected as rootstock and scion, respectively, and grafted to evaluate their compatibility. Seedlings were prepared for grafting at the appropriate time, specifically when they reached the vegetative stage, 25 days after sowing. Grafting was carried out early in the morning using the cleft grafting method (Supplementary Figure 1), provided the rootstock seedlings were sufficiently vigorous. Subsequent to grafting, all homografts were covered in clear plastic that maintained humidity levels between 90% and 95% and temperatures ranging from 25 to 28 °C (Mahapatra et al., 2025a). This environment was maintained to promote healing and reduce water loss. Two weeks after grafting, once the plants had survived and the graft junctions had fully healed, healthy and uniform plants of similar size were selected and transferred to the field.

Field preparation and transplantation

A comparative study of grafted and non-grafted tomato genotypes was conducted during the Rabi season of 2024–2025 (November 2024 to April 2025) to analyze yield performance. Four different genotypes were prepared for transplantation: G1—Shivam (non-grafted), G2—Arka Samrat (non-grafted), G3—Shivam/Arka Samrat (rootstock/scion), and G4—Arka Samrat/Shivam (rootstock/scion) (Table 1). Field preparation was carried out following the standard guidelines prescribed by State Agricultural University.

The experimental field measured 18 m × 35.5 m and was divided into 24 equal plots, each measuring 4 m × 5 m, separated by irrigation channels and ridges and furrows (Supplementary Figure 2). Each plot contained four ridges, with ten plants transplanted per ridge. The spacing between plants was maintained at 30 cm, and between ridges at 75 cm. Transplantation of the four genotypes was performed early in the morning under open irrigation conditions. Irrigation was carried out using controlled hydraulic isolation between plots to prevent lateral entry of water. Each plot was separated by bunds that were compacted to minimize seepage and each plot received separate irrigation through separate inlet channels with controlled manual flow gates. After transplantation, plants were allowed to acclimate to the field environment to ensure proper establishment and growth. Irrigation was scheduled every two days, while weeding was carried out every 15 days to maintain optimal growing conditions. To support the indeterminate growth habit of tomato plants, staking and trellising were implemented at 25 days after transplantation (DAT), along with continuous pruning to promote healthy development. At 40 DAT, drought stress was induced by withholding irrigation for 10 consecutive days, after which regular irrigation was resumed. Soil moisture content was monitored using soil tensiometer declined to 45–50% from 85 to 90% from field capacity by the end of drought stress period. No rainfall events occurred during the stress imposition period, as verified from whether data records (Supplementary Figure). The drought stress in this study was applied as a single controlled event rather than in recurring or increasing cycles. We also realize that

TABLE 1 Summary of genotypes/rootstock/scion.

Genotype code	Rootstock	Scion	Grafting status
G1	Shivam	—	Non-grafted
G2	Arka Samrat	—	Non-grafted
G3	Shivam	Arka Samrat	Grafted
G4	Arka Samrat	Shivam	Grafted

plant-based water status markers, such as relative water content or leaf water potential, were not assessed. Fruit set and harvest were conducted 14 times throughout the growth period until the plants reached senescence. Pest and disease management was implemented using integrated pest management (IPM) strategies, including the application of biocontrol agents, planting of trap plants (*Tagetes erecta*—Marigold), and deployment of blue and yellow sticky traps, as well as pheromone traps specifically targeting *Tuta absoluta* infestations.

Harvesting and sample preparation

Fruit harvesting began at 80 days after transplantation (DAT) and continued over a period of 60 days, with harvesting intervals ranging from 3 to 6 days. A total of approximately 14 harvests were conducted throughout the cropping cycle. Fruits were harvested at the mature stage, identified by a color change from yellowish-red to red. Harvested fruits were collected separately from each plot, and the total fruit weight per plot was recorded for yield analysis. In addition to yield measurement, selected plants were permanently tagged at the beginning of the experiment, and fruit samples at each harvest were collected only from these tagged plants. Harvesting followed a consistent truss order and developmental stage, ensuring comparability across harvests. Fruits were sampled at uniform physiological maturity, thereby minimizing variability associated with ripening gradients along the plant. Fruits were collected from each genotype for the evaluation of both physical and chemical properties, as well as shelf-life assessment. The sampled fruits were stored under two different temperature conditions: 4 °C (cold storage) and 25 °C (ambient storage), each maintained at a relative humidity of 50 ± 5%. For physical characterization (e.g., firmness, size, weight loss), samples from both temperature conditions were used. However, for chemical analyses (e.g., total soluble solids, titratable acidity, lycopene, and vitamin C content), only fruits stored at 4 °C were utilized to maintain biochemical stability during storage.

Proximate analysis

Proximate analysis of tomato (*Solanum lycopersicum*) is essential for evaluating its nutritional composition and quality and is typically conducted following standardized protocols established by the Association of Official Analytical Chemists

(AOAC International, 2016). Moisture content was determined gravimetrically by oven drying the sample at 105 °C until a constant weight is achieved, providing a key indicator of water content, which is critical for determining shelf life and texture (AOAC Method 925.10). Crude protein was quantified using the Kjeldahl method, which involved acid digestion, distillation, and titration to determine total nitrogen content. This value was then converted to protein content using a standard nitrogen-to-protein conversion factor (AOAC Method 978.04). Crude fat (lipid content) was measured by Soxhlet extraction using petroleum ether as the solvent (AOAC Method 920.39). Crude fiber was analyzed through sequential acid and alkali digestion, representing the indigestible carbohydrate fraction in the sample (AOAC Method 962.09). Ash content, which reflects the total mineral content, was determined by incinerating the sample in a muffle furnace at 550 °C until a constant weight is reached (AOAC Method 942.05). Finally, carbohydrate content was calculated by difference, subtracting the sum of moisture, protein, fat, fiber, and ash percentages from 100% (Ahmed et al., 2020).

Post-harvest quality assessment

Post-harvest quality evaluation of tomatoes was conducted to assess shelf life, fruit weight retention, and color changes during storage. For this purpose, freshly harvested fruits from each genotype and treatment were selected at uniform ripeness (yellowish-red to red color stage). The fruits were gently washed, air-dried, and individually weighed before storage. To evaluate shelf life, fruits were placed in sterile, transparent zip-lock bags measuring 5 × 6 inches. Each bag contained fruits from a single treatment replicate, and the bags were loosely sealed to allow minimal air exchange while preventing contamination. The samples were stored under two temperature conditions: cold storage at 4 °C and ambient storage at 25 °C, both maintained at a relative humidity of 50 ± 5%. Observations were recorded every 5 days, up to 25 days post-harvest. At each interval, fruits were examined for visual deterioration (such as shrinkage, wrinkling, and fungal growth), weighed to assess weight loss, and photographed to document color changes. Fruit color was visually assessed using standardized ripening color stages and quantified by colorimeter (ColorFlex EZ, Hunter Lab) and representative images were taken under consistent lighting conditions for comparison. These parameters were used to evaluate the relative storability and physical degradation patterns of grafted and non-grafted tomato genotypes under different storage conditions.

Chemical characterization

Total soluble solids analysis

Tomato juice was extracted by homogenizing three fruits from each treatment and control group using a high-speed food blender for 2 min, following the procedure described by Cherono et al. (2018). The homogenized pulp was then filtered through a clean muslin cloth to obtain clear juice. Total soluble solids (TSS) were

measured using a digital refractometer. Prior to each measurement, the refractometer was calibrated using two drops of distilled water, which registered a baseline reading of 0 °Brix. Subsequently, one to two drops of tomato juice were placed on the refractometer prism to determine the TSS value. After each sample reading, the refractometer was thoroughly cleaned with distilled water and dried to prevent cross-contamination. The TSS values were recorded and expressed in degrees Brix (°Brix).

Titrateable acidity

Titrateable acidity was determined using the acid-base titration method, as described by AOAC International (2016). A 10 mL aliquot of freshly extracted tomato juice was diluted with 40 mL of distilled water and titrated against 0.1 N sodium hydroxide (NaOH) solution using phenolphthalein as an indicator. The endpoint was marked by the appearance of a faint pink color, which persisted for at least 30 s. The volume of NaOH used was recorded, and the titrateable acidity was calculated and expressed as a percentage of citric acid equivalent, which is the predominant organic acid in tomatoes. All samples were analyzed in triplicate to ensure accuracy.

Lycopene content

Lycopene concentration was measured spectrophotometrically using the method described by Munhuwiyi (2012), with slight modifications. Approximately 5 g of homogenized tomato pulp was mixed with a solvent mixture of hexane:acetone:ethanol (2:1:1 v/v/v) and vortexed for 10 min. The mixture was then filtered, and 1 mL of the upper hexane layer was transferred to a cuvette. Absorbance was measured at 503 nm, the characteristic absorption maximum for lycopene, using a UV-Visible spectrophotometer equipped with 1 cm path-length quartz cuvettes. The instrument was baseline-corrected using hexane as the blank. Lycopene content was calculated using the extinction coefficient and expressed as mg of lycopene per 100 g of fresh weight. All samples were analyzed in triplicate to ensure reliability.

Replication and unit analysis

The trial followed a randomized design, with each treatment and control duplicated at the plot level. Each plot was an individual experimental unit. Three representative fruits from each plot were selected for biochemical and quality analysis. Fruits were chosen from plants with uniform vigor and gathered from the same truss order (middle canopy) to reduce positional and developmental variability.

Fruits were picked at the same physiological maturity level, transported to the laboratory, gently washed, blotted dry, and processed on the same day to prevent post-harvest metabolic fluctuation. Individual fruit measurements within a plot were grouped as subsamples and averaged to provide a single value per plot for statistical analysis. The small number of plot-level biological duplicates may compromise statistical power and

sensitivity to modest treatment effects; this will be addressed in future investigations with higher replication.

Statistical analysis

All data were subjected to statistical analysis using JMP Pro (Version 18, SAS Institute Inc., Cary, NC, USA). Descriptive statistics (mean $\pm$ standard deviation) were calculated for each variable. Two-way analysis of variance (ANOVA) was performed. The treatment effects were assessed using a linear mixed-effects model (LMM). Fixed factors comprised genotype (scion $\times$ rootstock), irrigation regime, and their interaction. To account for experimental heterogeneity, each block/plot was regarded as a random effect to evaluate the effects of grafting and drought stress on morphological traits, yield components, and fruit quality parameters. When significant differences were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was used for mean separation. Normality and homogeneity of variance were checked using Shapiro–Wilk and Levene's tests, respectively.

Results

Morphological differences between grafted and non-grafted tomato genotypes under drought stress

Under drought stress conditions, the grafted genotypes—Shivam/Arka Samrat (G2) and Arka Samrat/Shivam (G3)—exhibited significantly better morphological traits compared to the non-grafted genotypes, Shivam (G1) and Arka Samrat (G4) (Figures 1, 2). Grafted plants showed increased plant height, greater stem diameter, and larger leaf area. Notably, G2 recorded the tallest plants and widest stems, followed closely by G3, indicating strong graft compatibility and vigorous rootstock influence. Both grafted genotypes also maintained leaf turgor and greener foliage for longer durations during drought, while non-grafted plants exhibited early wilting, leaf rolling, and stunted growth.

Under drought stress conditions, grafted tomato genotypes—Shivam/Arka Samrat (G2) and Arka Samrat/Shivam (G3)—exhibited significantly improved morphological traits compared to their non-grafted counterparts, Shivam (G1) and Arka Samrat (G4). The grafted plants demonstrated greater vegetative vigor, with G2 achieving the highest plant height by 60th day (108 ± 2.48), followed closely by G3 (109 ± 2.63 cm), both significantly exceeding measurements recorded in non-grafted genotypes ($p < 0.05$) Table 2. Similarly, leaf area was notably larger in grafted plants, with G2 and G3 averaging 70 ± 0.5 cm² and 52 ± 0.2 cm², respectively, compared to 60 ± 8.9 cm² and 50 ± 0.8 cm² for G1 and G4. Leaf Area Index (LAI) followed the same trend, with grafted genotypes showing higher values (3.6 ± 0.1 for G2 and 3.4 ± 0.1 for G3) relative to non-grafted plants. Moreover, the number of branches per plant was significantly greater in grafted treatments (12.5 ± 0.4 for G2 and 11.8 ± 0.5 for G3) than in non-grafted genotypes (8.3 ± 0.3 for G1

and 7.9 ± 0.2 for G4). These morphological enhancements in grafted tomatoes were accompanied by delayed onset of wilting and reduced drought-induced stress symptoms, indicating enhanced drought tolerance. Statistical analysis confirmed that all observed differences were significant ($p < 0.05$), highlighting the beneficial effect of grafting on maintaining vegetative growth under water-limited conditions.

Yield and reproductive response of grafted and non-grafted tomato genotypes under drought stress

Tomato genotypes exhibited variable yield and reproductive responses under drought stress conditions. While the total cumulative yield across all treatments was approximately 2 tones (Figure 3), individual genotype performance varied significantly. Under drought stress, Arka Samrat/Shivam (G3) maintained relatively high productivity (234 kg), whereas Shivam/Arka Samrat (G2) showed the total yield of 143 kg. In control conditions, G3 also performed better than G2, though both grafted combinations yielded less than their total potential observed under normal irrigation. On a per-plant basis, G3 recorded the highest average fruit weight (2.9 kg/plant), followed closely by Arka Samrat (G4) at 2.8 kg/plant, indicating that grafting contributed to yield stability under drought, though not always leading to the highest absolute yield (Table 2). In terms of reproductive traits, G4 exhibited the highest number of flowers per plant, even under drought stress, followed by G3.

Fruit pulp quality, shelf life, and spectral reflectance of tomato genotypes

Grafted tomato genotypes demonstrated improved post-harvest characteristics compared to non-grafted counterparts under drought stress. Fruit pulp firmness and consistency were better retained in grafted combinations, particularly Arka Samrat/Shivam (G3), which maintained higher pulp density and reduced softening during storage (Figures 4, 5). This was observed under both temperature conditions (4 °C and 25 °C). At 4 °C, grafted genotypes (G3 and G2) retained acceptable post-harvest quality for up to 25 days, while at 25 °C, spoilage signs such as weight loss, shriveling, and fungal growth appeared by 20–22 days. In contrast, non-grafted genotypes (G1 and G4) began to show significant deterioration by 15–17 days, particularly under ambient temperature. Shelf life was evaluated through visual observation, percentage weight loss, firmness reduction, and external color degradation. Spectral reflectance analysis (400–700 nm) revealed that grafted fruits maintained lower reflectance values in the red region (600–680 nm) throughout the storage period (Figure 6). Notably, G3 exhibited a stable spectral profile, with slower shifts in hue and saturation, whereas non-grafted fruits showed rapid spectral changes.

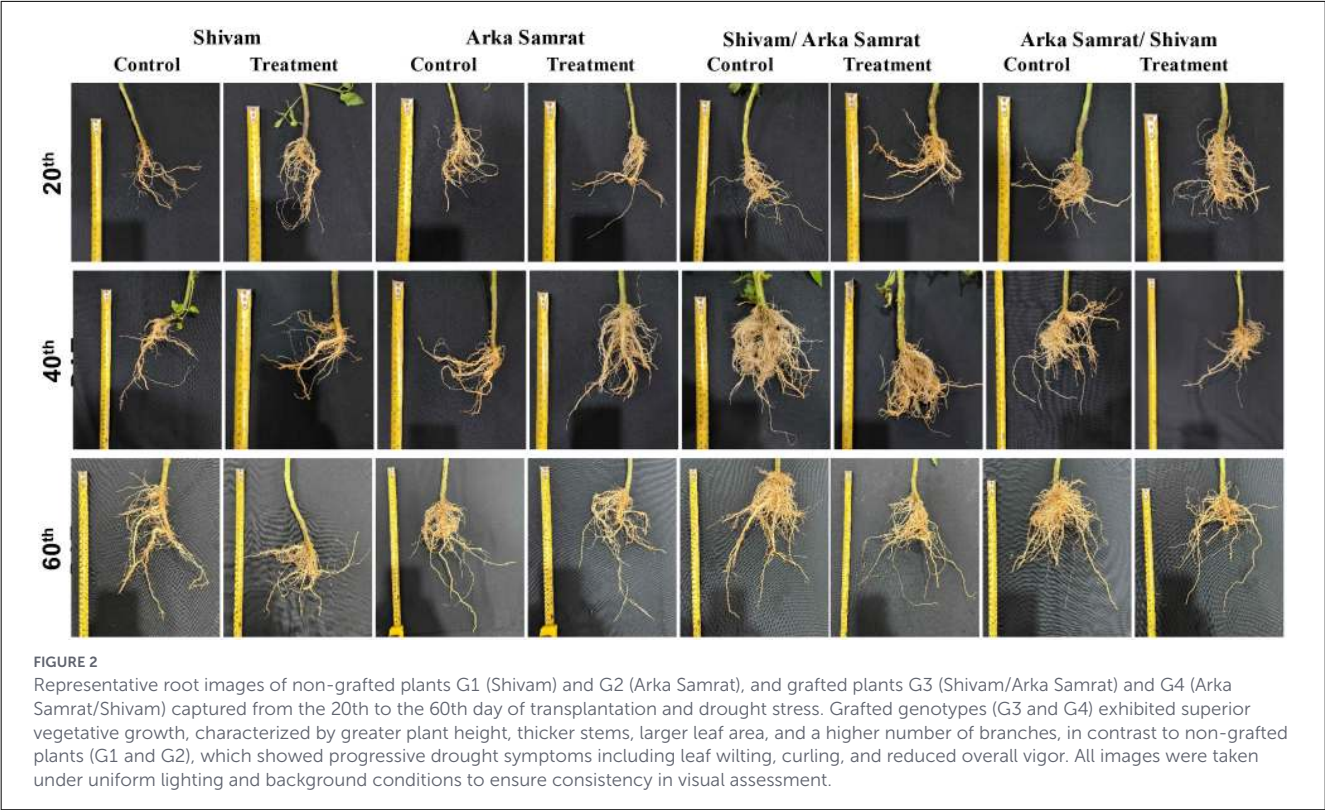


TABLE 2 Morphological traits and yield performance of grafted vs. non-grafted tomato genotypes under drought stress.

Day	Genotype	Treatments	pH of soil (<i>n</i> = 3)	Height of plants (in cm) (<i>n</i> = 15)	No of branches/plant (<i>n</i> = 15)	No of leaves (<i>n</i> = 15)	Leaf area (in cm ²) (<i>n</i> = 9)	Leaf area index (<i>n</i> = 3)	No. of flowers (<i>n</i> = 15)	No of Fruiting Branches (<i>n</i> = 15)
20 th day	Shivam	Control	6 ± 0.29 ^a	18.00 ± 1.32 ^c	3.33 ± 0.47 ^c	5.27 ± 0.68 ^a	23.2 ± 4.09 ^{abc}	0.03867 ± 0.0031 ^a	NA	NA
		Stress	5.8 ± 0.17 ^a	23.33 ± 3.74 ^b	4.53 ± 1.54 ^{bc}	5.27 ± 0.68 ^a	22.53 ± 6.85 ^{abc}	0.03756 ± 0.0086 ^a	NA	NA
	Arka Samrat	Control	5.6 ± 0.17 ^a	19.13 ± 1.78 ^c	3.73 ± 0.68 ^{bc}	5.13 ± 0.50 ^a	13.94 ± 2.74 ^c	0.02324 ± 0.0027 ^a	NA	NA
		Stress	6 ± 0.29 ^a	17.87 ± 2.94 ^c	3.73 ± 0.57 ^{bc}	5.13 ± 0.50 ^a	16.19 ± 4.29 ^{bc}	0.02698 ± 0.0061 ^a	NA	NA
	Shivam/Arka Samrat	Control	5.6 ± 0.16 ^a	27.8 ± 1.42 ^a	7.00 ± 0.63 ^a	5.67 ± 0.94 ^a	31.44 ± 8.74 ^a	0.05241 ± 0.0140 ^a	NA	NA
		Stress	6 ± 0.29 ^a	28.33 ± 3.03 ^a	7.13 ± 0.62 ^a	5.53 ± 0.88 ^a	24.72 ± 7.52 ^{ab}	0.04120 ± 0.0072 ^a	NA	NA
	Arka Samrat/Shivam	Control	5.8 ± 0.33 ^a	24.47 ± 1.59 ^b	7.13 ± 0.34 ^a	5.53 ± 0.88 ^a	25.64 ± 9.82 ^{ab}	0.04273 ± 0.0154 ^a	NA	NA
		Stress	6.1 ± 0.17 ^a	23.4 ± 1.50 ^b	6.67 ± 0.6 ^a	5.67 ± 0.94 ^a	22.14 ± 6.71 ^{abc}	0.03691 ± 0.0069 ^a	NA	NA
40 th day	Shivam	Control	6.3 ± 0.17 ^a	54.87 ± 4.44 ^{cd}	11.13 ± 1.71 ^b	6.87 ± 0.50 ^a	58.77 ± 16.24 ^a	0.09795 ± 0.0233 ^a	17.9 ± 0.25 ^{ab}	5.9 ± 0.27 ^{ab}
		Stress	5.8 ± 0.17 ^a	50.67 ± 2.02 ^{ef}	10.13 ± 0.72 ^{bc}	6.87 ± 0.50 ^a	46.17 ± 11.33 ^{ab}	0.07694 ± 0.0010 ^a	17.1 ± 0.45 ^{ab}	5.7 ± 0.18 ^c
	Arka Samrat	Control	6.0 ± 0.29 ^a	51.67 ± 2.12 ^{def}	10.67 ± 1.14 ^{bc}	6.80 ± 0.75 ^a	57.93 ± 10.50 ^{ab}	0.09656 ± 0.0147 ^a	18.3 ± 0.28 ^a	6.0 ± 0.19 ^a
		Stress	6.0 ± 0.29 ^a	48.27 ± 3.57 ^f	9.67 ± 0.60 ^c	6.80 ± 0.75 ^a	39.97 ± 9.54 ^b	0.06662 ± 0.0018 ^a	17.0 ± 0.34 ^{abc}	5.8 ± 0.20 ^{bc}
	Shivam/Arka Samrat	Control	6.0 ± 0.29 ^a	70.33 ± 1.99 ^a	15.27 ± 1.29 ^a	6.53 ± 1.71 ^a	64.42 ± 10.61 ^a	0.10737 ± 0.0133 ^a	20.3 ± 0.12 ^{ab}	7.9 ± 0.22 ^{abc}
		Stress	6.2 ± 0.17 ^a	69.00 ± 6.76 ^c	11.13 ± 0.72 ^b	6.87 ± 0.50 ^a	47.94 ± 9.52 ^{ab}	0.07991 ± 0.0081 ^a	18.6 ± 0.40 ^c	7.4 ± 0.19 ^d
	Arka Samrat/Shivam	Control	6.1 ± 0.33 ^a	64.53 ± 1.02 ^b	16.47 ± 0.96 ^a	6.47 ± 1.26 ^a	52.74 ± 13.54 ^{ab}	0.08798 ± 0.0135 ^a	23.8 ± 0.31 ^{bc}	8.9 ± 0.22 ^{abc}
		Stress	6.3 ± 0.3 ^a	63.67 ± 1.92 ^{de}	10.40 ± 0.80 ^{bc}	6.87 ± 0.50 ^a	46.44 ± 9.81 ^{ab}	0.07741 ± 0.0051 ^a	21.6 ± 0.40 ^c	8.2 ± 0.23 ^d
60 th day	Shivam	Control	6.1 ± 0.33 ^a	95.53 ± 6.34 ^c	26.67 ± 2.39 ^c	7.07 ± 0.25 ^b	61.7 ± 8.97 ^{ab}	0.10876 ± 0.0079 ^a	57.6 ± 0.35 ^{ab}	10.7 ± 0.26 ^a
		Stress	5.8 ± 0.17 ^a	88.93 ± 3.21 ^d	20.93 ± 2.46 ^d	7.07 ± 0.25 ^b	46.07 ± 18.09 ^{bc}	0.07863 ± 0.0156 ^a	57.0 ± 0.39 ^{abc}	9.7 ± 0.18 ^b
	Arka Samrat	Control	6.0 ± 0.29 ^a	97.93 ± 5.13 ^{bc}	29.00 ± 1.46 ^b	7.07 ± 0.25 ^b	55.14 ± 5.73 ^{abc}	0.09190 ± 0.0044 ^a	58.1 ± 0.36 ^a	10.9 ± 0.19 ^a
		Stress	6.0 ± 0.29 ^a	90.00 ± 4.62 ^d	22.60 ± 1.40 ^d	6.87 ± 0.50 ^b	56.5 ± 12.36 ^{abc}	0.09417 ± 0.0162 ^a	56.7 ± 0.30 ^{bcd}	9.7 ± 0.22 ^b
	Shivam/Arka Samrat	Control	6.0 ± 0.29 ^a	109.6 ± 2.63 ^a	32.00 ± 1.67 ^a	8.87 ± 0.50 ^a	70.21 ± 20.51 ^a	0.11701 ± 0.0324 ^a	106.7 ± 0.26 ^{bcd}	19.9 ± 0.23 ^{ab}
		Stress	6.2 ± 0.17 ^a	102.8 ± 4.72 ^b	26.87 ± 1.15 ^c	7.13 ± 0.50 ^b	53.76 ± 16.37 ^{abc}	0.08960 ± 0.0160 ^a	99.5 ± 0.1 ^c	18.5 ± 0.19 ^c
	Arka Samrat/Shivam	Control	6.2 ± 0.33 ^a	108 ± 2.48 ^a	30.93 ± 1.24 ^a	8.87 ± 0.50 ^a	53.34 ± 9.82 ^{abc}	0.08889 ± 0.0062 ^a	126.3 ± 0.25 ^{cd}	22.4 ± 0.23 ^{ab}
		Stress	6.3 ± 0.17 ^a	99.13 ± 2.70 ^{bc}	26.00 ± 0.97 ^c	6.87 ± 0.50 ^b	38.96 ± 8.31 ^c	0.06494 ± 0.0024 ^a	118.5 ± 0.13 ^c	21.1 ± 0.22 ^c

Values are mean ± SE. Different lowercase letters indicate significant differences among treatments at $p \leq 0.05$.

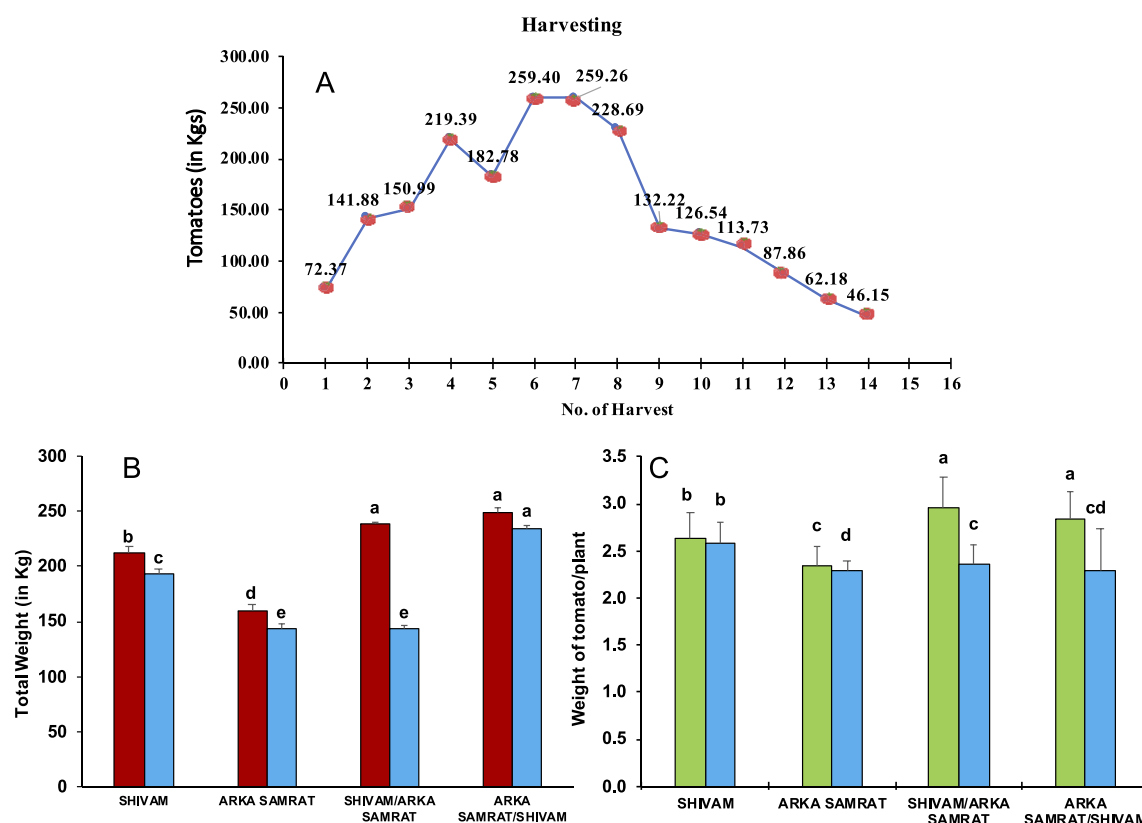


FIGURE 3

Impact of grafting on tomato yield under drought stress, (A) Total fruit harvest per genotype, (B) cumulative fruit weight, and (C) average fruit weight per plant under drought conditions. The graphs represent performance of non-grafted plants G1 (Shivam) and G2 (Arka Samrat), and grafted plants G3 (Shivam/Arka Samrat) and G4 (Arka Samrat/Shivam). Grafted genotypes (G3 and G4) consistently outperformed non-grafted counterparts across all yield parameters, demonstrating significantly higher fruit production, total yield, and fruit weight per plant. Values are mean $\pm$ SE ($n = 15$). Different lowercase letters indicate significant differences among treatments at $p \leq 0.05$.

Post-harvest nutritional quality and biochemical parameters of tomato genotypes

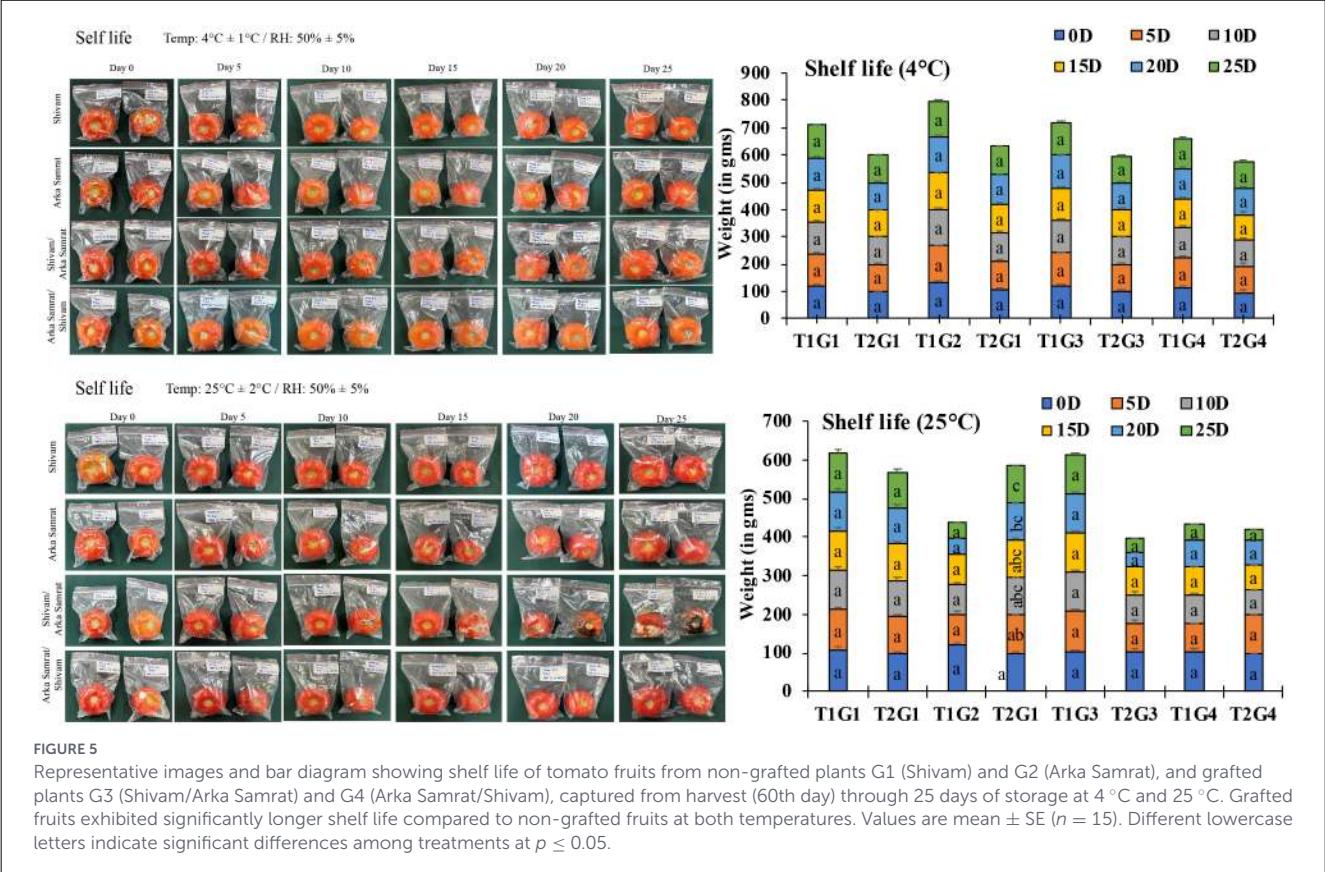
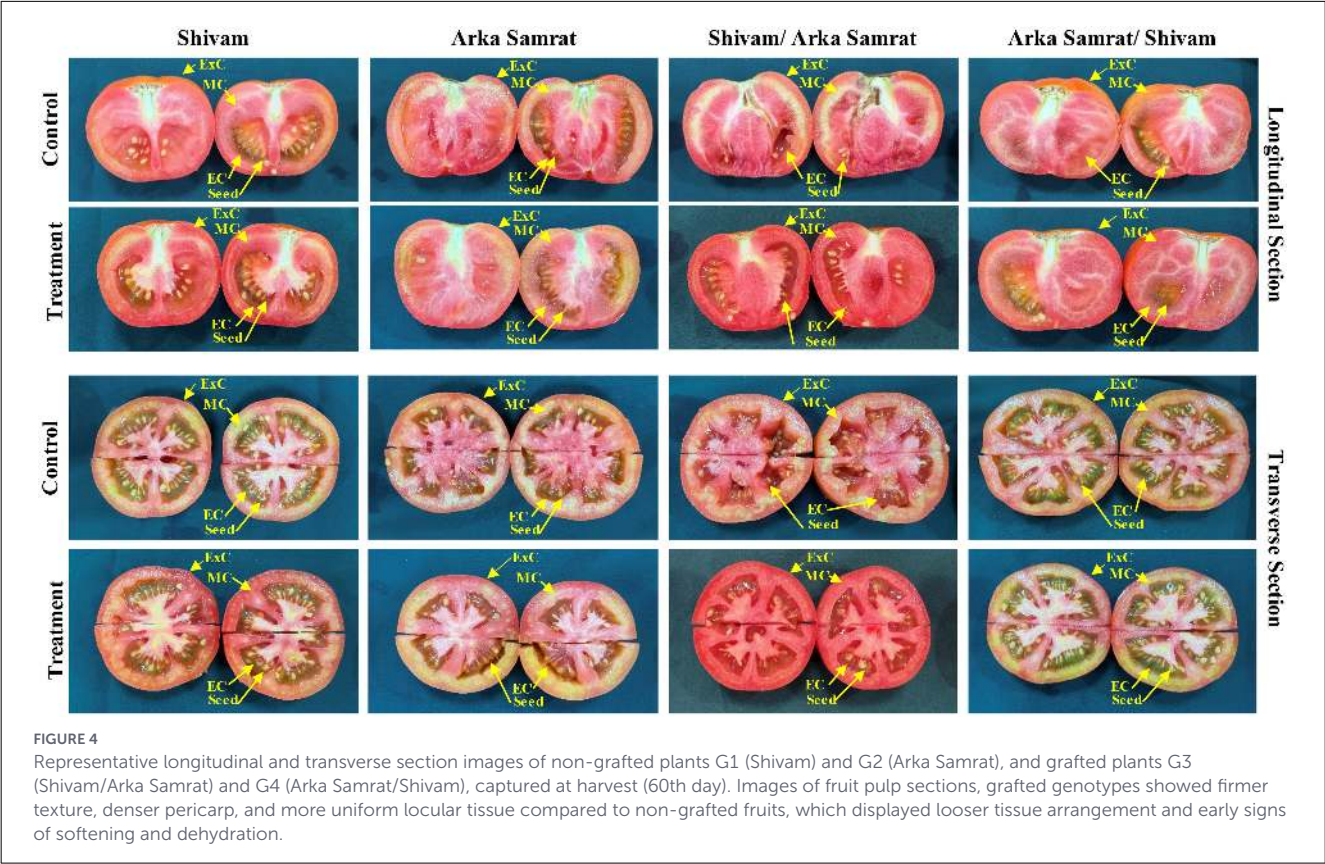
In addition to improved morphological and yield traits, grafted tomato genotypes also demonstrated superior nutritional and biochemical quality under drought stress. Proximate analysis, performed according to AOAC International (2016) methods, revealed that grafted fruits—particularly Arka Samrat/Shivam (G3)—had higher crude protein content (Table 3) and lower moisture loss compared to non-grafted counterparts. Ash and fiber contents were marginally higher in G3 and Shivam/Arka Samrat (G2), while fat and carbohydrate content remained within comparable ranges across genotypes.

In terms of soluble solids, G3 fruits recorded the highest °Brix value (5.3 ± 0.2 °Brix), followed by G2 (5.0 ± 0.1 °Brix), whereas non-grafted G1 and G4 genotypes exhibited slightly lower readings (4.6 – 4.8 °Brix) (Figure 7). pH measurements further indicated that grafted fruits retained better acidity balance, with G3 maintaining a pH of 4.20 ± 0.05 , in contrast to G1 and G4, which showed a higher pH (4.35 – 4.40) (Figure 7).

Titrateable acidity, lycopene, and carotenoid content

Significant differences were observed in titrateable acidity (TA) (Figure 7) and pigment concentrations (lycopene and total carotenoids) between grafted and non-grafted tomato genotypes under drought stress. Grafted genotypes, especially G3 (Arka Samrat/Shivam), maintained higher titrateable acidity ($0.48 \pm 0.01\%$) (Figure 8), compared to G1 and G4, which recorded lower values (0.39 – 0.42%) ($p < 0.05$). Higher TA levels in grafted tomatoes correlated with their extended shelf life and resistance to spoilage under ambient conditions.

In terms of nutritional pigments, lycopene content was significantly higher in grafted fruits, with G3 containing 8.2 ± 0.3 mg/100 g fresh weight (FW) and G2 with 7.8 ± 0.2 mg/100 g FW, compared to 6.3 ± 0.2 mg/100 g FW in G1 and 6.0 ± 0.1 mg/100 g FW in G4. Total carotenoid content followed a similar pattern, highest in G3 (11.5 ± 0.4 mg/100 g FW) and lowest in G4 (8.9 ± 0.3 mg/100 g FW).



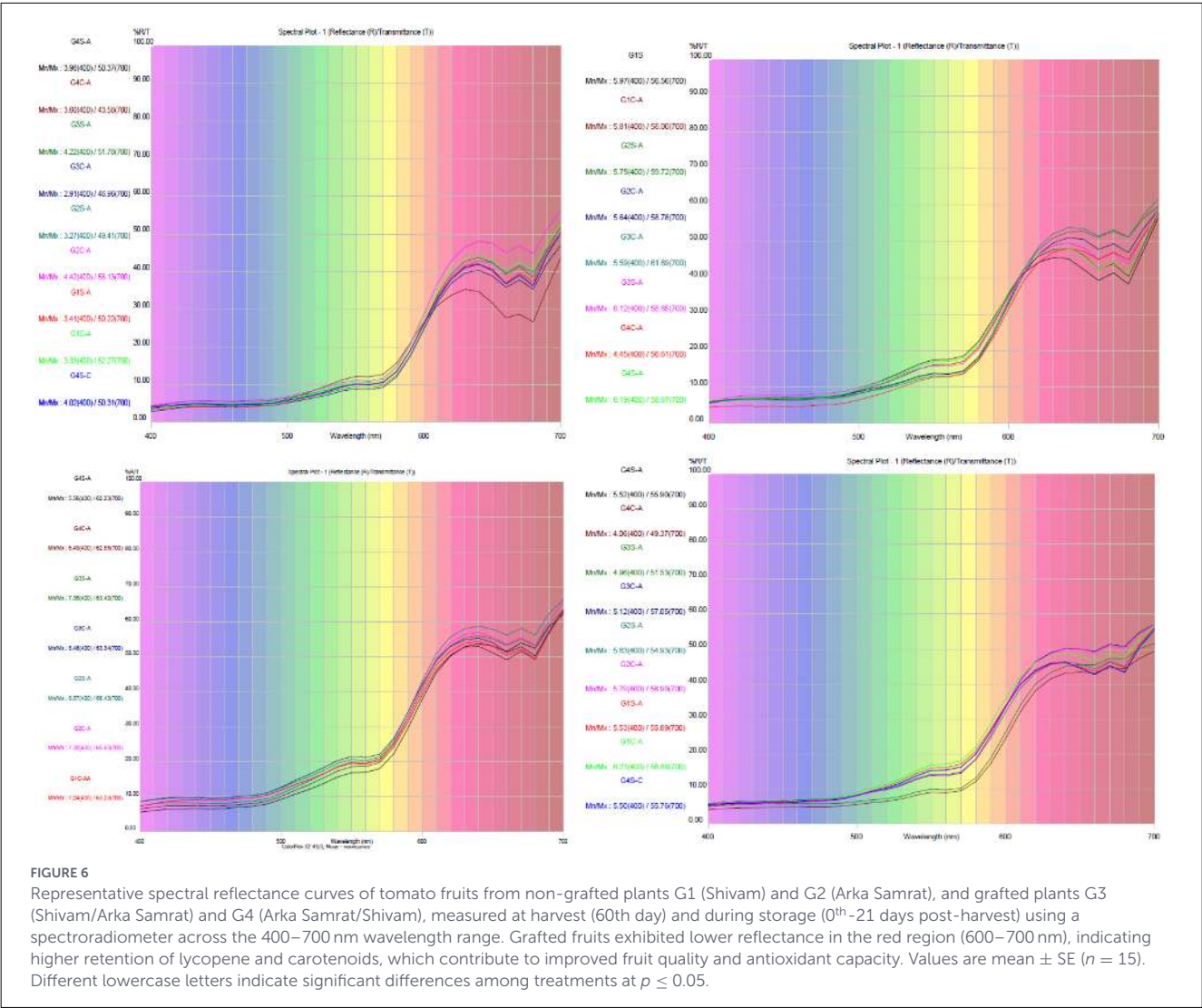


FIGURE 6 Representative spectral reflectance curves of tomato fruits from non-grafted plants G1 (Shivam) and G2 (Arka Samrat), and grafted plants G3 (Shivam/Arka Samrat) and G4 (Arka Samrat/Shivam), measured at harvest (60th day) and during storage (0th–21 days post-harvest) using a spectroradiometer across the 400–700 nm wavelength range. Grafted fruits exhibited lower reflectance in the red region (600–700 nm), indicating higher retention of lycopene and carotenoids, which contribute to improved fruit quality and antioxidant capacity. Values are mean $\pm$ SE ($n = 15$). Different lowercase letters indicate significant differences among treatments at $p \leq 0.05$.

TABLE 3 Proximate composition analysis of grafted and non-grafted tomato genotypes under drought stress.

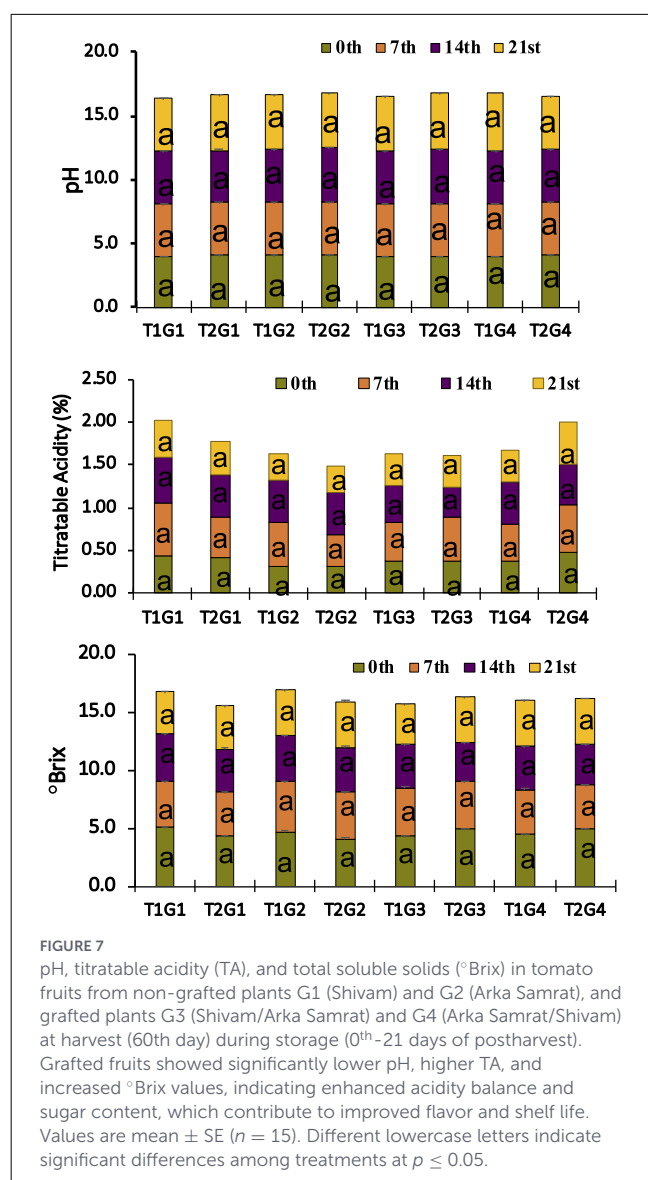
Genotype	Treatment	Moisture (%)	Ash (%)	Protein (g/100 g)	Fat (g/100 g)	Fiber (g/100 g)	Carbohydrate (g/100 g)	Energy (KJ/100 g)
Shivam	Control	89.95 $\pm$ 0.397 ^{ab}	0.85 $\pm$ 0.023 ^{ab}	0.73 $\pm$ 0.156 ^b	1.77 $\pm$ 0.170 ^a	1.34 $\pm$ 0.015 ^a	5.37 $\pm$ 0.443 ^{ab}	40.29 $\pm$ 0.60 ^a
	Stress	91.21 $\pm$ 0.760 ^{ab}	0.88 $\pm$ 0.019 ^{ab}	1.37 $\pm$ 0.067 ^a	2.04 $\pm$ 0.366 ^a	1.32 $\pm$ 0.090 ^a	3.19 $\pm$ 0.688 ^b	36.55 $\pm$ 3.41 ^a
Arka Samrat	Control	91.86 $\pm$ 0.452 ^a	0.60 $\pm$ 0.095 ^c	0.73 $\pm$ 0.155 ^b	0.77 $\pm$ 0.169 ^a	1.67 $\pm$ 0.114 ^a	4.36 $\pm$ 0.883 ^{ab}	27.33 $\pm$ 1.46 ^a
	Stress	88.35 $\pm$ 0.925 ^b	0.97 $\pm$ 0.006 ^a	1.08 $\pm$ 0.022 ^{ab}	1.48 $\pm$ 0.401 ^a	1.28 $\pm$ 0.209 ^a	6.85 $\pm$ 1.151 ^a	45.01 $\pm$ 4.18 ^a
Shivam/Arka Samrat	Control	91.48 $\pm$ 0.987 ^{ab}	0.85 $\pm$ 0.023 ^{ab}	1.33 $\pm$ 0.104 ^a	1.14 $\pm$ 0.059 ^a	0.87 $\pm$ 0.064 ^a	4.32 $\pm$ 0.953 ^{ab}	32.89 $\pm$ 3.56 ^a
	Stress	90.19 $\pm$ 0.317 ^{ab}	0.97 $\pm$ 0.012 ^a	0.63 $\pm$ 0.119 ^b	1.64 $\pm$ 0.106 ^a	1.69 $\pm$ 0.312 ^a	4.88 $\pm$ 0.345 ^{ab}	36.84 $\pm$ 0.87 ^a
Arka Samrat/Shivam	Control	92.49 $\pm$ 0.675 ^a	0.77 $\pm$ 0.017 ^{bc}	0.65 $\pm$ 0.079 ^b	1.44 $\pm$ 0.517 ^a	0.89 $\pm$ 0.038 ^a	3.76 $\pm$ 0.259 ^{ab}	30.60 $\pm$ 4.38 ^a
	Stress	90.92 $\pm$ 0.104 ^{ab}	0.79 $\pm$ 0.006 ^{ab}	1.03 $\pm$ 0.093 ^{ab}	1.43 $\pm$ 0.259 ^a	1.61 $\pm$ 0.635 ^a	4.22 $\pm$ 0.543 ^{ab}	33.84 $\pm$ 3.29 ^a

Values are mean $\pm$ SE. Different lowercase letters indicate significant differences among treatments at $p \leq 0.05$.

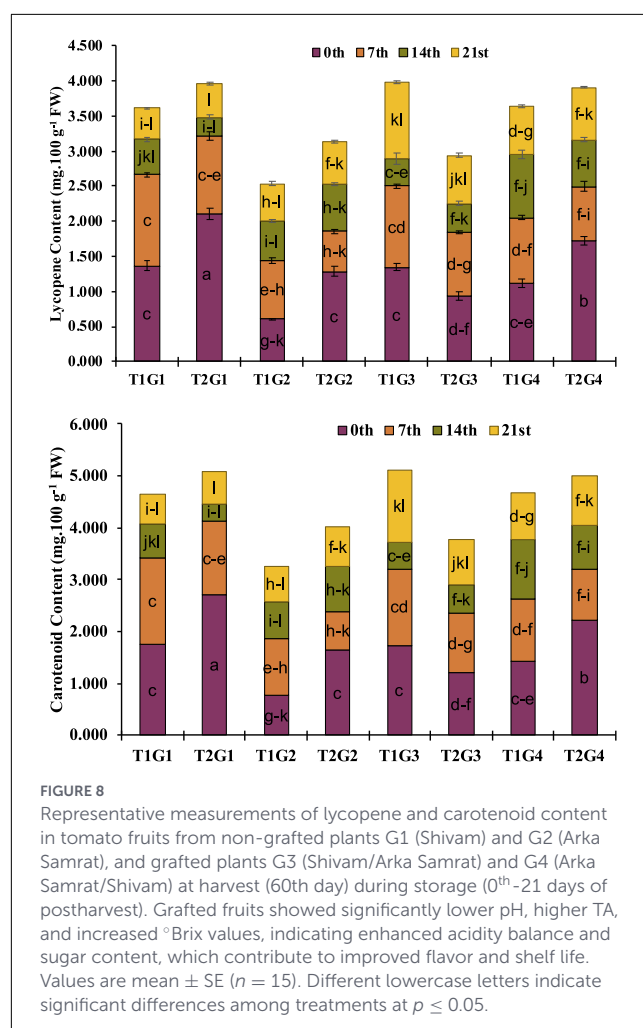
Discussion

Grafting has evolved as a viable method for supplementing traditional breeding programs and providing a faster way to

alleviate both biotic and abiotic stressors. Grafting, as opposed to time-consuming and expensive breeding approaches, allows for the instant improvement of crop resilience by combining the beneficial qualities of two genotypes—typically, a stress-tolerant rootstock



and a high-yielding scion. Tomatoes (*Solanum lycopersicum*), a highly perishable and commercially important crop, can experience large yield losses due to climate changes and biotic difficulties such as leaf curl disease. These pressures not only diminish fruit yield, but they also have an impact on overall plant health and market quality. Thus, grafting provides a realistic and sustainable method of mitigating these impacts and ensuring steady productivity in severe environmental situations. The current study focuses on the major benefits of grafting tomato genotypes under drought stress, exhibiting improvements in morphological features, yield stability, post-harvest quality, and biochemical indicators. These findings support a growing body of literature that highlights grafting as an effective agronomic method for improving abiotic stress resistance in horticultural crops. Grafting improves plant vigor, health, and precocity by encouraging the formation of more strong and efficient root systems than non-grafted plants (Musa et al., 2020). This increased root biomass considerably improves water and nutrient uptake, which is especially beneficial under abiotic



stress conditions like drought (Lee and Oda, 2003; Schwarz et al., 2010). Grafting tomato onto vigorous rootstocks has been shown to improve morphological characteristics such as plant height, stem diameter, and leaf area, resulting in improved physiological functioning under low water availability (Colla et al., 2010b; Hassan M. M. et al., 2021). Furthermore, grafted plants exhibit delayed onset of stress symptoms such as leaf rolling and wilting, most likely due to improved root-to-shoot communication and balanced hormonal control (Kawaguchi, 2008). These combined benefits result in not only increased stress resilience, but also higher fruit yield and quality, making grafting an important agronomic practice in current horticulture crop production.

Grafted tomato combinations (G2: Shivam/Arka Samrat and G3: Arka Samrat/Shivam) outperformed non-grafted plants in terms of vegetative development under drought stress, as shown by increased plant height, stem diameter, leaf area, and branching. These findings are consistent with previous research indicating that grafting increases root biomass, water and nutrient absorption efficiency under stress conditions (Schwarz et al., 2010; Morade et al., 2025). The larger leaf area index seen in grafted plants is likely due to continuous photosynthetic capability, allowing for ongoing development during periods of inadequate water supply (Colla et al., 2010b). Furthermore, grafted plants demonstrated delayed

start of drought-induced symptoms such as leaf rolling and wilting, indicating enhanced root-to-shoot communication and hormonal modulation of transpiration and stomatal conductance (Kawaguchi et al., 2008; Hassan S. U. et al., 2021). Furthermore, grafted plants exhibited delayed onset of drought-induced symptoms such as leaf rolling and wilting, indicating improved root-to-shoot signaling and hormonal regulation of transpiration and stomatal conductance (Kawaguchi et al., 2008; Hassan M. M. et al., 2021), which is consistent with previous findings (Yildiztugay et al., 2019).

One important measure of stress resistance is yield stability during drought. In this study, compared to non-grafted controls, grafted genotypes—especially G3—maintained more blooms and fruits per plant throughout drought. This enhanced reproductive performance validates previous findings that grafting increases fruit set and reduces stress-induced reproductive failure (Ruiz et al., 2018). Better carbohydrate partitioning and hormonal balance, especially with regard to auxins and cytokinins that control flower development and fruit growth, may be linked to grafted plants' capacity to maintain flowering and fruit retention under water stress (Lee et al., 2010; Colla et al., 2013).

The present research's evidence that grafting-mediated drought resistance at the field level results in notable post-harvest benefits is a major contribution. Under both ambient (25 °C) and cold storage (4 °C) conditions, grafted fruits demonstrated increased firmness, decreased weight loss, and a longer shelf life. Better preservation of cell wall integrity and slower enzymatic breakdown during storage are indicated by the G3 fruits' enhanced pulp firmness and delayed softening (Rouphael et al., 2010; Shibli et al., 2016). Notably, non-grafted fruits degraded more quickly, especially at room temperature, while grafted fruits maintained acceptable quality for up to 25 days at 4 °C. These findings demonstrate how grafting can lower metabolic activity and postpone senescence in post-harvest storage (Kyriacou et al., 2017; Singh et al., 2017).

The post-harvest interpretation is further strengthened by the combination of biochemical data and spectral reflectance analysis. According to Shi and Le Maguer (2000) and Rao and Rao (2007), grafted fruits showed reduced reflectance in the red spectral region, suggesting better preservation of lycopene and carotenoids, important antioxidants and quality drivers in tomato fruit. In line with previous findings relating pigment stability to consumer acceptance, the slower spectrum changes seen in grafted fruits indicate delayed pigment degradation and browning, resulting to improved visual quality and longer shelf life (Martínez-Valverde et al., 2002).

Grafted fruits showed better moisture retention and increased levels of crude protein, ash, fiber content, °Brix, and titratable acidity, according to biochemical and proximate tests. Together, these characteristics improve taste, nutritional value, and microbiological stability while being stored (Nunes et al., 2018; Martínez-Valverde et al., 2002). According to Chen et al. (2017), grafted fruits have a lower pH because they break down organic acids more slowly, delaying spoiling and improving storage stability. Furthermore, grafted fruits' much increased lycopene and total carotenoid levels indicate improved antioxidant capability, which is crucial in drought stress situations that cause oxidative damage (Zhou et al., 2018; Rao and Rao, 2007). These results are

consistent with other studies that suggested grafting enhances fruit nutritional quality by modifying stress responses and metabolism (Colla et al., 2013).

Complex physiological and molecular interactions between rootstock and scion, such as increased hydraulic conductivity, hormonal signaling, and antioxidant defense mechanisms, are probably responsible for the improved drought tolerance and fruit quality seen in grafted tomatoes (Gautam et al., 2015; Hassan M. M. et al., 2021). Under drought circumstances, rootstocks may encourage deeper and more effective root systems, improving access to soil moisture and nutrients (Colla et al., 2010b; Morade et al., 2025). Additionally, it has been demonstrated that grafting affects the expression of stress-responsive genes related to cell wall remodeling, osmolyte accumulation, and antioxidant enzyme activity (Cohen et al., 2009; Liu et al., 2018).

Despite the well-established benefits of grafting for tomato drought tolerance, this work adds to the body of knowledge by directly connecting field-level drought responses with fruit biochemical quality and post-harvest performance (Kawaguchi et al., 2008). The results show that grafting-mediated stress tolerance goes beyond yield stabilization to provide observable post-harvest and nutritional benefits by employing reciprocal graft combinations of commercially grown varieties (Shivam and Arka Samrat) and integrating morphological, yield, post-harvest, biochemical, and spectral analyses. These findings demonstrate the usefulness of grafting as a climate-resilient method for producing tomatoes sustainably in areas with limited water resources. The findings indicate that appropriate local rootstock-scion combinations can increase water absorption, nutrient acquisition, and stress tolerance, hence helping to stabilize yields and preserve nutritional quality during times of restricted water supply. However, the lack of a standard commercial rootstock prevents direct performance benchmarking. Besides, the results are also confined to validate that they are resistant to acute drought stress, but long-term yield stability under chronic drought requires validation. This limitation is acknowledged, and more comparative and long-term field investigations are required to validate these findings and optimize rootstock selection for commercial use under drought circumstances.

Conclusion

The current study highlights the effectiveness of grafting as a sustainable agronomic intervention to improve post-harvest performance and drought tolerance in tomato farming. Under conditions of water scarcity, grafted genotypes, especially G3 (Arka Samrat/Shivam), showed significant benefits in vegetative growth, yield stability, fruit quality, and biochemical robustness. These advantages are ascribed to the rootstock's augmented antioxidant defense mechanisms, better physiological and hormonal regulation, and increased root vitality. Notably, grafting conserved reproductive potential, considerably increased fruit shelf life, and postponed the onset of drought-induced symptoms—all essential characteristics for preserving productivity and quality under climate-induced stress. The results support the

function of grafting in regulating morphological, physiological, and metabolic responses to drought and are consistent with and add to previous research. The superior nutritional and post-harvest attributes observed in grafted fruits also highlight grafting as a viable approach to meet market and consumer demands for high-quality produce, even under challenging environmental conditions. Overall, grafting offers a practical, scalable solution for enhancing the resilience and profitability of tomato production in drought-prone areas. Future research should focus on optimizing rootstock–scion combinations, understanding underlying molecular mechanisms, and integrating grafting with precision irrigation and nutrient strategies to further enhance crop sustainability and resource use efficiency.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

Author contributions

PM: Investigation, Methodology, Validation, Writing – original draft. MP: Funding acquisition, Supervision, Validation, Visualization, Writing – review & editing. SM: Conceptualization, Funding acquisition, Project administration, Resources, Writing – review & editing.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fsufs.2026.1717713/full#supplementary-material>

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