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Research Article

POSTHARVEST QUALITY AND SHELF-LIFE ASSESSMENT OF SWEET PEPPER (*Capsicum annuum* L.) UNDER AMBIENT STORAGE CONDITIONS

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Abstract

Sweet pepper (*Capsicum annuum* L.) is a highly perishable, nutrient-rich vegetable, and maintaining its postharvest quality at room temperature is a major challenge. This study evaluated the fruit quality and shelf life of 11 (G1,G2,G3,G4,G5,G6,G7,G8,G9,G10,G11) sweet pepper genotypes stored at ambient storage conditions (24.73±0.21°C, 69.26±0.04% RH) for a period of 27 days. The experiment arranged in a Completely Randomized Design (CRD) was carried out under laboratory conditions with three replications over period of September 2024 to March 2025. The maximum respiration rate (1723 µmol g^{-1} s^{-1}), TPC (130.98 mg $100g^{-1}$ DW), carotenoids (0.849mg $100g^{-1}$DW), and anthocyanin (1.08 mg $100g^{-1}$ FW) were recorded in G7, and G10 had the highest chlorophyll b (0.102 mg g-1). Maximum vitamin C (173.46 mg $100g^{-1}$ FW), TFC exhibited by G11 higher than other varieties. Significant quality reductions was occurred by day 20. At this stage, G5 retained the highest vitamin C (146.38 mg $100g^{-1}$ FW) and DPPH activity (56.74%). G7 had higher retention of TPC (80.97 mg $100g^{-1}$ DW), carotenoids (0.627 mg g-1 FW) and anthocyanin (0.22 mg $100g^{-1}$ FW); while G9 and G10 were better in retaining the chlorophyll a (0.051 mg g-1 FW) and TFC (93.68 mg $100g^{-1}$ DW). G4, G9 and G10 genotypes had longer shelf life (24.67, 25.61 and 26.67 days respectively) retaining the higher overall quality. Conversely, G1 and G2 had a shorter shelf life and poorer nutrient retention, associated with higher respiration rates. Thus, the genotypes G4, G9 and G10 are recommended to store for longer duration(24-27 days) at room temperature with minimum loss in quality. However, it needs to verify again before being conferring final recommendation.

Introduction

Sweet pepper (*Capsicum annuum* L.), also called bell pepper, is one of the most widely grown and consumed vegetable crops worldwide. Sweet peppers are native to Central and South America, where they were domesticated almost 9,000 years ago. Columbus brought them to Europe in the late 15th century, thinking they were a milder form of black pepper. Though they originated in Europe, they have been disseminated all over the world and play a central in cooking due to their bright colors and mild sweet flavor. It is important due to its bright color, nutritive and culinary properties (Poverenov et al*.,* 2014). Sweet peppers are members of the Solanaceae family and they are a good source of vitamins A and C, antioxidants; capsaicinoids, flavonoids which are bioactive compounds responsible for their health promoting properties (Howard et al*.,* 2000).

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There has been an increase in sweet pepper consumption worldwide with growing awareness of its nutritional attributes as well as its visual appeal and uses in the home, health food, pharmaceutical, and cosmetics industries (Bosland and Votava, 2012). Nevertheless, their perishability makes it difficult to maintain them in good condition and extend their shelf life especially when stored under room temperature conditions (Díaz-Pérez et al.,2007).

Postharvest quality and duration of shelf-life are important for the market acceptance and value of sweet pepper. During postharvest, physiological and biochemical processes such as respiration, transpiration and senescence speed up the deterioration thus leading to a decrease in commercial acceptance (González-Aguilar et al., 2004). These modifications lead to the loss of firmness, degradation in color and weight, and vulnerability to microbial spoilage which affects both the sensory as well as nutritional quality (Lownds et al., 1994). Such problems are further aggravated when stored at room temperature, which is the case in areas with weak cold-chain facilities since it accelerates metabolic and spoilage processes due to higher temperatures. The postharvest life of sweet peppers depends on both internal factors, such as genetics, pepper maturity and physiological traits [such as cell wall constitution and antioxidant potential (Ben-Yehoshua, 1985) and external factors such as temperature, relative humidity, handling after harvest (Saltveit, 2002). Postharvest performance in stored fruit varies greatly among genotypes, with some being thicker pericarp and having a higher wax content that reduces loss of specific water from mature green stages and resists damage (Lownds et al., 1994). Discovery of genotypes with good shelf life when kept at room temperature is very important in resource poor areas, especially in developing countries (Deepa et al., 2006).

Quality of sweet peppers is normally measured by external factors (color, gloss, firmness) and internal traits (nutritive content, flavor and texture). Sensory characteristics such as sweetness and crispness influence consumer preference rates while nutritional quality including vitamins and antioxidants are essential for health-based diets (Howard et al., 2000). Storage at room temperature (20-30ºC) stimulates respiration and ethylene production, resulting in weight loss, chlorophyll degradation and nutrient loss, which increases vulnerability to pathogens such as *Alternaria alternata* and *Botrytis cinerea* (Díaz-Pérez et al., 2007). Genotypes with thicker pericarp and higher antioxidant levels retain better quality because antioxidants can reduce the free radical formation in storage (Deepa et al., 2006). Postharvest loss is estimated to range from 30 to 50% in some areas thereby contributing to food waste and economic losses, especially in less developed countries where storage at room temperature is common (FAO, 2019). Breeding for improved postharvest characteristics and treatments such as edible coatings or modified atmosphere packaging are potential solutions to extend shelf life (Ali et al., 2011). The current study primarily aimed at the screening of desired genotypes with better postharvest quality and keeping quality under room temperature storage. The specific objectives of this research are-to investigate the fruit quality changes in different sweet pepper genotypes during postharvest storage under room temperature and to evaluate shelf life of different sweet pepper genotypes under room temperature.

Materials and Methods

Experimental Site

The experiment was carried out in the laboratory of the Department of Horticulture at Sylhet Agricultural University, Bangladesh from September 2024 to March 2025. The site is located in the north-east part of Bangladesh (from 23.57° to 25.13° North latitude and 90.56° to 92.21° East longitude) under AEZ-20 at an elevation of 30 m above the sea level. The climate is subtropical, with mild temperature, peculiar precipitation distribution and humidity variation featuring a highly acidic silty clay loam soil and the soil pH ranges from 4.7 to 6.9.

Experiment design and layout

A completely randomized design (CRD) was used to conduct the experiment and gave a comparison of unbiased shelf-life assessment of 11 sweet pepper genotypes. Each genotype was replicated three times, with each replication consisting of four individual fruits, making up a total of 132 fruits (11 genotypes x 3 replications x 4 fruits per-replication). The fruits were harvested at commercial maturity and kept in controlled conditions in order to observe postharvest shelf life. A non-destructive and destructive quality assessment was made after a specific period of time namely day 0, day 10, and day 20. A sample of 33 fruits at every time of evaluation was analyzed, which included one randomly selected fruit of each three replications at each genotype. This sampling approach ensured that each genotype was represented equally at every assessment stage while minimizing the number of fruits removed from storage at each time point.

Fruit materials

Mature green sweet peppers (*Capsicum annuum* L.) with uniform green color, firm and fully developed were carefully harvested at commercial maturity stage from a local horticultural farm located at Sylhet Agricultural University, Bangladesh – a place where farming is known to thrive. The harvesting was done manually in the early morning to keep field heat to a minimum, this keep the peppers fresh and puts them on shelf-life focus by minimalizing what spoilage might accrue from the heat. In order to avoid mechanical harm (bruises/lacerations) the peppers were transported in a perforated plastic box that allowed air flow to maintain quality and reduce moisture levels. Upon arrival, the peppers were sorted to eliminate those with damage (cut or bruised), diseases (e.g., fungal infections) and non uniforms features (e.g., size of appearance), so that high quality and uniform-looking pepper would be used for further applications, likely in research, commercial or processing operations, thereby preserving the ability to market them for desired purposes.

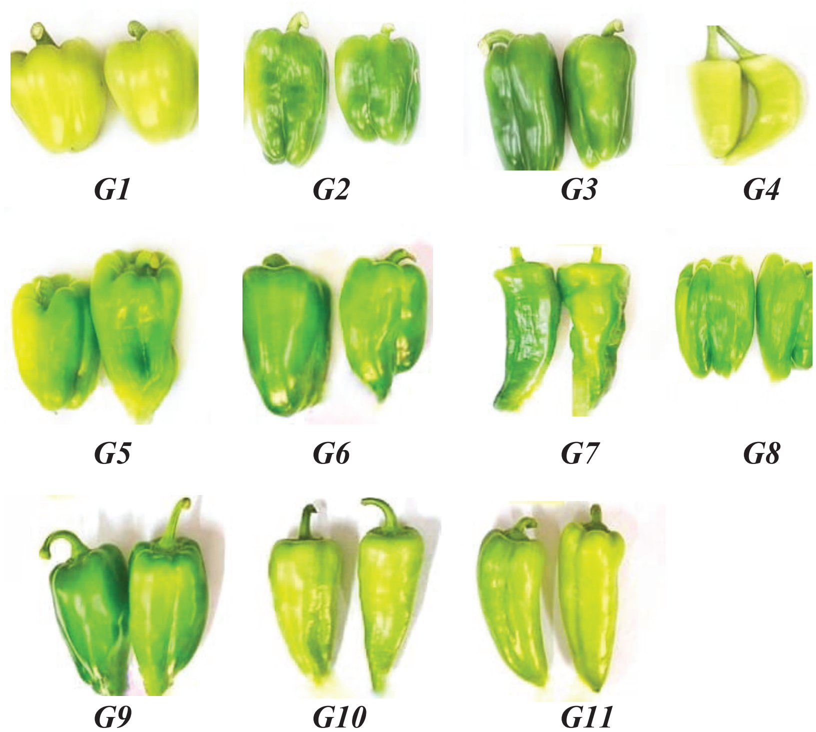

Figure 1. Picture of selected Sweet Pepper genotypes.

Fruit preparation and storage

Fruits were selected, washed with running tap water to eliminate the dirt on the surface and air- dried at room temperature. All replicates were packed in a perforated polyethylene bags (0.03 mm, 10% perforation) to provide enough ventilation and reduce undue loss of moisture content. The bags were kept on open desk in a ventilated room at room temperature.

Storage temperature and humidity

Ambient temperature oscillated based on an average of 24.73±0.21°C and 69.26±0.04% RH. The temperature and humidity of the storage environment were monitored daily with a digital temperature and humidity logger (Model: RC-4HC, Elitech). The summary of the temperature and relative humidity fluctuations is depicted in Figure 2.

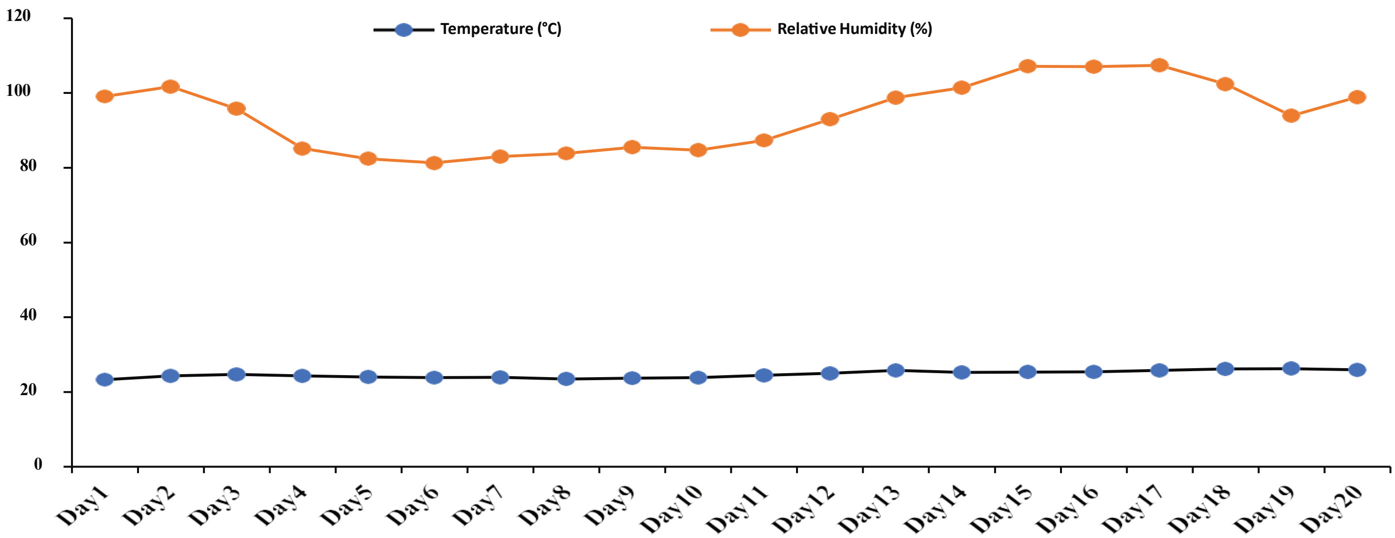

Figure 2. Temperature and relative humidity during the experiment.

The analytical methodology used

Determination of vitamin C (mg/100g FW)

Vitamin C was calculated by using a method developed by Salkić *et al.,* (2009). 1.0 g fresh sample in 10 ml of 0.056 M sodium oxalate for 2 minutes, filter after 5 minutes. 0.5 ml extract diluted to 5.0 ml with 0.056 M sodium oxalate. Absorbance was measured at 266 nm using a UV-Visible spectrometer (Model UV-1900, Shimadzu, Japan) with 0.056 M sodium oxalate as a blank. Calibration curves were constructed using L-ascorbic acid as a standard.

Assay of antioxidant activity (TPC and TFC)

The dry weight sample (1 g) was homogenized with 6 mL of 80% ethanol in order to quantify the total phenolic and flavonoid (Debnath *et al.,* 2018). The total phenolic and flavonoid content was then measured by centrifuging the ethanolic extract at 12,000 rpm for 20 min at 4 ◦C. To measure the concentration of total phenolic, the Folin–Ciocalteu colorimetric method was applied, with a minor changes. Using 7.5% sodium carbonate and the Folin-Ciocalteu reagent, a blue solution was generated. The absorbance of the blue-colored solution that had evolved after 90 minutes in a water bath at 30 ˚C was measured at 765 nm. The total phenolic content was reported as gallic acid standard equivalent (mg) on a fresh weight basis (mg GAE·g -1 FW). Flavonoids were measured using the AlCl3 technique, with quercetin acting as a reference. The absorbance solutions were produced with 10% AlCl3, 1 M NaOH, and 5% NaNO2. The absorbance was measured using the spectrophotometer at 510 nm in contrast to a blank. The result was presented as the mg of quercetin equivalent per g of dry weight samples.

Determination of total antioxidant (DPPH activity)

Total antioxidant activity (DPPH) was carried out following slight modification from Susanti *et al*. (2007). The DPPH (2,2-diphenyl-1-picrylhydrazyl) scavenging assay was used to determine the total antioxidant activity of methanol extract of French leaves and pods sample. For the determination 5 mg dried sample was homogenized in methanol, and the absorbance was measured by spectrophotometer at 517 nm.

Quantification of anthocyanin

For the quantification of anthocyanins, 100 mg of fresh sweet pepper fruit was homogenized in 3 mL of acidic ethanol (95% ethanol with 1.5N HCl). The mixture was incubated at 4 °C for 1 hour with gentle agitation, followed by centrifugation at 8,000 revolutions per minute for 10 minutes at 4 °C (Model BKC-TL4MII, China). The absorbance of the supernatant was subsequently assessed at 530 nm and 657 nm utilizing a UV–Visible spectrophotometer (Model UV-1900i, Shimadzu, Japan), with minor modifications to the methodologies outlined by Chu *et al.* (2013) and Sharmin *et al.* (2024).

$$\text{QAnthocyanin} = (A530 - 0.25 \times A657) \times M{-}1;$$

QAnthocyanin represents the quantity of anthocyanin; A530 and A657 denote absorbance at specified wavelengths; M signifies the mass of the fresh sweet pepper (mg).

Determination of Chl a and Chl b and carotenoids

For the assay for carotenoid content in fresh fruit, weigh 0.2 g of fresh leaf and place it into a previously cleaned mortar as above. Add 6 ml of the 80% acetone (by mixing 80 ml acetone with 20 ml distilled water). The sample must be completely crushed and milled to maximize pigment extraction with a mortar and pestal (high polish if possible). Centrifuge the homogenized suspension at 12,000 g for 20 min in centrifuge tubes. The clear supernatant was collected after centrifugation. Examine the absorbance of the supernatant at wavelengths ranging from 470 nm, 645 nm, and to 663 nm with a spectrophotometer. The 80% acetone is used as the blank for the calibration in absorbance measurements.

Respiration

This specific procedure was made in order to determine the respiration rate of a 10g capsicum sample, using the PP Systems EGM-5 Portable CO_2 Gas Analyzer connected to a 480ml hermetically closed chamber (following procedures given for the specific methodology). Ten-gram sample of fresh capsicum fruit that was not damaged was taken and put in a 480-ml sealed jar; the latter was checked with care to ensure no air entrap or contaminated air within that might affect CO_2 measurements. In order to acquire the output, a sample's number was inserted and the measurement time of data was programmed in accordance with experimental regimen by PP Systems EGM-5 Portable CO2 Gas Analyzer. A 15-sec stabilization time was observed to enable the analyzer to obtain a baseline for reliable data recording. The CO_2 produced by the capsicum sample was then monitored during a 180s period, which represented respiration rate of the fruit during release of carbon dioxide as part of metabolic activity. Once measurements were complete, the chamber was opened to allow residing CO_2 to dissipate and fresh air was flushed through the jar for a few minutes to fully decant any remaining gas thereby preventing cross contamination between samples. The system was then re-maneuvered to accommodate the next sample of capsicum and precision, and set up was maintained throughout the trial for consistency in order to accurately evaluate respiration rate of the capsicum fruit. Respiration rate was calculated using the formula:

$$\textbf{Respiration Rate (RR)} = (S \times V\_free \times 60) / (W \times 1000)$$

Where, S: Slope of CO_2 increase = $\Delta CO_2 / \Delta t$,
V_free: Free volume of the chamber (chamber volume - sample volume),
W: Mass of the sample,
60: Converts minutes to hours and
1000: Converts liters to milliliters and accounts for kg.

Shelf-life

To determine the shelf life of sweet peppers (*Capsicum annuum* L.), each pepper was individually wrapped in low-density polyethylene (LDPE: food-grade) bags that were tightly sealed with a little head space to allow for minimal gas exchange, and with all LDPE bags labeled by variety name. The peppers were observed for color, texture as well as defects every two days and notes on the specific observations made combined with photography records before the bags were resealed for further storage. When any of the peppers indicated spoilage or damage, that is, fadeout and or great deterioration (rot), they were promptly discarded, the place was entirely cleaned so that no contamination was present in other samples. The data obtained, as well as the time of collecting, were noted and through their average shelf life for all the cultivars and sorts was calculated to examine the length of period during which these peppers can be used commercially.

Data Collection and Statistical Analysis

Sampling was performed at day 0,10 and 20 days of storage for all parameters with exception of shelf life. Each assay was carried out in triplicate and the results were presented as mean ± SD. And shelf life was considered when fruits had the presence of 20 days on average. Statistical analyses were performed with the R 3.4 software package (The R Foundation) by using analysis of variance (ANOVA), and other statistics was carried out by Microsoft Excel.

Results

Physiological assessment: Respiration rate of sweet pepper genotypes during Storage

The 27-day storage study of sweet pepper 11 genotypes at room temperature (24.73±0.21°C and 69.26±0.04% relative humidity) revealed significant variations in respiration rates (CO_2 production in µmol $g^{-1}s^{-1}$) (Figure 3). On day 0, G6 exhibited the highest rate (1723 µmol $g^{-1}s^{-1}$), while G8 (582.67 µmol $g^{-1}s^{-1}$) and G10 (623.67 µmol $g^{-1}s^{-1}$) had the lowest. By Day 10, G3 (1226.67 µmol µmol $g^{-1}s^{-1}$) and G10 (1154.67 µmol µmol $g^{-1}s^{-1}$) showed peak rates, with G11 (579 µmol µmol $g^{-1}s^{-1}$) and G_4 (594.33 µmol µmol $g^{-1}s^{-1}$) being the lowest. On Day 20, G1 had the highest rate (1220.67 µmol µmol $g^{-1}s^{-1}$), while G_{11}(542.67 µmol $g^{-1}s^{-1}$) remained the lowest.

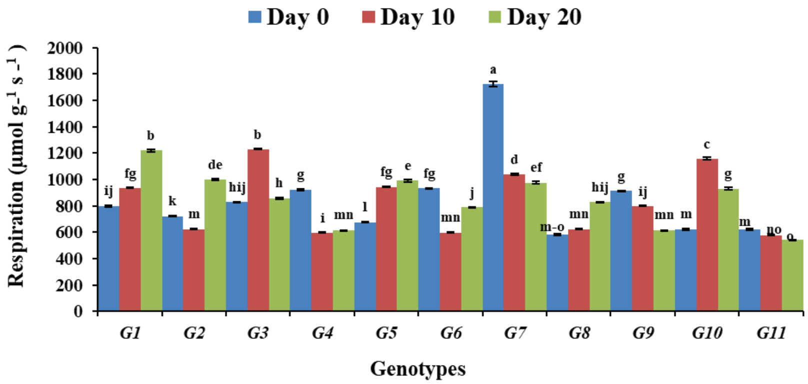

Figure 3. Respiration rate of Sweet Pepper genotypes during storage.

Pigment degradation and color changes

Chlorophyll a and chlorophyll b of sweet pepper genotypes during storage

Chlorophyll a content varied significantly among genotypes and storage days (Figure 4). At day 0, it's visible that chlorophyll a level was highest, ranging from 0.020 mg g-^{1}FW (G_2) to 0.074 mg g-^{1}FW (G_7), with G_7 exhibiting the highest value, followed by G_9, G_3, G_5, and G_6. By day 10, chlorophyll a content significantly declined across all genotypes, ranging from 0.018 mg g^{-1} FW (V_9) to 0.067 mg g^{-1} FW (V18), with G_7 and G_9 retaining the highest levels, while G_2 and G_8 showed the lowest. After 20 days, chlorophyll a level further decreased, ranging from mg g^{-1} FW (G5) to 0.051 mg g^{-1} FW (G9 and G10), with G9 and G10 maintaining the highest retention, and G5, G11, G6, and G8 exhibiting the lowest.

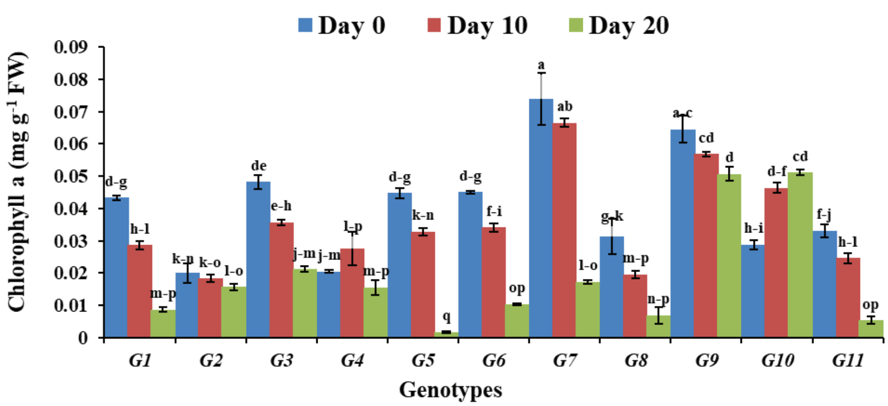

Figure 4. Chlorophyll a of Sweet Pepper genotypes during storage.

Chlorophyll b content varied significantly among genotypes and storage days (Figure 5). At day 0, Chlorophyll b levels were highest among the genotypes studied, ranging from 0.023 mg g^{-1} FW (G1) to 0.102 mg g^{-1} FW (G10), with G10 exhibiting the highest and statistically similar values to G7, G9, G3, G4, G2, and G6, indicating robust initial Chlorophyll b content. At day 10, Chlorophyll b levels significantly decreased across all genotypes, ranging from 0.004 mg g^{-1} FW (G9) to 0.045 mg g^{-1} FW (G7), with G7 and G3 retaining the highest content, while G9 showed the lowest. After 20 days, Chlorophyll b levels dropped further, ranging from 0.001 mg g^{-1} FW (G9) to 0.040 mg g^{-1} FW (G3), with G3 and G2 having the best stability and G9, G8, G7, G5, and G10 having the lowest.

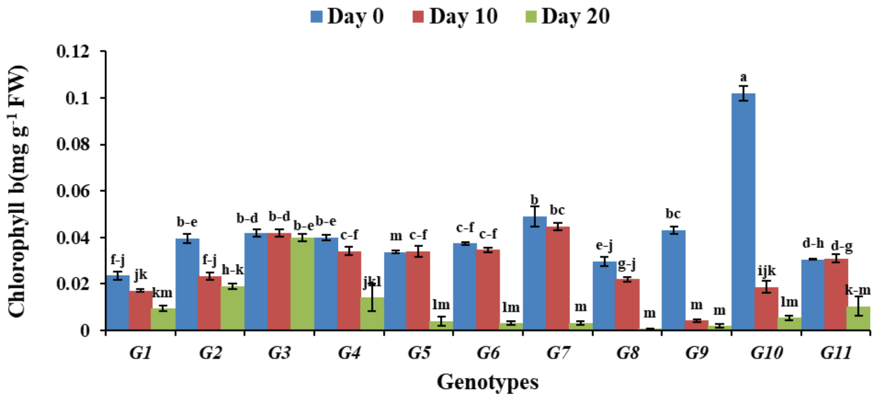

Figure 5. Chlorophyll b of Sweet pepper genotypes during storage.

Carotenoids in Sweet pepper genotypes throughout storage

Carotenoid contributions became apparent among different genotypes and storage days (Figure 6). At day 0, carotenoid contents were the greatest between the genotypes ranging from 0.315 mg g-1 FW (G2) to 0.849 mg g-1 FW(G7), in which G7 and G9 did show both the highest but not significantly different values, followed by G3, G6, G5, G4, G11 and G10 primarily due to strong initial carotenoid content as indicated in Figure 6. Between days 1 and 10 carotenoids decreased significantly in all genotypes, from 0.154 mg g-1 FW(G2) to 0.774 mg g-1 FW (G7), remaining as the genotype with higher readout G7 while G2 levels were the lowest. A further reduction in the carotenoid content after day 20 is observed from 0.093 mg g-1 FW in G2 to 0.627 mg g-1 FW (G7), with G7 having significantly higher levels and G2 and G8 were found to have lowest amounts, respectively.

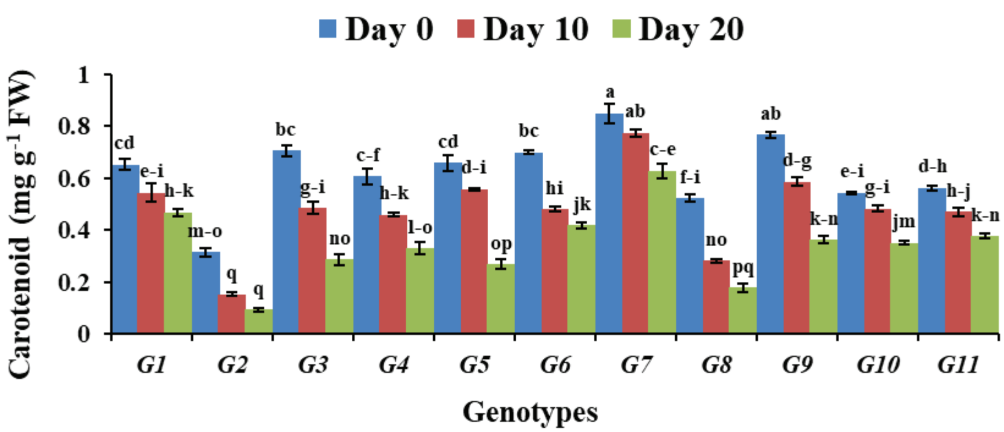

Figure 6. Carotenoids of Sweet pepper genotypes during storage.

Anthocyanin content of Sweet Pepper Genotypes during Storage

Anthocyanins in sweet pepper genotypes stored for 27 days at room temperature (Figure 7). Differences in anthocyanin content were observed among the studied sweet pepper genotypes during storage time for up to 27 days under controlled environmental conditions (room temperature). The highest concentration of anthocyanins was present at Day 0 reaching level of between 0.44 mg $100g^{-1}$ FW (G5) to 1.08 mg DW (100 mg g^{-1}) G4 and G7 At day 10, anthocyanin content had significantly decreased, from 0.20 mg $100g^{-1}$ FW (for G2) to 0.46 mg $100g^{-1}$ FW (G7), with highest remains in G7, G11 and G10 but lowest for G1 and G2. At Day 20, anthocyanin content decreased further from 0.09 mg $100g^{-1}$ FW (G1 and G2) to 0.25 mg $100g^{-1}$ FW (G10); however, in the shelf life samples, G10 and G11 showed overall higher retention, whereas G1, G2 and G8 had lower levels of these compounds.

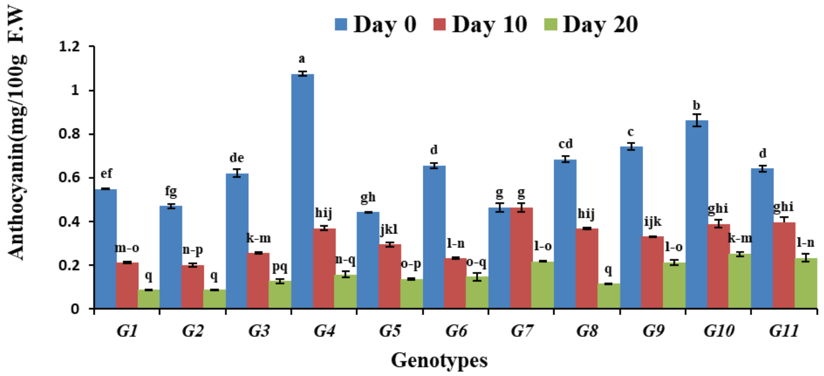

Figure 7. Anthocyanin content of Sweet Pepper genotypes during storage.

Loss of bio active compound and antioxidant capacity

Sweet pepper Genotype in Vitamin C content during storage

The concentration of vitamin C showed significant differences among genotypes and storage days. As presented in Figure 8, on day 0 the Vitamin C values exhibited significant differences across genotypes with values ranging from 135.07 (G1) to 173.46 mg/100g FW (G11), whilst G11, G5, G8, G3, G9, G10 and G2 displaying the highest and similar values suggesting strong initial Vitamin C content. It was measured that both color components decreased during storage but remained at acceptable levels at day 7 aerobic packaging Figure30-Cloar-. At day 10, the values of Vitamin C decreased significantly in all genotypes from 113.44 mg $100g^{-1}$ FW(G1) to 163.47 mg $100g^{-1}$ FW (G11), presenting the greatest retention in G11, G5, G8, G9 and G10 and lower among them was observed for G1. The Vitamin C content decreased with a variation from 146.38 mg $100g^{-1}$ FW (G5) to 30.66 mg $100g^{-1}$ FW (G4), after 20 days G11 and G5 preserved higher levels, whereas the lowest was achieved by G4

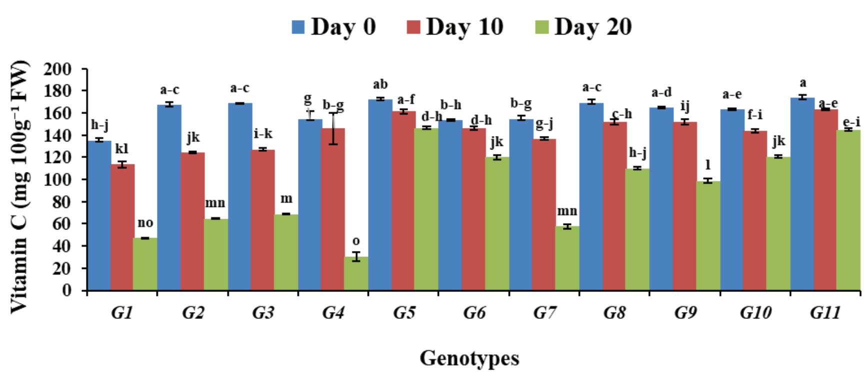

Figure 8. Vitamin C content of Sweet pepper genotypes during storage.

Determination of Antioxidant activities of stored sweet pepper genotypes

Total Flavonoid Content -TFC

The TFC varied markedly among genotypes and storage days (Figure 9). This cultivar was characterized by higher TFC levels than the other genotypes, with older leaves reaching up to 138.67 mg $100g^{-1}$ (G5) and newly-formed leaves having a maximum amount of 125.05 mg $100g^{-1}$ in average at day 4. At day 10, the TFC values significantly dropped in all genotypes and were between 64.35 mg $100g^{-1}$ DW (G2) and 93.

mg/100 g DW(G9), and G5) were the lowest with retention of flavonoid content, whereas in G2 was retained the least. After 20 days, TFC values were comparable to the previous day for almost all treatments (31.95 mg 100g⁻¹ DW in G4 and 93.68 mg 100g⁻¹DW in G9) except for G9 which maintained as much flavonoids as on day16. Treatment G6 showed the highest flavonoid content and G4 showed the lowest level.

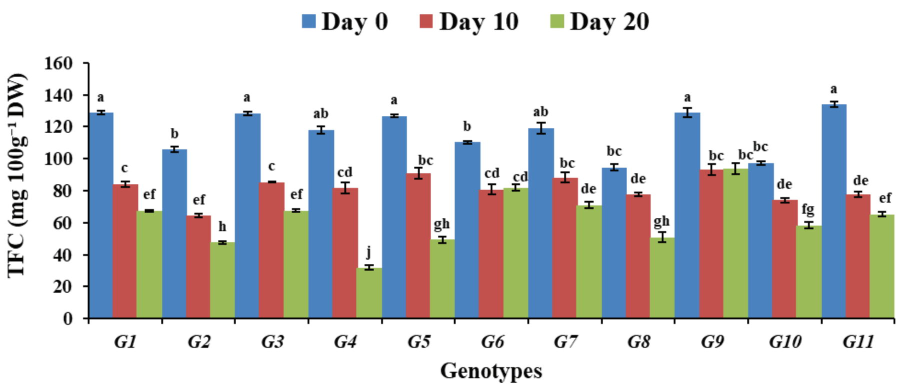

Figure 9. TFC content of Sweet pepper genotypes during storage.

Total Phenolic Content-TPC

Significant differences of TPC were observed among genotypes and storage days (Figure 10). At day 0, TPC values at figure10, were the highest within tested genotypes, and varied between 71.38 mg 100g⁻¹ DW (G4) to 130.98 mg 100g⁻¹ DW (G7), with G7, G8, G5, G11 G3, G10 and G9 having the highest and statistically similar values indicating good initial phenolic content. At day 10, all genotypes showed a significant reduction in TPC values ranging between 55.51 mg 100g ⁻¹ DW (G2) and 86.68 mg 100g ⁻¹ DW (G8), where G8 and G7presented the highest retention of phenolic content at this time, while G2 had the lowest one. At 20 days, TPC values continued to decrease, varying between 80.97 ±36 mg 100g⁻¹ DW (G7) and 23.08 ±14 mg 100g⁻¹ DW (G10), G7 being the variety with higher phenolics content while G10 and G6 were the lowest ones.

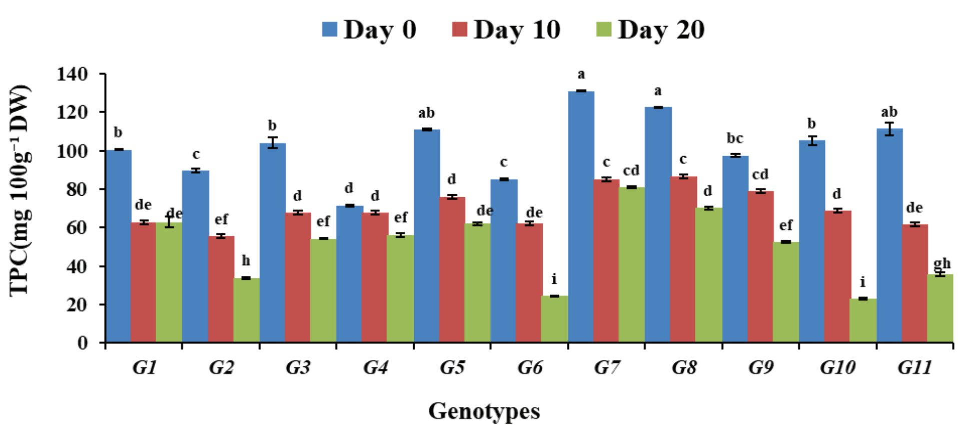

Figure 10. TPC content of sweet pepper genotypes during storage.

2 Diphenyl 1 Picrylhydrazyl -DPPH

DPPH activity was revealed significant variations across different genotypes and storage days (Figure 11). At day 0, DPPH values were the highest among the genotypes studied, ranging from 87.34% to

91.64%, with G11, G6, G4, G10, G5, G2, and G10 showing the highest and statistically similar result, indicating robust initial antioxidant activity.

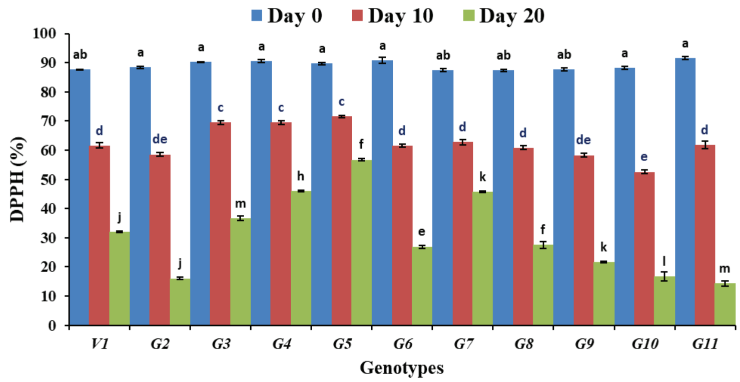

Figure 11. DPPH radical scavenging activity of Sweet pepper genotypes during Storage.

At day 10, DPPH values significantly decreased across all genotypes, ranging from 52.56% (G10) to 71.53% (G5), with G5 and G3 exhibiting the highest retention of antioxidant activity, while G10 showed the lowest. After 20 days, DPPH activity further declined, ranging from 14.31% (G11) to 56.74% (G5), with G5 maintaining the highest antioxidant activity and G11, G2 and G10 showing the

Shelf Life

The longest shelf-life resulted G4 (26.67 ± 0.58 days), followed by G9 (25.33 ± 0.58 days) and G10 (24.67 ± 0.58 days). The shortest life-span was observed in G2 (18.33 ± 0.58 days) and G3 (18.67 ± 0.58 days). G4, G9, and G10 has been the shelf-life while the lowest is for G2 and G3. (Figure 12)

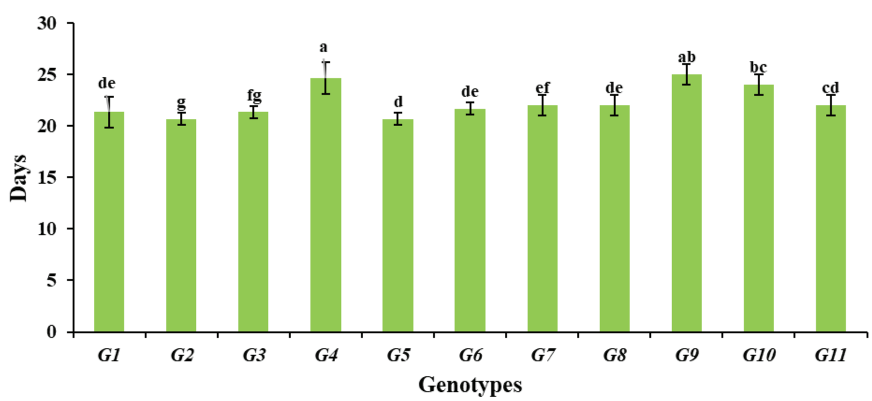

Figure 12. Shelf life of sweet pepper genotypes during storage.

Comparative evaluation of responses among Sweet pepper genotypes on storability

Significant relationships between different postharvest quality variables of sweet pepper genotypes were detected by Pearson's correlation (Figure 13). The antioxidant compounds and activity showed high correlations. In particular, TPC was highly significantly positively associated with DPPH radical scavenging activity ($r = 0.84$, $p < 0.001$). Also, Vit-C was positively associated with TPC ($r = 0.72$, $p < 0.01$) and DPPH ($r = 0.72$, $p < 0.01$). Also, the components of pigment exhibited significant inter-relationships. ChlA and ChlB showed a significant positive correlation with each other ($r = 0.77$, $p < 0.05$). Carotenoid (CT) concentration was highly correlated with ChlB and this relationship was linearly related ($r = 0.78$, $p < 0.05$). On the other hand, Respiration Rate (RC) showed a weak and insignificant negative correlation with most quality attributes such as Vitamin C ($r = -0.17$($p \geq 0.05$).

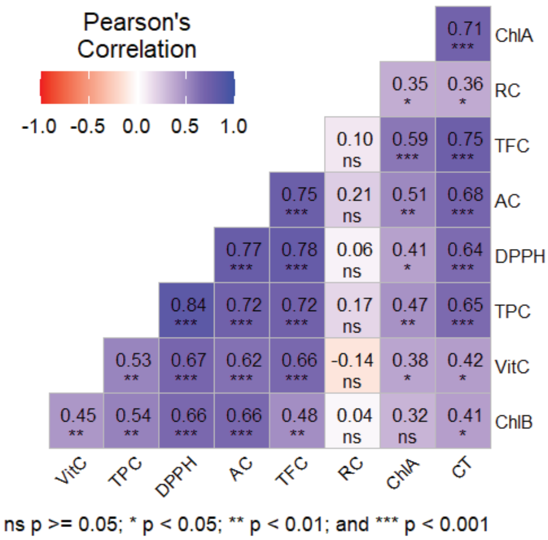

Figure 13. Correlation coefficients of physiological, nutritional and phytochemical traits of sweet pepper genotypes during storage. Here, ChB-Chlorophyll b, Vitc-Vitamin C, TPC- Total Phenolic Content, DPPH-2 Diphenyl 1 Picrylhydrazyl-Anthocyanin content, TFC- Total Flavonoid Content, RC-Respiration content, ChlA- Chlorophyll a, CT-Carotenoid.

Principal component analysis (PCA) based on post-harvest quality trait has defined the groupings of variables (Figure 14). The first two PCs (Dim1 and Dim2) explained 73.71% of the total variance with a 58.83% contribution from Dim1 alone. The variable loadings plot displayed a distinct clustering of variables into two major clusters. One group positively correlated with Dim1 included those major antioxidant and pigment compounds such as VitC, DPPH (scavenging activity of DPPH radical), TPC, and AC. Another cluster comprised of ChlA and ChlB was also positively related to Dim1, but had a stronger positive loading on Dim2. In contrast, the Respiration Rate (RC) was separated in the negative side of Dim1 and showed a negative correlation with antioxidant and pigment related parameters.

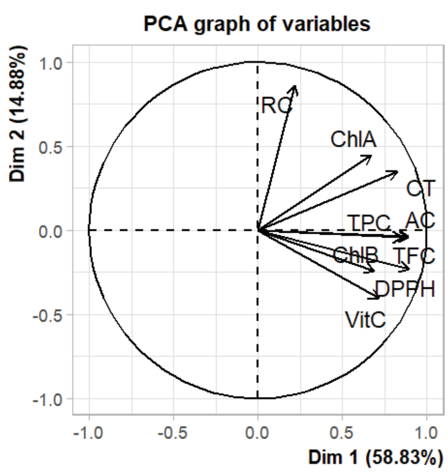

Figure 14. Physical component analysis (PCA) of physiological, nutritional and phytochemical traits of sweet pepper genotypes during storage. Here, ChB-Chlorophyll b, Vitc-Vitamin C, TPC- Total Phenolic Content, DPPH-2 Diphenyl 1 Picrylhydrazyl-Anthocyanin content, TFC- Total Flavonoid Content, RC-Respiration content, ChlA- Chlorophyll a, CT-Carotenoid.

Discussion

Ambient storage experiment with 11 sweet pepper genotypes (G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, G11) showed significant differences among the genotypes for shelf-life respiration rate, chlorophyll a, chlorophyll b, total phenolic content (TPC), total flavonoid contents (TFC), vitamin C (Vit C) and carotenoids content, DPPH radical scavenging activity. These results highlight the importance of interactions between genotypic traits, metabolic activity and environmental factors in influencing postharvest quality retention, especially under resource-limited conditions devoid of cold storage facility.

At the beginning of storage (Day 0), recorded genotypes were different in their biochemical content with G7 had the highest respiration activity (1723 µmol g^{-1} s^{-1}); TPC (130.98 mg $100g^{-1}$); carotenoids (0.849 mg g^{-1} FW), and anthocyanin contents (1.08 mg $100g^{-1}$ FW); G10 led the Chl b content as well as it accumulated this pigment up to Day 9 when its increased to double that of other genotypes; G11 had the greatest total flavonoid content (TFC) until the end of the storage period, whereas vitamin C (VitC) concentration increased after the 12th day, both G5, G3, and G6 has high DPPH radical scavenging percent which ranged between 90.20 % at Day-9–91.64 % DW throughout stored at ambient conditions so they could be considered or selected within cucumber germplasm soaking analogues. These values represent the levels of strong pigments and antioxidants as in preharvest, which are important for nutritional quality (Howard *et al.,* 2000). However, by Day 20 all the parameters were significantly reduced and this time G5 retained the highest VitC (146.38 mg $100g^{-1}$) and DPPH activity (56.74%) DW, G7 for TPC (80.97 mg $100g^{-1}$DW), carotenoids (0.627 mg g^{-1} FW) and anthocyanin (0.22 mg $100g^{-1}$FW), while G9 and G10 Chl a (0.051 mg g^{-1} FW) and TFC(93.68 mg 100g-DW), respectively, and finally V10 for Chl b(0.040mg g–1 FW). On the other hand, G2 and G1 showed the minimum shelf life (18.33 ± 0.58, and 18.67 ± 0.58 days) and nutrient retention (anthocyanin: 0.09 mg·100 g^{-1} FW; carotenoids: 0.093mg-1g^{1}FW), likely due to a higher rate of respiration, as well as a thinner pericarp-as proposed by Lownds et al. (1994).

Respiration rate was a primary quality loss determinant, in line with Howard et al. (2000) who observed that faster respiration leads to a more rapid degradation of pigments and antioxidants by increasing oxidative stress and carbohydrate exhaustion. Genotypes with low respiration rates, G11 (542.67 µmol g^{-1} s^{-1} at Day 20), presented potential postharvest resistance, however a significant loss in DPPH activity and Chl a content (14.31%DW) and (0.005 mg g^{-1}FW) suggest that reduced respiration alone is not capable of preserving all quality attributes if the initial degradation rate is high. On the other hand, G7 maintained a high initial respiration but still had more nutrients in store which could also have been due to a thicker pericarp that not as much of it could be lost through respiratory metabolism and/or higher activities of antioxidant enzyme for scavenging free radicals leading to reduced oxidative damage (Deepa et al., 2006). Environmental parameters, particularly the impact of temperature peaks (26.23°C on Day 19) and low humidity (57.48% on Day 6), were highly determinant for quality deterioration. Díaz-Pérez et al. *(2007) observed that temperatures above 20 °C and RH below 85% cause respiration and transpiration,* mg $100g^{-1}$ DW softening and nutrient degradation. The temperature peak and the increase in respiration both occurred by Day 30, in genotypes such as G1 (1220.67 µmol g^{-1} s^{-1} on Day 20), which accelerated losses of anthocyanin, carotenoids, and VitC. Low humidity induced most likely a high level of transpiration, which was related to the decreased integrity of the pericarp and hence increased degradation chlorophyll, especially in G2 and G1 that presented overall shortest shelf life. The present results reveal the difficulty of extending shelf life under ambient conditions, notably in tropical countries where such variations are frequent (Kader, 2005).

There was a wide range of differences among genotypes, when shelf life was considered with excellent results for additional G4 (26.67 ± 0.58 days), G9 (25.33 ± 0.58 days), and G10 (24.67 ± 0.58 days) with other variants. These genotypes may have underlying structural adaptations, for example a thicker pericarp or more stable cell walls resulting in reduced loss of water and prevent tissue softening, such as that observed by Lownds *et al.* (1994). On the other hand, the higher and lower rate of vegetables deterioration seen on G2 and G3 respectively indicates genetic predispositions to quicker senescence that may be due to thinner pericarp or reduced antioxidant capacity (Smith et al., 2006). These higher performing G5, G7 and G9 isozymes across characteristics of interest support potential biochemical adaptations to increased antioxidant enzyme levels involved in oxidant stress amelioration during storage (Hodges and Toivonen, 2008). For example, high Vit C and DPPH activity retention of G5 indicates effective scavenging of reactive oxygen species such as ROS to maintain nutritional quality (Yahia et al., 2001).

Reduction in anthocyanin, carotenoids and chlorophylls indicates the metabolic degradation of pigments at room temperature. The breakdown of anthocyanin in G1 and G2 is probably resulting from enzymatic oxidation of the fruit and a shift in pH as Zhang et al. (2012). Carotenoids degradation, very pronounced in G2 (0.093 mg g^{-1} FW at Day 20), can also occur by photo-oxidation and lipoxygenase activity that degrades liposoluble pigments (Rao and Rao, 2007). Degradation of chlorophyll noticed in all the genotypes is due to action of enzymes such as chlorophyllase and peroxidase that cleave Chl a and Chl b to form colorless catabolites (Lim et al., 2007). The high levels of retention of Chl a in G9 and G10 imply lower enzymatic activity due to genetic factors controlling senescence.

TPC and TFC losses were high, % of retention was higher in G7 followed by 20. Phenolic compounds which are responsible for antioxidant potential, were prone to oxidation by polyphenol oxidase especially at higher temperatures (Ghasemnezhad et al., 2011). That the retention in G7 was still high may indicate that an initial high TPC provided a better buffer against oxidative losses. Likewise, the high TFC retention of G9 indicates genotypic superiority for flavonoid formation or maintenance and that it should be pursued in breeding programs (Doña et al., 2009). VitC breakdown, being more in G4 (30.66 mg $100g^{-1}$ at Day 20), due to its thermal and oxygen sensitivity; as an evidence, it is known that ascorbic acid gets oxidized into dehydroascorbic acid under atmospheric conditions (Yahia et al., 2001). G5's high Vit C retention rate underscores its potential for preserving nutrient quality in energy poor regions.

The high positive and significant correlation between TPC with DPPH activity indicates that phenolic compounds are the main antioxidant contributors in stored sweet peppers which has been previously reported in Capsicum (Medina-Juárez, 2020). The strong correlations observed between Vitamin C, TPC and DPPH demonstrate a common antioxidant mechanism that in combination assist to reduce postharvest oxidative spoilage as occurs with other horticultural crops (Kaur and Kapoor, 2002). The high correlation between Chl a and b and between Chlb and carotenoids, suggests tightly adjusted pigment metabolism during senescence. On the PCA plot these pigments cluster with antioxidants such as Vitamin C and TPC on to the positive side of Dim1 thereby constituting a unified "Quality Preservation" axis. Genotypes that exist on the positive site of this axis inherently have slower rate of senescence and better phytochemical retention. Importantly, RS was decoupled on the negative end of Dim1, indicating a basic trade-off between metabolism and additionality. The negative correlation indicates that high respiration enhances the catabolism of essential pigments and antioxidants (Saltveit, 2019). Thus, a major consideration for extending shelf-life is the selection of genotypes that have inherently lower respiration rates because it directly delays loss of nutritional quality along with visual (Paull and Chen, 2019).

The findings of this study have important implications for smallholder farmers in developing countries who rely on room temperature storage. G4, G9 and G10 provided practical value inside humid tropical regions which has no refrigeration for the maintenance of quality in an effort to minimize the postharvest losses which stands at about 30–50% (FAO, 2019). Nevertheless, the variation in genotypic performance indicates that breeder´s work must focus on traits related to thicker pericarp, higher wax content and higher antioxidants levels are soon to be profiled such as storability (Bosland and Votava, 2012). Molecular approaches, as those based on markers for the genes involved in cell wall strength or antioxidant biosynthesis, would help to explain how G5 and G7 performed better (Zhang et al., 2012).

Conclusion

This research confirms that sweet pepper storability under ambient conditions is a factor that is determined by the genotypic variation. Genotypes that performed best- G4, G9 and G10- attained the highest shelf life, as they were composed of low rate of respiration, and high retention of antioxidants and pigments. These characteristics are important parameters in the selection of varieties that fit in storage without refrigeration. Future study needs to be on post-harvest methods like edible coatings that can complement these intrinsic physiological benefits to minimize losses in resource constrained supply chains.

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