

Storage-Dependent Variations between Physicochemical and Shelf-Life Quality Attributes in Jujube Cultivars

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ABSTRACT

Jujube (*Ziziphus mauritiana* Lamk.) is a nutritious and climate-resilient fruit crop; however, its commercial potential is constrained by rapid postharvest deterioration and limited storage life. This study evaluated the combined effects of hot water treatment (HWT; 40, 45, and 50°C) and storage temperature (ambient: 26 ± 1°C and cold storage: 14 ± 1°C) on fruit quality, oxidative metabolism, antioxidant defense, and shelf life during 30 days of storage. Physicochemical attributes, reactive oxygen species (ROS) accumulation, antioxidant enzyme activities, and stress-related responses were assessed. Storage duration increased weight loss (0.001–28.31%) and total soluble solids (10.58–22.16 °Brix), while titratable acidity declined (0.2894–0.1781%), indicating enhanced ripening and senescence. Correlation analysis showed a strong positive relationship between weight loss and TSS ($r = 0.839$) and a negative association between weight loss and TA ($r = -0.636$), demonstrating the close relationship between moisture loss, sugar accumulation, and acid degradation. Among the treatments, HWT at 50°C was most effective in preserving fruit quality, reducing weight loss from 18.79% in untreated fruit to 15.02% while maintaining higher ascorbic acid content. This treatment also significantly reduced hydrogen peroxide (H₂O₂) and malondialdehyde (MDA) accumulation and enhanced the activities of superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase, thereby strengthening antioxidant defense and reducing oxidative damage. Overall, combining 50°C HWT with cold storage at 14°C effectively delayed senescence, maintained fruit quality, enhanced antioxidant protection, and extended the storage life of jujube fruit.

Keywords: *Ziziphus mauritiana*, Hot water treatment, Cold storage, Oxidative stress, Antioxidant enzymes.

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INTRODUCTION

Jujube (*Ziziphus mauritiana* Lamk.), a member of the Rhamnaceae family, is one of the most widely cultivated fruit species of the genus *Ziziphus* in tropical and subtropical regions, whereas *Ziziphus jujuba* Mill. predominates in temperate climates. These species are native to North Africa, Afghanistan, northern India, southern China, Malaysia, and Australia, but have become naturalized across tropical Africa, the Middle East, Sri Lanka, and several Mediterranean countries

(Yao, 2013; Yao, 2025).

Owing to its remarkable adaptability, jujube has emerged as an important fruit crop for sustainable agriculture and food security in regions affected by climatic stresses. Jujube possesses exceptional tolerance to drought, salinity, high temperatures, and poor soil conditions, enabling successful cultivation in arid and semi-arid environments where many conventional fruit crops fail to thrive. Its ability to maintain stable fruit production under adverse environmental conditions highlights its significance as a climate-resilient crop capable of supporting sustainable food systems and rural livelihoods. Furthermore, the species requires relatively low agricultural inputs and exhibits a long productive lifespan, making it particularly suitable for resource-limited production systems. Consequently, jujube has gained increasing attention for its potential contribution to food and nutritional security under changing climatic scenarios (Rao et al., 2014; Yamin and Tadampali, 2025). The fruit is highly valued for its pleasant flavor, attractive appearance, and outstanding nutritional composition. Fresh jujube fruits are rich in carbohydrates, dietary fiber, vitamins, minerals, phenolic compounds, and antioxidants, particularly vitamin C, which contributes substantially to their nutritional and medicinal properties. In addition to fresh consumption, jujube fruits are processed into a wide range of value-added products, including dried fruits, candies, pickles, juices, jams, and fruit butter, thereby enhancing their commercial and industrial importance (Rath et al., 2024). Botanically classified as a drupe, jujube exhibits considerable variation in fruit morphology, ranging from round to oblong and elongated forms, with substantial differences in size, color, texture, and firmness among cultivars (Zhang and Ye, 2026). During ripening, fruits undergo pronounced physiological and biochemical changes, including sugar accumulation, acid degradation, firmness loss, and skin color development, all of which strongly influence fruit quality, storage behavior, and consumer acceptance. Considerable genetic diversity exists among jujube cultivars, resulting in substantial variation in physical, physicochemical, and biochemical characteristics. Fruit weight has been reported to range from 3.8 to 39.5 g, while fruit length and diameter vary between 1.82–5.80 cm and 1.1–4.7 cm, respectively. Mature fruits

generally contain 81–97% edible pulp, emphasizing their suitability for fresh consumption and processing applications (Lin et al., 2011). These morphological traits are influenced by genotype, environmental conditions, orchard management practices, and harvest maturity, and are closely associated with important quality attributes such as texture, juiciness, sweetness, and consumer preference. Larger fruits with a higher pulp percentage are generally preferred in domestic and export markets due to their superior edible portion and processing efficiency (Şumalan et al., 2025). Moreover, fruit morphology significantly affects postharvest performance, including moisture loss, respiration rate, susceptibility to mechanical injury, and storage life (Zeraatgar et al., 2019).

The biochemical composition of jujube fruit further contributes to its nutritional and commercial value. Total soluble solids (TSS) typically range from 12–23%, while titratable acidity (TA) varies between 0.13–1.42%, depending on cultivar, maturity stage, and growing conditions. Total sugars range from 3.1–14.5%, with reducing sugars accounting for 1.4–9.7%. Sucrose, glucose, and fructose constitute the major sugar fractions, whereas approximately 1% starch is progressively converted into soluble sugars during ripening, enhancing sweetness and overall fruit palatability (Zhao et al., 2024; Ahmed et al., 2025; Patil et al., 2026). These physicochemical attributes are important determinants of fruit quality, processing suitability, storage potential, and market acceptability. Among the nutritional constituents, vitamin C is particularly abundant in jujube fruits and often occurs at concentrations exceeding those found in many commonly consumed fruits. As a potent antioxidant, vitamin C contributes to immune function, collagen synthesis, iron absorption, and protection against oxidative stress, thereby enhancing the health-promoting value of jujube fruits (Sahin and Sonmez, 2025). However, its concentration varies considerably among cultivars and is influenced by environmental conditions, fruit maturity, and postharvest handling practices. Recent advances in molecular marker technologies have provided powerful tools for assessing genetic diversity, phylogenetic relationships, and cultivar

identification in horticultural crops. The integration of molecular characterization with physicochemical evaluation offers a comprehensive approach for germplasm conservation, cultivar improvement, and breeding programs. In this context, Abdel-Sattar et al. (2021) evaluated the genetic diversity and fruit quality attributes of five *Ziziphus mauritiana* cultivars, Komethry, Pakstany, Um-Sulaem, Toffahy, and Peyuan, grown under Saudi Arabian conditions. Significant variation was observed among cultivars in both genetic makeup and fruit quality traits, demonstrating the existence of substantial diversity within the species.

Physicochemical analyses revealed marked differences between fruit and leaf tissues. Fruit samples exhibited significantly higher TSS (11.70 °Brix) and titratable acidity (0.32%) compared with leaves (0.97 °Brix and 0.09%, respectively), reflecting the richer biochemical composition and superior sensory quality of the edible fruit tissues. Conversely, leaf tissues exhibited a higher pH (5.47) than fruits (4.77), indicating the relatively acidic nature of the fruit pulp. These findings highlight the considerable biochemical diversity present within *Z. mauritiana* germplasm and emphasize the importance of integrating molecular and physicochemical analyses for the identification of superior cultivars with enhanced fruit quality, environmental adaptability, and nutritional value. Such information is essential for future breeding, conservation, and horticultural improvement programs aimed at increasing the productivity and market competitiveness of jujube cultivation in arid and semi-arid regions (Jailani et al., 2020). Ber (*Ziziphus mauritiana* Lamk.) is an economically important fruit crop widely cultivated in tropical and subtropical regions due to its adaptability to harsh environmental conditions and its high nutritional value. Following harvest, fruits are generally stored under ambient conditions (25–35 °C), where they maintain acceptable market quality for only 4–15 days depending on cultivar, harvest maturity, and postharvest handling practices. Considerable variation in storage performance has been reported among cultivars, with Sanauar-5, Ponda, Rashmi, and Umran exhibiting relatively superior shelf life

and postharvest stability (Chang, 2021; Ghafir et al., 2013). For prolonged storage and maintenance of fruit quality, temperatures around 10 °C with approximately 79% relative humidity are considered optimal. During storage, fruits undergo a series of physiological and biochemical changes associated with ripening and senescence. Enhanced enzymatic activities stimulate metabolic transformations, resulting in increased concentrations of total sugars and carotenoids through the conversion of complex carbohydrates into simpler sugars and the development of characteristic fruit pigmentation. Conversely, titratable acidity, pectin substances, and tannins progressively decline, leading to reduced astringency, softer texture, and improved palatability. These biochemical modifications substantially influence fruit flavor, texture, nutritional quality, storage behavior, and consumer acceptance (Kumar et al., 2024; González et al., 2023). China remains the leading producer of jujube and related *Ziziphus* species, accounting for more than 40% of global production. However, the cultivation of Jujube fruit has expanded considerably in many countries owing to its exceptional tolerance to drought, salinity, and poor soil conditions, combined with increasing consumer demand and recognition of its nutritional benefits. Consequently, interest in commercial production, postharvest management, and value-added processing of fruits has increased substantially, particularly in arid and semi-arid regions of Asia, Africa, and the Middle East. Beyond its economic importance, *Z. mauritiana* plays a significant role in food security, environmental sustainability, and rural livelihoods. The species is extensively utilized for fresh consumption and processing into various value-added products, including dried fruits, candies, pickles, juices, jams, fruit butter, and powders.

In addition, leaves and branches are used as livestock fodder, while stems serve as fuelwood and fencing material in rural communities. The species thrives in regions receiving less than 300–500 mm annual rainfall and can withstand summer temperatures exceeding 40 °C, highlighting its suitability for climate-resilient agricultural systems. Another important member of the genus,

Zizyphus lotus, is naturally distributed throughout arid and semi-arid regions of Africa, the Mediterranean Basin, and the Middle East. Similar to *Z. mauritiana*, this species exhibits remarkable adaptation to harsh environmental conditions and poor soils, contributing to soil conservation and desertification control (Bencheikh et al., 2023). Furthermore, *Z. lotus* has long been utilized in traditional medicine for the treatment of diabetes, bronchitis, digestive disorders, insomnia, and diarrhea. Various plant parts contain bioactive compounds, including flavonoids, alkaloids, saponins, phenolic acids, and tannins, which exhibit antioxidant, antimicrobial, anti-inflammatory, antidiabetic, and sedative properties. These characteristics have stimulated growing scientific interest in the potential application of *Zizyphus* species in functional foods, nutraceuticals, pharmaceuticals, and sustainable agricultural systems. Jujube fruits are highly versatile and consumed in numerous forms, including fresh, dried, candied, pickled, and processed beverages. They are particularly valued for their exceptional vitamin C content, which often exceeds that of many commonly consumed fruits and contributes substantially to their antioxidant capacity. Nutritionally, the fruits contain approximately 20–30% total sugars, up to 2.5% crude protein, and around 12.8% carbohydrates, making them an important source of dietary energy and health-promoting compounds. The high levels of phenolics and ascorbic acid further enhance their antioxidant potential and associated health benefits, including protection against oxidative stress and support of overall human health. Despite the increasing commercial importance of jujube fruits, postharvest losses remain a major challenge due to rapid moisture loss, accelerated ripening, and senescence during storage. Various postharvest technologies have been explored to mitigate these losses; however, information regarding the combined effects of hot water treatment (HWT) and storage temperature on the physicochemical quality and shelf life of jujube fruit remains limited. Furthermore, the physiological responses of different jujube cultivars to HWT under ambient and refrigerated storage conditions have not been comprehensively evaluated. Therefore, the present study was undertaken to investigate the effects of storage temperature (ambient storage at 26 ± 1 °C

and cold storage at 14 ± 1 °C) and pre-storage hot water treatments (40, 45, and 50 °C) on the postharvest quality and shelf life of two commercially important jujube cultivars, Farmi and Gola. Specifically, the study aimed to evaluate changes in key physicochemical attributes, including weight loss, total soluble solids (TSS), titratable acidity (TA), pH, moisture content, and ascorbic acid concentration during storage. In addition, the effectiveness of HWT in reducing quality deterioration, minimizing weight loss, delaying ripening, and extending marketable shelf life was assessed. The study further compared the storage performance of Farmi and Gola cultivars under different HWT and storage combinations to identify superior cultivar–treatment interactions. Ultimately, the findings are expected to provide a scientifically validated postharvest management strategy integrating optimal hot water treatment and storage temperature for improving fruit quality retention, extending shelf life, and reducing postharvest losses of jujube fruits in tropical and subtropical production systems.

MATERIALS AND METHODS

Mature jujube fruits (*Zizyphus mauritiana* Lamk.) at the yellowish-green physiological maturity stage were harvested manually from a commercial orchard was carried out during the early morning hours to minimize field heat accumulation and reduce physiological stress on the fruits. Only healthy fruits exhibiting uniform size, shape, color development, and maturity were selected for the study. Fruits showing any signs of mechanical injury, insect infestation, disease infection, physiological disorders, or other visible defects were excluded to ensure uniformity and consistency of the experimental material. Immediately after harvest, the selected fruits were carefully packed in corrugated cardboard boxes lined with soft cushioning material to minimize bruising and mechanical damage during handling and transportation. The harvested samples were then transported under ambient conditions to the Postharvest Research Laboratory for further processing and experimentation. Upon arrival, the fruits were subjected to a second round of sorting and grading to eliminate any fruits that may have been damaged during transport or exhibited undesirable variations in maturity and quality characteristics. Before treatment application, the

fruits were thoroughly washed with clean tap water to remove adhering dust particles, field debris, pesticide residues, and other surface contaminants. Following washing, the fruits were placed on clean laboratory benches and allowed to air dry naturally at room temperature until all surface moisture had completely evaporated. This drying step was essential to prevent dilution of treatment solutions and to ensure uniform treatment application and reliable analytical measurements throughout the study. After sample preparation, the fruits were randomly allocated to the respective treatment groups according to the experimental plan. The experiment was conducted using a Completely Randomized Design (CRD) arranged in a two-factor factorial structure (Table 1). The first factor comprised the designated postharvest treatments, while the second factor consisted of the storage conditions evaluated during the experiment. Each treatment combination was replicated three times to improve statistical precision, minimize

experimental error, and enhance the reliability of the results. Each replication consisted of an equal number of fruits, and all experimental units were randomly assigned to treatments to avoid positional or handling biases. Throughout the storage period, fruits were maintained under carefully controlled and uniform experimental conditions. Standardized handling, sampling, and evaluation procedures were followed across all treatment groups to ensure consistency and reproducibility of observations. The factorial arrangement enabled the assessment of both the individual and interactive effects of postharvest treatments and storage conditions on the physicochemical quality attributes, ripening behavior, and shelf life of jujube fruits. This experimental approach provided a robust framework for evaluating treatment efficacy and identifying suitable postharvest management strategies for maintaining fruit quality and extending storage life.

Table 1: Factorial arrangement for research analysis.

Factor A: Hot Water Treatment	Factor B: Cold & Ambient Storage
$T_0 = 0\text{ }^{\circ}\text{C}$	$D_1 = 0\text{ day}$
$T_1 = 40\text{ }^{\circ}\text{C}$	$D_2 = 15\text{ days}$
$T_2 = 45\text{ }^{\circ}\text{C}$	$D_3 = 30\text{ days}$
$T_3 = 50\text{ }^{\circ}\text{C}$	

Physicochemical and Biochemical Analyses

pH Determination: The pH of jujube fruit samples was determined using a digital pH meter (OHAUS, Model: Starter 3100). Before measurement, the instrument was calibrated using standard buffer solutions of known pH to ensure accuracy and reliability of the readings. Fresh fruit pulp was homogenized thoroughly to obtain a representative sample. The electrode was immersed directly into the homogenized pulp, and the pH value was recorded once the reading stabilized. Measurements were performed in triplicate for each treatment replicate, and the mean values were used for subsequent statistical analyses.

Total Soluble Solids (TSS): Total soluble solids (TSS) content was determined using a portable analog refractometer (HINOTEK WZS-80; range: 0–80 °Brix). Fresh juice was extracted from the fruit pulp by gently squeezing the tissue through a

clean muslin cloth to obtain a clear filtrate. A few drops of the extracted juice were placed uniformly on the prism surface of the refractometer, ensuring the absence of air bubbles. The TSS content was recorded directly as °Brix under adequate illumination. After each measurement, the prism surface was thoroughly rinsed with distilled water and wiped dry with a lint-free tissue to prevent cross-contamination. All determinations were conducted in triplicate, and average values were expressed as °Brix.

Titrateable Acidity (TA): Titrateable acidity was determined following the standard acid-base titration method. A 10 mL aliquot of freshly extracted jujube juice was transferred into a clean 100 mL beaker, and 2–3 drops of phenolphthalein indicator were added. The sample was titrated against a standardized 0.1 N sodium hydroxide (NaOH) solution until the appearance of a faint but persistent pink endpoint. The volume of NaOH

consumed was recorded accurately and used to calculate titratable acidity, which was expressed as a percentage citric acid equivalent. All analyses were conducted in triplicate, and the mean values were used for statistical evaluation.

Sugar–Acid Ratio (Ripening Index): The sugar–acid ratio, also referred to as the ripening index, was calculated by dividing the total soluble solids (TSS) value by the corresponding titratable acidity (TA) value for each sample:

Sugar–Acid Ratio = TSS (°Brix) / TA (%): This parameter was used as an indicator of fruit maturity, eating quality, and flavor balance. Higher values generally reflect increased sweetness, reduced acidity, and advanced ripening. Calculations were performed individually for each replicate before averaging.

Ascorbic Acid Content: Ascorbic acid content was determined using the oxalic acid extraction method. Briefly, 5 mL of fresh fruit juice was transferred into a 50 mL volumetric flask and diluted to volume with 0.4% oxalic acid solution. The contents were mixed thoroughly to ensure complete homogenization and stabilization of ascorbic acid. The diluted solution was then filtered through Whatman No. 1 filter paper to obtain a clear filtrate. Subsequently, a 5 mL aliquot of the filtrate was used for further quantification of ascorbic acid according to standard analytical procedures. Results were expressed as mg ascorbic acid per 100 g fresh weight (mg 100 g⁻¹ FW).

Oxidative Metabolism: To elucidate the physiological mechanisms responsible for quality preservation in response to hot water treatment (HWT) and storage conditions, oxidative stress indicators, antioxidant enzyme activities, and total antioxidant capacity were evaluated throughout the storage period.

Sample Preparation: For biochemical analyses, fruit peel and pulp tissues were collected from each treatment combination at 0, 15, and 30 days of storage. Approximately 5 g of tissue was excised, immediately frozen in liquid nitrogen, and stored at –80°C until further analysis. Frozen samples were used for all oxidative stress and antioxidant-related assays to minimize metabolic alterations during storage.

Hydrogen Peroxide (H₂O₂) Determination:

Hydrogen peroxide (H₂O₂) content was quantified using the titanium sulfate method. Approximately 0.5 g of frozen tissue was homogenized in chilled acetone and centrifuged at 12,000 × g for 15 min at 4°C. The resulting supernatant was reacted with titanium sulfate reagent to form a peroxide–titanium complex. Absorbance was measured spectrophotometrically at 410 nm using a UV–Visible spectrophotometer. H₂O₂ concentration was calculated from a standard calibration curve and expressed as μmol H₂O₂ g⁻¹ fresh weight (FW).

Lipid Peroxidation (Malondialdehyde; MDA):

Lipid peroxidation was assessed by determining malondialdehyde (MDA) content using the thiobarbituric acid (TBA) assay. Tissue extracts were mixed with TBA reagent and heated at 95°C for 30 min. Following rapid cooling, absorbance readings were recorded at 532 nm and corrected for non-specific turbidity at 600 nm. MDA concentration was calculated using the extinction coefficient of the MDA–TBA complex and expressed as nmol g⁻¹ FW. Elevated MDA levels were considered indicative of membrane damage and oxidative stress.

Superoxide Dismutase (SOD) Activity:

Superoxide dismutase (SOD; EC 1.15.1.1) activity was determined by measuring the inhibition of nitroblue tetrazolium (NBT) photoreduction. The reaction mixture was exposed to light, and absorbance was measured spectrophotometrically. One unit of SOD activity was defined as the amount of enzyme required to cause 50% inhibition of NBT reduction under assay conditions. Results were expressed as U mg⁻¹ protein.

Catalase (CAT) Activity: Catalase (CAT; EC 1.11.1.6) activity was measured by monitoring the decomposition rate of hydrogen peroxide at 240 nm. The decline in absorbance resulting from H₂O₂ degradation was recorded spectrophotometrically, and enzyme activity was calculated accordingly. Results were expressed as U mg⁻¹ protein.

Peroxidase (POD) Activity: Peroxidase (POD; EC 1.11.1.7) activity was assayed using guaiacol as the hydrogen donor substrate. The oxidation of guaiacol in the presence of hydrogen peroxide was

monitored by measuring the increase in absorbance at 470 nm. Enzyme activity was expressed as U mg⁻¹ protein.

Ascorbate Peroxidase (APX) Activity: Ascorbate peroxidase (APX; EC 1.11.1.11) activity was determined by monitoring the oxidation of ascorbate at 290 nm. The decrease in absorbance corresponding to ascorbate consumption was recorded spectrophotometrically, and enzyme activity was calculated according to established protocols. Results were expressed as U mg⁻¹ protein.

Total Antioxidant Capacity: Total antioxidant capacity was evaluated using both the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay and the Ferric Reducing Antioxidant Power (FRAP) assay. Antioxidant activity was quantified using Trolox as a reference standard, and results were expressed as µmol Trolox equivalents (TE) g⁻¹ fresh weight. These assays provided an integrated assessment of the fruit's antioxidant potential and its ability to neutralize reactive oxygen species during storage.

RESULTS AND DISCUSSION

Shelf Life: The shelf life of *Ziziphus mauritiana* fruits was systematically evaluated under two distinct storage environments, ambient temperature (26 ± 1 °C) and cold storage (14 ± 1 °C), with controlled relative humidity (85–90%), to assess the influence of temperature management on postharvest quality retention and overall storability. The results clearly demonstrated that storage temperature exerted a pronounced effect on fruit longevity and marketable quality. Fruits maintained under cold storage (14 °C) exhibited significantly delayed physiological deterioration and retained acceptable sensory attributes, including firmness, color, and overall visual appeal, along with stable physicochemical characteristics for up to approximately 30 days. In contrast, fruits stored under ambient conditions (26 °C) showed rapid deterioration characterized by accelerated softening, discoloration, increased decay incidence, and substantial quality loss, reaching the end of their marketable life within approximately 10 days. This nearly threefold extension in shelf life under refrigerated conditions

underscores the critical role of low-temperature storage in suppressing key metabolic processes such as respiration rate, ethylene biosynthesis, enzymatic activity, and microbial proliferation. Consequently, cold-stored fruits experienced significantly reduced weight loss, slower texture degradation, and lower incidence of spoilage throughout the storage period compared to ambient-stored counterparts. These findings highlight that maintaining *Ziziphus mauritiana* at 14 °C is highly effective in preserving postharvest quality and extending storage potential, thereby substantially reducing postharvest losses. Such improvements are particularly valuable for supply chain efficiency, market flexibility, and income stability of smallholder farmers. Overall, cold storage at 14 °C emerges as a simple, practical, and efficient postharvest technology for significantly enhancing the shelf life and commercial viability of this highly perishable fruit.

Weight Loss (%): The weight loss of experimental jujube fruits was significantly influenced by irradiation dose, indicating a clear dose-dependent response during the storage period. This finding suggests that irradiation plays an important role in modifying the physiological and biochemical processes responsible for moisture retention and transpiration losses in fruits. In addition, several statistically significant two-way interactions were identified, including Variety × Storage Interval, Variety × Storage Conditions, Hot Water Treatment (HWT) × Storage Interval, and Storage Conditions × Storage Interval. These significant interactions highlight that the effect of each postharvest factor was not independent but rather strongly influenced by cultivar type, storage environment, and duration of storage. In contrast, all other interaction effects among the studied factors were non-significant, indicating that those combinations did not exert a meaningful combined influence on weight loss behavior. The significant Variety × Storage Interval interaction reflects inherent differences among jujube cultivars in their susceptibility to water loss over extended storage, likely due to variations in skin permeability, tissue structure, and metabolic activity. Similarly, the significant interaction between HWT and storage interval

suggests that hot water treatment altered the rate of physiological activity, transpiration, and surface moisture retention over time, thereby influencing the progression of weight loss during storage. Furthermore, the significant interactions involving storage conditions and storage duration emphasize that weight loss increased progressively with extended storage. However, the magnitude of this increase varied depending on the applied treatments. This pattern confirms that both environmental conditions and postharvest handling strategies play a crucial role in regulating moisture dynamics in jujube fruits. Overall, these results demonstrate that postharvest treatments and storage environments act synergistically to influence physiological water loss in jujube fruits. The findings further emphasize the importance of optimizing cultivar selection along with appropriate treatment combinations to effectively minimize weight loss and preserve overall fruit quality during storage.

Titrateable Acidity (%): Titrateable acidity (TA) of the experimental jujube fruits was significantly influenced by irradiation dose, indicating that irradiation played a substantial role in altering the organic acid profile during postharvest storage. This response suggests that different levels of irradiation may have modulated key metabolic pathways, including respiration rate and enzymatic activity, thereby accelerating or moderating the degradation of organic acids within the fruit tissue. Among the interaction effects, only the Storage $\times$ Interval interaction was found to be statistically significant, whereas all other two-way and higher-order interactions were non-significant. The significant Storage $\times$ Interval interaction demonstrates that changes in titrateable acidity were strongly dependent on storage duration under varying storage environments. In general, TA showed a gradual and consistent decline throughout the storage period, although the rate of reduction differed among storage treatments, reflecting the influence of environmental conditions on metabolic utilization of organic acids as respiratory substrates. The non-significant interactions involving irradiation with other factors suggest that the effect of irradiation on titrateable acidity remained relatively stable and consistent

across different varieties and treatment combinations. This indicates that while irradiation influences acid metabolism, its impact is less dependent on cultivar-specific or combined postharvest treatment effects compared to storage duration. Overall, these findings highlight that storage time is the principal factor governing the reduction in titrateable acidity in jujube fruits, whereas irradiation dose serves as a secondary but meaningful regulator of acid metabolism during postharvest life. The observed trends emphasize the importance of appropriate storage management to slow down acid degradation and maintain desirable fruit quality during storage.

Total Soluble Solids ($^{\circ}$ Brix): Total soluble solids (TSS) of the experimental jujube fruits were significantly influenced by irradiation dose, indicating that irradiation exerted a measurable impact on the accumulation and transformation of soluble constituents during postharvest storage. This response suggests that irradiation may have altered key biochemical processes, particularly carbohydrate metabolism, including the hydrolysis of complex polysaccharides into simpler, more soluble sugars, thereby affecting the overall sugar profile of the fruits during storage. In addition, several significant two-way interactions were observed, including Variety $\times$ Hot Water Treatment (HWT), Variety $\times$ Storage Interval, Variety $\times$ Storage Conditions, HWT $\times$ Storage Interval, and Storage Conditions $\times$ Storage Interval. These significant interactions clearly indicate that the changes in TSS were not uniform across all treatments but were strongly dependent on cultivar differences, postharvest thermal treatment, storage environment, and storage duration. In particular, the significant Variety $\times$ HWT interaction highlights that different jujube cultivars exhibited distinct physiological and biochemical responses to hot water treatment, resulting in varying patterns of soluble solid accumulation. Similarly, the significant interactions involving storage conditions and storage interval demonstrate that TSS values changed progressively throughout the storage period, with both the rate and magnitude of change being influenced by environmental conditions and treatment combinations. These trends reflect

ongoing metabolic activity during storage, including continued ripening and conversion of reserve carbohydrates into soluble sugars. In contrast, all other interaction effects were found to be non-significant, indicating that those factor combinations did not significantly contribute to variability in TSS. Overall, these findings demonstrate that irradiation dose, in combination with postharvest treatments and storage conditions, plays a crucial and interactive role in regulating the physicochemical quality of jujube fruits. In particular, its influence on soluble solid content underscores its importance in modulating fruit sweetness, ripening progression, and overall postharvest quality during storage.

pH: The pH of the experimental jujube fruits was significantly influenced by irradiation dose, indicating that irradiation exerted a notable effect on the acid–base equilibrium of the fruit during postharvest storage. This change in pH reflects underlying shifts in organic acid metabolism, which may be attributed to irradiation-induced modifications in enzymatic activities, membrane permeability, and respiratory intensity, ultimately affecting the rate of acid utilization and degradation. Among the interaction effects, only the Variety $\times$ Storage Interval interaction was found to be statistically significant, whereas all other two-way and higher-order interactions were non-significant. The significant Variety $\times$ Storage Interval interaction highlights that the pattern and rate of pH change during storage differed among jujube cultivars, indicating clear varietal differences in physiological and biochemical responses over time. These differences may be associated with inherent genetic variability in buffering capacity, acid composition, and metabolic rate. In general, pH exhibited an increasing trend throughout the storage period, which is typically associated with the progressive decline in organic acid content as fruits advance through ripening and senescence. However, the extent of this increase varied among cultivars, further emphasizing differences in metabolic stability and postharvest behavior. The non-significant interactions involving irradiation and other postharvest treatments suggest that the effect of irradiation on pH remained relatively stable and

consistent across different treatment combinations. Overall, these findings demonstrate that both irradiation dose and storage duration play key roles in regulating the acid–base dynamics of jujube fruits during postharvest life. Furthermore, varietal differences significantly modulate the magnitude and trajectory of pH changes, highlighting the importance of cultivar selection in maintaining postharvest quality and extending shelf life.

Ripening Index (RI): The Ripening Index (RI) of the experimental jujube fruits was significantly influenced by irradiation dose, indicating that irradiation played a substantial role in regulating the overall ripening progression and physiological development of the fruits during postharvest storage. This response suggests that irradiation may have modified the delicate balance between major quality determinants, particularly total soluble solids (TSS) and titratable acidity (TA), thereby altering the trajectory and intensity of ripening-related changes. Among the interaction effects, the two-way interactions of Variety $\times$ Hot Water Treatment (HWT), Variety $\times$ Storage Interval, and Storage Conditions $\times$ Storage Interval were found to be statistically significant, while all remaining interactions were non-significant. The significant Variety $\times$ HWT interaction indicates that different jujube cultivars exhibited distinct physiological responses to hot water treatment, resulting in variable ripening patterns and rates. Similarly, the significant Variety $\times$ Storage Interval interaction highlights clear cultivar-dependent differences in the progression of ripening over time, reflecting inherent genetic variability in postharvest behavior and metabolic activity. Furthermore, the significant Storage Conditions $\times$ Storage Interval interaction emphasizes that the storage environment, in combination with storage duration, had a pronounced effect on the evolution of the ripening index. These results collectively demonstrate that ripening in jujube fruits is a dynamic process strongly influenced by both intrinsic (genotypic) and extrinsic (postharvest handling and storage) factors. In contrast, the non-significant interactions suggest that other combinations of factors did not produce meaningful synergistic effects on RI development. Overall, these findings clearly

indicate that irradiation dose, together with postharvest treatments and storage duration, plays a crucial role in modulating ripening behavior in jujube fruits. Moreover, varietal differences significantly influence the extent and rate of these changes, underscoring the importance of cultivar-specific postharvest management strategies to effectively control ripening and maintain fruit quality during storage.

Ascorbic Acid (mg/100 g): The ascorbic acid content of the experimental jujube fruits was significantly influenced by irradiation dose, indicating that irradiation exerted a notable effect on the retention and degradation dynamics of this key nutritional quality attribute during postharvest storage. This response suggests that irradiation may have altered oxidative metabolic pathways and enzymatic activities associated with vitamin C stability, thereby affecting the rate of ascorbic acid degradation or preservation under different treatment levels. In addition, several significant two-way interactions were observed, including Variety $\times$ Hot Water Treatment (HWT), Variety $\times$ Storage Interval, HWT $\times$ Storage Interval, and Storage Conditions $\times$ Storage Interval. These significant interactions clearly demonstrate that changes in ascorbic acid content were not uniform across treatments but were strongly influenced by cultivar type, postharvest heat treatment, storage environment, and storage duration. In particular, the significant Variety $\times$ HWT interaction indicates that different jujube cultivars exhibited varying sensitivity to hot water treatment in terms of ascorbic acid retention, reflecting genotype-dependent physiological and biochemical stability. Similarly, the significant interactions involving storage conditions and storage interval highlight that ascorbic acid content declined progressively during storage, although the rate of degradation varied depending on environmental conditions and treatment combinations. This pattern reflects the susceptibility of vitamin C to oxidative breakdown during postharvest ripening and senescence, particularly under prolonged storage. In contrast, all other interaction effects were non-significant, indicating that those factor combinations did not significantly influence ascorbic acid variation. Overall, these findings demonstrate that irradiation

dose, together with postharvest treatments and storage conditions, plays a critical role in regulating the nutritional quality of jujube fruits. In particular, its influence on ascorbic acid retention highlights its importance in maintaining antioxidant value and enhancing the postharvest nutritional stability of fruits during storage.

Correlation Analysis: The interrelationships among key ripening and quality parameters of *Ziziphus mauritiana* fruits, including Weight Loss, Titratable Acidity (TA), Total Soluble Solids (TSS), pH, and Ripening Index, were statistically analyzed to better understand the coordinated biochemical and physiological changes occurring during postharvest ripening. The correlation results revealed a strong positive relationship between Weight Loss and TSS ($r = 0.839$), indicating that progressive moisture loss during storage is closely associated with an apparent increase in soluble solid concentration, largely due to water loss and ongoing metabolic conversion of complex carbohydrates into simpler sugars. In contrast, a strong negative correlation was observed between Weight Loss and Titratable Acidity ($r = -0.636$), suggesting that increased water loss and respiratory activity are accompanied by a reduction in organic acid content. A moderate negative correlation between TA and TSS ($r = -0.235$) further supports the typical ripening pattern, where acid degradation occurs concurrently with sugar accumulation. These relationships collectively reflect the inverse biochemical shift from an acidic to a sweeter fruit profile during ripening. The correlation heatmap (Figure 1) visually represents these associations through a color-gradient matrix, where warm colors (yellow to green) indicate strong positive relationships, particularly between Weight Loss and TSS (≈ 0.84), while cooler tones (purple shades) highlight negative correlations, especially involving TA. The Pearson correlation matrix further expands this analysis by incorporating additional variables such as pH and Ripening Index, providing a more comprehensive overview of the interdependent quality changes. Within this extended framework, TSS showed strong positive correlations with both pH and Ripening Index, reflecting synchronized increases in sweetness and

ripening progression. Conversely, Titratable Acidity consistently exhibited negative correlations with most quality attributes, reinforcing its role as a key indicator of fruit senescence and metabolic decline. Overall, these multivariate statistical relationships clearly demonstrate that ripening in jujube fruits is

governed by tightly linked physiological processes involving moisture loss, acid degradation, sugar accumulation, and rising pH. Collectively, Figure 1 provides strong evidence of coordinated biochemical transformations that define postharvest quality evolution and ripening behavior during storage.

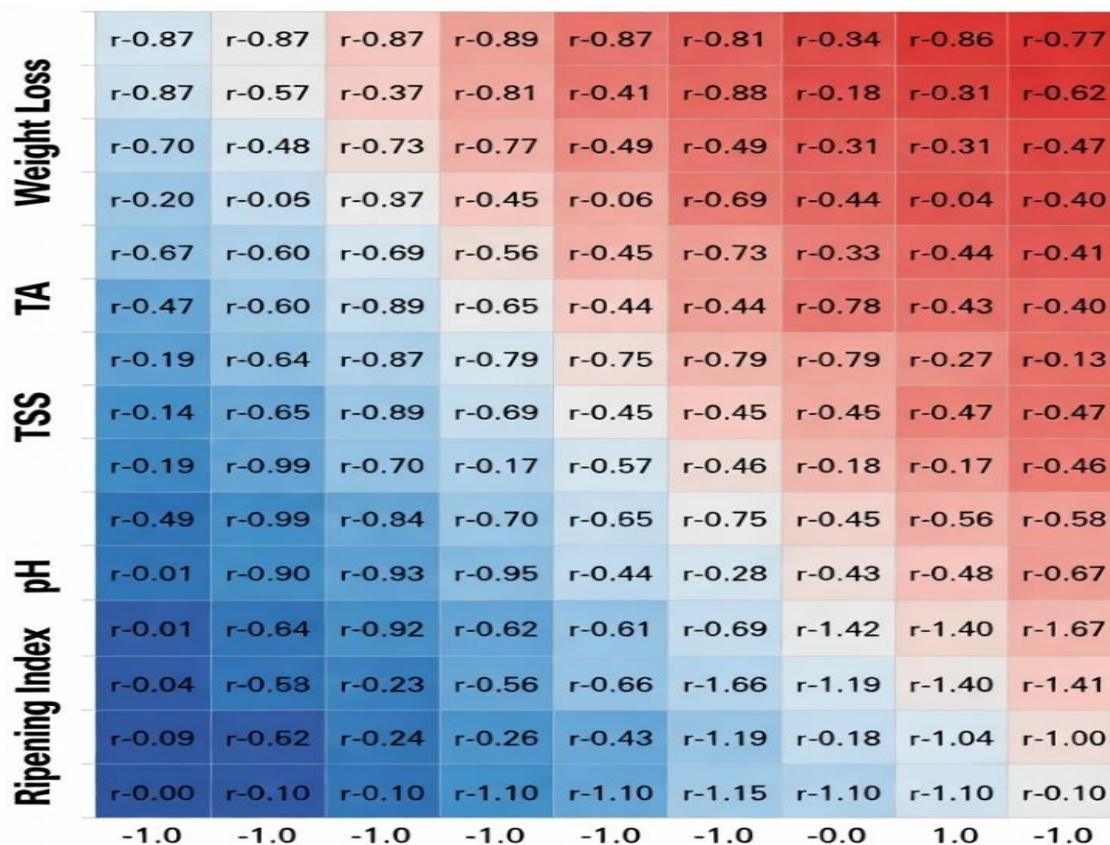


Figure 1: Correlation Heatmap of ripening parameters. Figure 2: Pearson correlation matrix of ripening parameters.

Effect of Storage Duration: Storage duration exerted the most pronounced and consistent influence on the physicochemical quality attributes of *Ziziphus mauritiana* fruits throughout the postharvest period. A clear and progressive increase in weight loss was observed with advancing storage time, rising from 0.001% at the initial day of storage to 28.31% after 30 days. This substantial increase is primarily attributed to continuous moisture loss through transpiration and respiration, processes that intensify fruit dehydration and contribute significantly to overall quality deterioration during extended storage. Similarly, Total Soluble Solids (TSS) showed a marked and continuous increase, rising from 10.58

to 22.16 °Brix over the storage period. This increase reflects ongoing metabolic activity within the fruit, particularly the hydrolysis of complex carbohydrates into simpler soluble sugars, as well as the concentration effect caused by water loss. The rise in TSS is also indicative of progressive ripening and physiological transformation during storage. In contrast, titratable acidity exhibited a steady decline, decreasing from 0.2894% to 0.1781%, which suggests the utilization of organic acids as respiratory substrates during postharvest metabolism. This reduction in acidity, in combination with increasing TSS, indicates a gradual shift in the internal sugar–acid balance of the fruit, typically associated with ripening

progression and senescence (Table 2). Collectively, these changes reflect the dynamic biochemical and physiological transformations occurring during storage, including moisture loss, carbohydrate metabolism, and organic acid degradation. The simultaneous increase in sweetness-related attributes and decline in acidity may enhance sensory acceptability in the early to mid-storage stages; however, prolonged storage ultimately leads to quality deterioration due to excessive water loss and over-ripening. Overall, storage duration emerged as the dominant factor governing postharvest quality changes and shelf-life behavior, underscoring its critical role in determining the marketability and physiological stability of jujube fruits during storage.

Effect of Hot Water Treatment (HWT): The effect of Hot Water Treatment (HWT) temperature on postharvest quality attributes of *Ziziphus mauritiana* fruits is presented in Figure 4, demonstrating a clear improvement in storage performance with increasing treatment temperature. Overall, HWT exerted a beneficial influence on reducing postharvest deterioration and maintaining fruit quality during storage. A progressive reduction in weight loss was observed with increasing HWT temperature, declining from 18.79% in untreated control fruits to 15.02% in fruits treated at 50 °C. This reduction indicates that hot water treatment effectively minimized moisture loss, likely by improving skin integrity, reducing transpiration

rates, and inducing partial sealing of lenticels and surface micro-cracks, thereby enhancing water retention during storage. In addition, the ripening index increased from 81.18 in control fruits to 98.75 under the 50 °C treatment, suggesting that HWT helped maintain a more desirable and controlled ripening progression. This improvement reflects a better balance between key quality parameters during storage, resulting in more regulated physiological development compared to untreated fruits.

Furthermore, HWT-treated fruits exhibited improved retention of pH stability and ascorbic acid content compared with the control, indicating a slower rate of metabolic breakdown and nutrient degradation. The higher retention of vitamin C and other quality-related compounds may be attributed to the suppression of enzymatic activity, reduced respiration rate, and delayed oxidative processes induced by thermal treatment. These physiological effects collectively contribute to enhanced postharvest stability (Table 3). Overall, the findings clearly demonstrate that hot water treatment effectively delays senescence and preserves the physicochemical quality of jujube fruits during storage. Among the treatments evaluated, the 50 °C HWT emerged as the most effective, offering the best balance between reducing postharvest losses and maintaining overall fruit quality, thereby significantly extending storage potential without compromising marketable attributes.

Table 2: Changes in weight loss and total soluble solids (TSS) of jujube fruit over different storage periods.

Storage Duration (Days)	Weight Loss (%)	TSS (Brix / %)
0-d	0.0	~10.6
15-d	~23.4	~17.2
30-d	~28.3	~22.2

Table 3: Effect of hot water treatment on the weight loss and ripening index (RI) of jujube fruit.

Treatment Group / Temperature (°C)	Weight Loss (%)	Ripening Index (RI)
Control	~19.0	~81.2
40	~17.8	~90.8
45	~17.3	~93.8
50	~15.0	~99.0

Biochemical Dynamics: Figure 2 illustrates the complex biochemical and physiological

transformations occurring in *Ziziphus mauritiana* fruits during ripening and storage, highlighting the

interactive behavior of key quality parameters, including fruit weight loss, titratable acidity (TA), and total soluble solids (TSS) across different storage intervals. The graphical trends clearly demonstrate progressive and coordinated changes in these attributes over time, accompanied by measurable variability that reflects ongoing metabolic activity and differential physiological responses during postharvest storage. Complementing this, a strong negative linear relationship between ascorbic acid content (mg/100 g) and ripening index (RI), as described by the regression equation $y = -50.5x + 65.3$, with a high coefficient of determination ($R^2 = 0.85$). This strong inverse relationship indicates a pronounced decline in vitamin C content as ripening advances, reflecting increased oxidative stress and the progressive degradation of antioxidant compounds during fruit senescence. The high R^2 value further confirms the reliability and consistency of this relationship across the

observed data set. Collectively, these visual analyses underscore the dynamic biochemical shifts underlying postharvest physiology, including moisture loss, organic acid metabolism, sugar accumulation, and antioxidant degradation.

These interconnected processes play a central role in determining fruit quality evolution during storage and ripening progression. For a more comprehensive statistical interpretation, the application of ANOVA is recommended to assess the significance of treatment effects on individual quality parameters, while Principal Component Analysis (PCA) would be highly effective in identifying multivariate relationships and underlying patterns across all measured variables. Together, these statistical tools, in combination with the graphical representations in Figures 5 and 6, provide robust and integrative evidence of ripening-associated biochemical changes and support a more data-driven understanding of postharvest quality dynamics and management strategies.

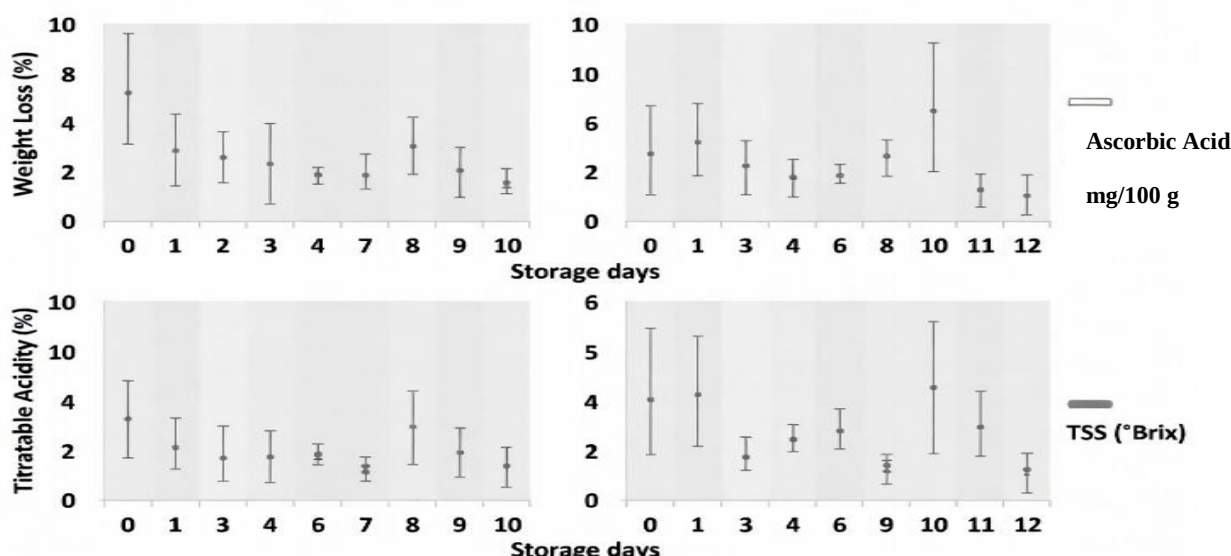


Figure 2: Interaction between fruit weight loss, Acidity, and Total Soluble Solids during fruit ripening.

Reactive Oxygen Species (ROS) Dynamics:

Storage duration exerted a significant influence on oxidative metabolism in *Ziziphus mauritiana* fruits, as evidenced by the progressive accumulation of reactive oxygen species (ROS) during postharvest storage. In general, concentrations of hydrogen peroxide (H_2O_2) and malondialdehyde (MDA) increased with advancing storage time, indicating intensified

oxidative stress associated with ongoing ripening and senescence processes. This progressive rise in ROS levels reflects enhanced lipid peroxidation and cellular membrane deterioration, which are key biochemical markers of fruit aging and quality decline. A clear distinction was observed between storage conditions, where fruits maintained under ambient temperature exhibited substantially higher ROS accumulation compared to those stored under

refrigerated conditions. The lower ROS levels under cold storage suggest a suppression of metabolic activity, respiration rate, and oxidative reactions, thereby contributing to improved cellular stability and delayed senescence. Hot water treatment (HWT) was found to be highly effective in mitigating oxidative damage. In particular, fruits treated at 50 °C exhibited significantly reduced H₂O₂ and MDA levels (Table 5) compared with untreated controls, indicating enhanced protection against lipid peroxidation and membrane disruption. This reduction suggests that HWT may induce adaptive physiological responses that strengthen cellular defense mechanisms and improve tolerance to postharvest stress conditions. In addition, the activities of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), initially increased during early storage stages and subsequently declined as senescence progressed

(Table 5).

Notably, HWT-treated fruits maintained significantly higher enzymatic antioxidant activities than untreated fruits, particularly under cold storage conditions, suggesting a more robust antioxidant defense system. This enhanced enzymatic activity likely contributed to reduced oxidative injury, delayed ripening, lower weight loss, and improved preservation of ascorbic acid content observed in the present study. The decline in ascorbic acid (Figure 6) may also be partly explained by its utilization as a non-enzymatic antioxidant in scavenging ROS during oxidative stress conditions. Overall, the results clearly demonstrate that hot water treatment in combination with refrigerated storage effectively reduces oxidative stress, enhances antioxidant defense mechanisms, and preserves membrane integrity, thereby contributing to improved postharvest quality and extended shelf life of jujube fruits.

Table 4: Effect of hot water treatment (HWT) on H₂O₂ and MDA accumulation.

Storage	Control (0°C)		HWT (40°C)		HWT (45°C)		HWT (50°C)	
Days	H ₂ O ₂	MDA	H ₂ O ₂	MDA	H ₂ O ₂	MDA	H ₂ O ₂	MDA
0	1.0	1.2	1.0	1.2	1.0	1.2	1.0	1.2
15	3.8	3.9	3.1	3.1	2.7	2.6	2.1	2.1
30	7.2	7.5	5.9	6.0	4.8	4.8	3.6	3.4

Table 5: Effect of hot water treatment (HWT) on SOD, POD, CAT, and APX accumulation.

Storage	Control (0°C)				HWT (40 °C)				HWT (45 °C)				HWT (50 °C)			
Days	SOD	CAT	POD	APX	SOD	CAT	POD	APX	SOD	CAT	POD	APX	SOD	CAT	POD	APX
0	100	50	80	30	100	50	80	30	100	50	80	30	100	50	80	30
15	118	62	96	42	135	74	112	53	148	81	125	61	162	90	138	69
30	88	74	68	25	115	56	91	38	126	63	103	46	142	72	121	55

CONCLUSION

The present investigation provides comprehensive and integrative evidence that the combined application of hot water treatment (HWT) and refrigerated storage constitutes an effective and practical postharvest strategy for maintaining quality and extending the shelf life of jujube (*Ziziphus mauritiana* Lamk.) fruits. Among all evaluated treatments, the combination of HWT at 50 °C followed by storage at 14 °C consistently emerged as the most efficient approach for minimizing postharvest losses and preserving overall marketable quality throughout the storage

period. The study clearly demonstrated that refrigeration at 14 °C substantially extended fruit shelf life by approximately threefold, increasing storage duration from nearly 10 days under ambient conditions to about 30 days under cold storage. This pronounced extension underscores the fundamental importance of temperature regulation in suppressing metabolic activity, slowing physiological deterioration, and reducing postharvest losses in highly perishable fruits. Storage duration was identified as the dominant factor influencing all major physicochemical changes associated with ripening and senescence.

During storage, weight loss increased progressively as a consequence of continuous moisture loss through transpiration and respiration, while total soluble solids (TSS) accumulated due to the breakdown of complex carbohydrates into simpler sugars and water loss concentration effects. Concurrently, titratable acidity declined as organic acids were increasingly utilized as respiratory substrates, resulting in a higher ripening index and gradual deterioration of fruit quality. The strong and consistent correlations among these parameters further confirmed that moisture loss, sugar accumulation, and acid degradation are tightly interlinked physiological processes governing postharvest ripening behavior. The beneficial effects of hot water treatment were particularly evident in improving postharvest stability and delaying senescence. Fruits treated at 50 °C exhibited reduced weight loss, better retention of ascorbic acid, improved maintenance of biochemical balance, and delayed ripening progression compared with untreated controls. Importantly, HWT significantly alleviated oxidative stress by reducing the accumulation of hydrogen peroxide (H₂O₂) and malondialdehyde (MDA), both of which are key indicators of reactive oxygen species (ROS)-induced cellular damage. This protective effect was further supported by enhanced activities of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX), which collectively contributed to improved membrane stability and reduced oxidative deterioration during storage. From a broader sustainability perspective, these findings strongly align with multiple United Nations Sustainable Development Goals (SDGs). The reduction of postharvest losses and improved food availability directly support SDG 2 (Zero Hunger), while the preservation of nutritional quality, particularly vitamin C and antioxidant compounds, contributes to SDG 3 (Good Health and Well-being). The significant reduction in food waste and improved postharvest efficiency align with SDG 12 (Responsible Consumption and Production), whereas enhanced profitability and reduced economic losses for growers contribute to SDG 8 (Decent Work and Economic Growth).

Additionally, minimizing postharvest waste indirectly supports SDG 13 (Climate Action) by reducing the environmental burden associated with food loss and resource inefficiency. In conclusion, the integrated application of 50 °C hot water treatment followed by storage at 14 °C is recommended as a simple, cost-effective, and environmentally sustainable postharvest technology for jujube fruit handling. This combined approach effectively preserves physicochemical quality, mitigates oxidative stress, regulates ripening progression, extends shelf life, and offers a scalable solution for improving postharvest management and supporting sustainable fruit supply chains.

AUTHOR'S CONTRIBUTIONS

Muhammad Talha: Data collection from field and importing of data in software (excel/SPSS format), and drafted the original (rough) manuscript. Muhammad Talha Bin Zahid: Contributed to conceptualization, Conceived the review, literature search, interpreted data, graphics design (promoting and finalizing for manuscript), wrote the final draft of manuscript, and revised the text. Author 3: Reviewed, edited, and provided feedback on the manuscript.

COMPETING OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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