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Enhancing Tomato Market Quality Standard through Light-emitting Diodes Technology

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ABSTRACT

Light-emitting diode (LED) is an emerging technology with a high application prospect as a preservation technique for fruits and vegetables at the postharvest phase. This study investigates the effect of different LED wavelengths on the quality attributes of tomatoes during market-display conditions. Tomatoes were illuminated with different sets of LED treatments during the 5 days of storage: white, red-blue (5R:1B), and blue-red (5B:1R) LEDs before placing them in a market-displayed condition. Key quality indices, including colour, firmness, pH, brix, and weight, were monitored throughout the display period. Functional regression models of the quality index for the displayed period were established. Compared to the control, the 5B:1R LED treatment reduced tomato redness and overall colour change by 17.9%, suggesting a delayed ripening effect. Acid strength increased with a pH drop of 0.6, 0.5, and 0.1 units for 5B:1R, 5R:1B, and white LEDs relative to the control. Firmness improved by 43.1%, 31.4%, and 18.3% for 5B:1R, white, and 5R:1B treatments. Additionally, weight was retained more effectively, with increases of 30% and 4.9% for 5B:1R and 5R:1B LEDs over the control. A quadratic regression model effectively described changes and trends in the tomato market quality indices investigated. These findings provide a foundation for predictive modelling of tomato shelf-life and quality under LED treatments in market-displayed environments.

Keywords: Tomatoes qualities, market-displayed condition, postharvest management, LED treatment

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INTRODUCTION

The Food and Agriculture Organisation (FAO) has identified tomatoes as one of the first four fruits that can lower the risk of prostate cancer and other cardiovascular

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ailments (Zhao et al., 2023). Their nutritional profile makes them an essential vegetable for a healthy diet. Due to their low calories and high fibre content, they are considered an excellent choice for digestive health and weight management (Clark & Slavin, 2013). Huang et al. (2018) also cited other benefits, including improving the immune system and reducing inflammation and age-related degeneration. These benefits are rarely obtained from tomatoes due to their quick progression to senescence, due to respiration and ethylene-associated activities. Panebianco et al. (2024) identified the factors affecting tomato quality and shelf life, including storage conditions, techniques, and ripening stages. Essential measures must be implemented to reduce losses during storage and on-the-market shelf conditions.

After harvest, tomatoes spend a longer duration of their postharvest life in the market. Extending shelf life and preservation of quality in this environment should be prioritised to ensure consumers receive the needed health benefits from tomatoes. At the same time, retailers also benefit economically by extending the shelf life and retaining the nutritional quality of their products. This calls for a robust preservation method that can uphold the effect of treatment for a longer period while tomatoes thrive in the market environment.

Common preservation techniques for tomato storage, such as cold room storage, modified atmosphere packaging (MAP), pulse light, ultrasonic wave, and coating, have limitations such as chilling injuries, high energy consumption, low efficiency, high-performance requirement, high cost of investment, and problem of adjusting to processing parameters (Salehi, 2022; Venkatachalam et al., 2024). In addition, an 18.96% average worldwide loss in tomatoes was attributed to storage conditions and techniques (Costa et al., 2022). Light-emitting diodes (LEDs) can overcome these limitations as they consume low energy when in operation, have a lifespan of 70,000-100,00 operating hours, are compact and portable, and their wavelength can be adjusted to suit specific plant requirements (Craver et al., 2019; Elliott & Lee, 2020; Gupta & Agarwal, 2017).

Plants harness the blue and red wavelengths of visible light for their growth and development (Chan et al., 2024). These wavelengths are crucial for the synthesis of chlorophyll and carotenoid pigments as shown in Fig. 1. The blue wavelength (400-500 nm) is absorbed by the cryptochrome receptor and can suppress gene expression for chlorophyll degradation while the red wavelength (600-700 nm) is absorbed by phytochrome receptor which accelerate the production of carotenoid pigment by activating the enzymes and transcriptional factors for its production (Liu & van Iersel, 2021). LED quality characteristics, including wavelengths, photoperiod, and intensity, influence plant morphology and functionality by eliciting responses at physiological and biochemical levels, enhancing bioactive compounds and physiological properties, and inducing resistance to ripening and cell wall degradation processes (Khan et al., 2022).

The application of LED technology in the postharvest management of tomatoes has gained increasing attention, yet key aspects of its effectiveness remain under investigation.

Martínez-Zamora et al. (2023) investigated the impact of LED illumination on the quality and bioactive compounds of tomatoes during cold storage and reported a reduction in firmness loss by 30–35% and an enhancement in redness by 27%. These findings suggest that LED treatments may contribute to quality retention under low-temperature storage; however, their applicability to ambient or retail display conditions has not been sufficiently addressed. In a related study, Panjai et al. (2019) examined the influence of LED lighting on tomato ripening and quality development. While the study confirmed positive effects on physiological parameters, it did not provide detailed insight into the specific roles of different spectral combinations or treatment durations. De Bruijn et al. (2023) developed models to study its impact on tomatoes' postharvest life. Interestingly, Nájera et al. (2018) reported that even short, daily exposures to LED light (one hour) could enhance organoleptic qualities by up to 60%, suggesting that intermittent lighting may be a viable strategy. However, the mechanisms underlying these sensory improvements remain poorly understood and warrant further investigation. Offiong et al. (2023) obtained a reduced pH value in tomatoes (2.81) when illuminated with blue/red LED light, comparable with tomatoes with no light treatment (3.05), and an increase in the brix value when exposed to red/blue LED light (4.06) compared to darkness (3.84). Furthermore, de Bruijn et al. (2023) took a more modelling-based approach to understanding LED effects on postharvest dynamics, which provides a useful framework but lacks integration with experimental validation. Finally, Nassarawa et al. (2021) broadly endorsed LEDs as a promising tool for enhancing quality and extending shelf life, though their review primarily summarised existing findings rather than critically assessing inconsistencies or limitations.

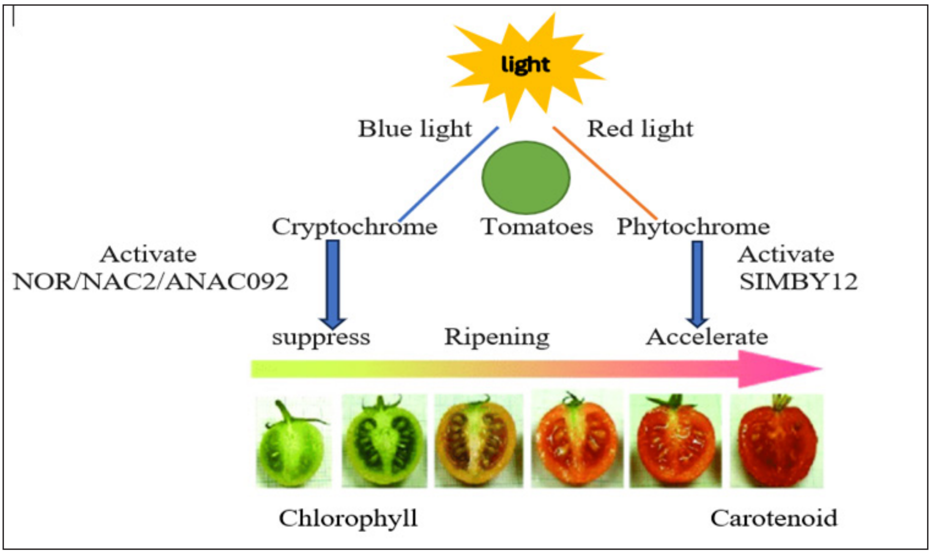

Figure 1. Schematic diagramme showing the effect of light on tomato ripening

During market-displayed environments, tomato quality indices hasten to senescence due to physicochemical reactions. Previous studies have shown that the changes in tomato fruit quality are associated with complex physical and chemical reactions that can be modelled with different empirical approaches, such as linear, power, logarithmic, and polynomial regression models (Kabaş et al., 2024; Qin et al., 2024). The Linear Regression model reveals a direct assessment of the relationship between the LED treatments and the quality index of tomatoes over time. It can reveal the improvement or degradation in quality metrics due to increasing exposure to LED wavelengths. The logarithm regression model assesses changes in quality indices over time and can reveal if the benefits of LED treatment are increasing or diminishing over a prolonged display time. Power regression can capture relationships when LED treatment varies with time in a non-linear pattern. The polynomial regression model allows flexibility, accommodating curvilinear relationships, and can identify optimal LED wavelengths that can maximise quality indices, revealing the nonuniformity of LED treatment effect across all levels of exposure.

Although some previous studies have investigated the treatment of tomatoes with different LED wavelengths, no attention was given to the effects of LED wavelengths on the quality of tomatoes in market environments after LED pre-treatment during storage. Prolonging the shelf life in the market environment and reducing the frequency of waste and spoilage is a major setbacks in the tomato supply chain. Studies on tomato preservation treatment in the market environment are scarce, as most studies focus on storage conditions. To describe the preservation impact of LED treatment on tomatoes and forecast the changes in the quality of tomatoes during display, the key objectives of this study were to (1) evaluate the impact of LED pretreatment on quality indices of tomatoes in market-displayed conditions, (2) established the corresponding regression models to study the quality changes in tomatoes which will provide the conceptual framework for modelling shelf-life predictions.

METHODS

Materials in the Study

Freshly harvested tomatoes acquired from the Lojing Highland farm in Malaysia were used for the study. A pre-selection was done to ensure uniform sizes and proper maturity stages, where tomatoes were grouped into the breaker and turning stages. Only those free from mechanical and physiological damage, with no infection and microbial growth, were used for the study. A total of 480 samples were randomly divided into four groups representing the control and LED treatments, with 120 samples in each group.

Light-emitting Diodes (LED) Treatment System

The LED multilayer treatment system (120 × 35 × 120 cm) primarily consists of four layers, with each layer housing each of the treatments (white, 5R:1B, 5B:1R LEDs, and the control group). The white LED represents a combination of red and blue light in equal proportions, creating a balanced spectrum. The 5R:1B LED provided a red-dominant environment with five parts red to one part blue, while the 5B:1R LED created a blue-dominant environment with five parts blue to one part red. A control group was included as a baseline reference. Together, these treatments allowed for a comparison of balanced, red-enriched, and blue-enriched spectra against standard conditions to evaluate their effects on tomatoes. The LED (T8, SMD 2835, China) of 15W, with wavelengths ranging from 400-750 nm, was 100 cm in length, and 2 lamps with the same wavelengths were installed in each layer. Each layer was subdivided into 6 units, with each unit measuring 20 × 35 cm. Measurement of light intensity was carried out using a light spectrum meter (Spectrum Technologies Inc. 3415F USA) in each of the units to ensure all units had uniform light intensity with no significant differences. These units were used for the display of samples, as no variability was expected to occur in these units due to light intensities. The LEDs were fixed 10 cm apart from each other in each layer.

Sample Treatment

The study comprises two phases: the storage phase and the market display phase. These two phases represent the conventional method of tomato handling after harvest, where tomatoes are stored for some days in cold chambers before being taken to the market for display. To mimic the conventional way of tomato handling after harvest, the storage and the market display phases were replicated in the study.

Storage Condition

At the storage phase, the treatments had a photoperiod of 16 hours of light and 8 hours of darkness. Tomato samples were pretreated for 5 days and later moved to the market-displayed environment, where they were kept for 24 days, and tomato quality indices were measured every 3 days. The temperature and relative humidity of the storage phase were adjusted to 5 °C and 90% to prevent fluctuations of these factors, which might introduce variability. This environmental condition was quoted by Martinez-Zamora (2023) as the condition suited for tomato storage.

Market Display Condition

The market display phase had a temperature and relative humidity of 24°C and 78%, which were average conditions obtained after careful measurement of the environmental conditions of the fruits and vegetables retail outlets in Malaysia using the Elitech Data logger (Gsp-6 USA). A 100-W white bulb illuminated the tomato samples throughout the display period to replicate the market environment. The arrangement of each replicate follows the same setting as under storage conditions.

480 sample of tomatoes were used in the study, which consisted of four replicates in each treatment, and 30 samples in each replicate. Three samples were randomly withdrawn from each replicate every 3 days, resulting in 12 samples for each treatment used for data collection for each measurement day. Five quality indices were chosen for investigation, which are colour, firmness, pH, total soluble solids (TSS), and weight, because these indices influence consumer preferences in the market, and these quality indices were obtained from each tomato samples.

Statistical Methods

Analysis of variance (ANOVA) and Duncan Multiple Range Test (DMRT) were used in analysing data that follows the Gaussian distribution. In contrast, the Kruskal-Wallis and the Bonferroni Post Hoc analyses were used to analyse data that did not conform to the Gaussian distribution theory.

Procedures for Quality Index Determination

Colour Measurement

A colourimeter (3nh NR-145, China) assessed the specimens' colour measurements. The colourimeter was calibrated using the manufacturer's instructions with the colourimeter white tiles. After warming up the colourimeter for 5 minutes, it was placed on the surface of each sample and activated to take the reading with no gap between the instrument and the surface of the specimen. The L (lightness), a* (redness), b* (yellowness), and $\Delta\varepsilon$ (differences in colour changes) values were measured. Figure 2 shows the visual description of the colour parameters (L*, a* and b*). Colour changes ($\Delta\varepsilon$) were calculated using the equation.

$$\Delta\varepsilon = [(L_1 - L_0)^2 + (a_1^* - a_0^*)^2 + (b_1^* - b_0^*)^2]^{1/2} \quad [1]$$

where $\Delta\varepsilon$are the changes in the colour of the tomato samples. The subscripts “0” and “1" are the initial (before treatment and the final (after treatment) measurement of colour.

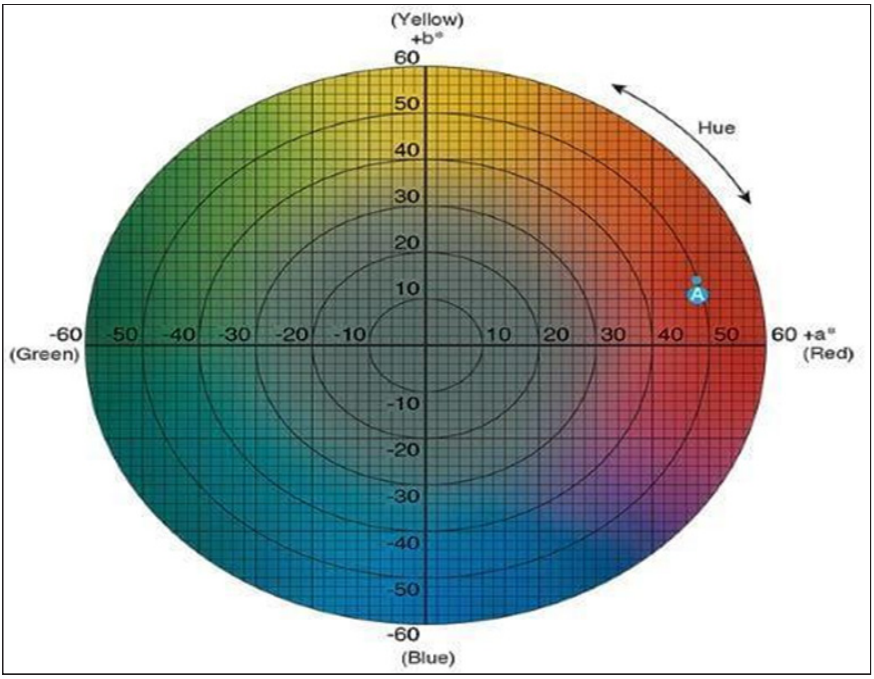

Figure 2. Colour wheel showing changes in colour and brightness for L, a*, and b* colour parameters. The a* value is represented by the horizontal axis measurement where it increases from -60 to +60 showing the degradation of green pigment and accumulation of red colour, while the vertical axis measurement represents the progression of colour from blue to yellow which represents the b* value, while hue established the relationship between the a* and b* values

Firmness Measurement

The puncture test, with a handheld penetrometer (Tianpeng GY-1 12228, China, of 15 kg/m^2 capacity and a cylindrical probe diametre of 3.5 mm), was conducted to measure the firmness of the specimen. The test was carried out at two opposite sides of the equatorial plane randomly selected in each specimen, and the probe was inserted to a depth of 10 mm. The maximum force was recorded as the firmness of each specimen expressed as kg/m^2 (Zhao et al., 2023).

pH Measurement

The pH meter was first calibrated using a 4, 7, and 10 buffer solution to ensure accurate measurements. Each sample was subdivided into three parts and squeezed to obtain the juice; the combined juices were stirred for uniformity. The solution obtained was measured with a digital pH meter (Extech, pH100 China).

Total Soluble Solids Measurement

A digital refractometer (model PAL-BX/A3590, Atago, Tokyo, Japan) was employed to measure the concentration of total soluble solids in the tomato samples. Each sample was sliced into three portions, and each portion was squeezed to release juice greater than 2 drops and placed in the refractometer to obtain the Brix value. The average readings from the three slices were used as the soluble solids of each tomato expressed as a percentage.

Weight Measurement

A tree (HRB-103, USA) high precision scale milligram lab balance of 0.1 mg readability was used to measure the weight of tomatoes. Tomatoes were measured before treatment, after treatment, and every 3 days in a market display condition. Weight loss was calculated using the equation below

$$\text{Weight loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad [2]$$

where $W_1 - W_2$ are the initial and weight loss before and after treatment (g)

Regression Models of Different Quality Indicators during Market Display

Regression models are powerful mathematical tools for establishing relationships between parameters and their predicted outcomes. It captures the fundamental trends and can be used to explain underlying mechanisms in associated data, To identify the best model for fitting the data, four functional regression models were employed in analysing the data such as; the linear regression model: Data were fitted into this model to establish the relationship between the various variables exposed to different LED treatments over time in the Market displayed environment. The model assumes a steady rate of change and is given by the equation:

$$y = \beta_0 + \beta_1 x + \varepsilon \quad [3]$$

Logarithmic regression: A logarithmic model was used to assess the suitability of nonlinear relationships between the dependent and non-dependent variables. The model is expressed as:

$$y = \beta_0 + \beta_1 log(x) + \varepsilon \quad [4]$$

Polynomial regression: Polynomial regression, which involves the use of higher-order terms, was employed to capture potential nonlinear relationships. Different degrees of polynomials were tested to determine the optimal fit. The second-order term was used, which is represented by

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \varepsilon \qquad [5]$$

Power regression Model: Data were fitted into the power model to analyse the relationships between the dependent variable and the independent variable when raised to power. This model is represented by

$$y = \beta_0 x^{\beta_1} + \varepsilon \qquad [6]$$

where

Y = Tomato variables influenced by different LED treatments,

X = Time of display (days),

B_0 = intercept,

β_1 =is the slope, and

ε = error term.

Each of these models was fitted to the data of each treatment for each variable, and the coefficient of determination (R^2) was obtained. The adjusted R^2, which explains the magnitude of variance captured by the model based on the number of predictors, was computed as shown in Equation 7. The model with the highest Adjusted R^2 was chosen for each treatment and subjected to evaluation to determine the treatment that best fits the data and can describe the dynamics of tomato quality in the market-displayed environment. The model's performances were evaluated using two metrics, including the coefficient of determination (R^2), mean absolute error (MAE), which measures the average absolute differences between predicted and actual values, and the root mean squared error (RMSE), which measures the average proportion of errors between observed and predicted values. These metrics are widely used in assessing regression problems (Han et al, 2022). These metrics were calculated according to Equations 8 and 9.

$$Adjusted\ R^2 = 1 - \left(\frac{(1-R^2)(n-1)}{n-k-1}\right) \qquad [7]$$

where

R^2 = Coefficient of Determination

n = Number of observations

k = Number of predictors

$$\text{MAE} = \frac{1}{Z}\sum_{i=1}^{z} (x_i - y_i) \quad [8]$$

$$\text{RMSE} = \sqrt{\frac{1}{Z}\sum_{i=1}^{z} (x_i - y_i)^2} \quad [9]$$

where

Z = Number of observations

x = Predicted values

y = Actual values

The arithmetic mean of the absolute error (MAE) assesses the regression models. An MAE value closer to zero indicates the most accurate regression. The root mean square error (RMSE), which is also employed in regression model evaluation, shows sensitivity to outliers (Kabaş et al., 2024). Both metrics take values from 0 to infinity, with lower values close to 0 indicating higher accuracy of the model. The coefficient of determination (R^2) measures the goodness of fit and explains the variance in the predicted variable relative to the observed variables. It takes values between 0 and 1, and the closer the R^2 is to 1, the higher the accuracy of the model. The model with the highest R^2 values, lowest MAE, and RMSE was chosen as the best fit for the data, which explains the phenomenon of the variables.

RESULTS AND DISCUSSION

Light Intensities of LED Treatments

Table 1 shows the light intensities of the LED treatments used in the study. it could be seen that across the 6 sections of each treatment compartment, sections B, C, D, and E show no significant differences with each other across all treatments. This shows that the light intensities across these sections will ensure even distribution of light to the samples.

Table 1
Average LED intensities from the multi-layer rack where tomatoes were placed for treatment, with the significant differences of each section

Light	**Average intensity in each section (µmol^{-2}s^{-1})**					
	A	**B**	**C**	**D**	**E**	**F**
White LED	102^b	112^a	118^a	119^a	117^a	100^b
5R:1B LED	58^c	87^a	101^a	95^a	85^{ab}	48^c
5B:1R LED	57^b	94^a	107^a	107^a	101^a	58^b

Effect of LED Wavelengths on the Quality Index of Market-displayed Tomatoes

Effect of LED Pretreatment on the Colour of Market-displayed Tomatoes

Colour is a vital factor that influences consumers' preferences and purchasing decisions, as the perception of colour can affect the evaluation of the quality and appeal of tomatoes (Jürkenbeck et al., 2020). Fig. 3 visualises the tomato samples after treatment and how the treatments delayed ripening in tomatoes during the 24 days of market display. Before treatment, all the samples were relatively at the same maturity stage. After treatment, the control samples reached the deep red maturity stage on day 9 of the display, the 5R:1B LED-treated samples extended till day 15 of the display, while the white and the 5B:1R LEDs extended till day 21 and 24, respectively.

An increase in the a-value leads to more red colour accumulation as brightness diminishes; likewise, an increase in the b-value leads to higher accumulation in yellow colour on the tomato's surface. Fig. 4a shows that the brightness (L*) value of tomatoes decreases continuously as the display period increases, indicating that the colour becomes darker with time. 3.5, 8.3, and 7.5 % increases in brightness over the control for 5R:1B, 5B:1R, and white LEDs, respectively, were observed, showing that the different LED treatments delayed the darkening of tomatoes' colour as displayed time increases. A significant difference was observed between the treatments and the control, but none was observed between the three LED treatments. Choi & Park (2023) submit that ripening in tomatoes corresponds with the decrease in brightness of the pigment as the accumulation of various colours darkens the colour of the tomatoes.

The trend for a-value (Fig. 4b) shows significant increases within the first 6 days and a moderate increase in subsequent days of market display. A percentage decrease over the control of 9.8, 19, 9, and 13.8 % in a-value was observed for 5R:1B, 5B:1R, and white LEDs, showing that LED treatments can delay redness on the surface of tomatoes, with 5B:1R LED being the most effective. The trend for b* value (Fig. 4c) shows an increase in the yellowness of tomatoes from days 1-3, a constant rate from days 3-9, a further increase from days 9-15 and a decrease in subsequent days of display. On its peak day of accumulation, percentage increases of 8.4,k 20.3 and 5.8 % were observed over the control for 5R:1B, 5B:1R, and white LEDs, respectively, indicating that LED treatment maintained the yellowness in tomatoes over time, while 5B:1R LED reflected the most effective treatment as market-display time increases. Significant differences were observed between the treatments and the control ($P < 0.05$).

Delta E (ΔE) measures the quantifiable difference between two colours within the colour space, assessing how these colours differ in the human eye. The initial ΔE values (before treatment) show relatively close differences between the tomatoes in each treatment. The ΔE trend (Fig. 4d) increases for all treatments over time, suggesting that the colour differences become more pronounced as display time progresses. The control had the

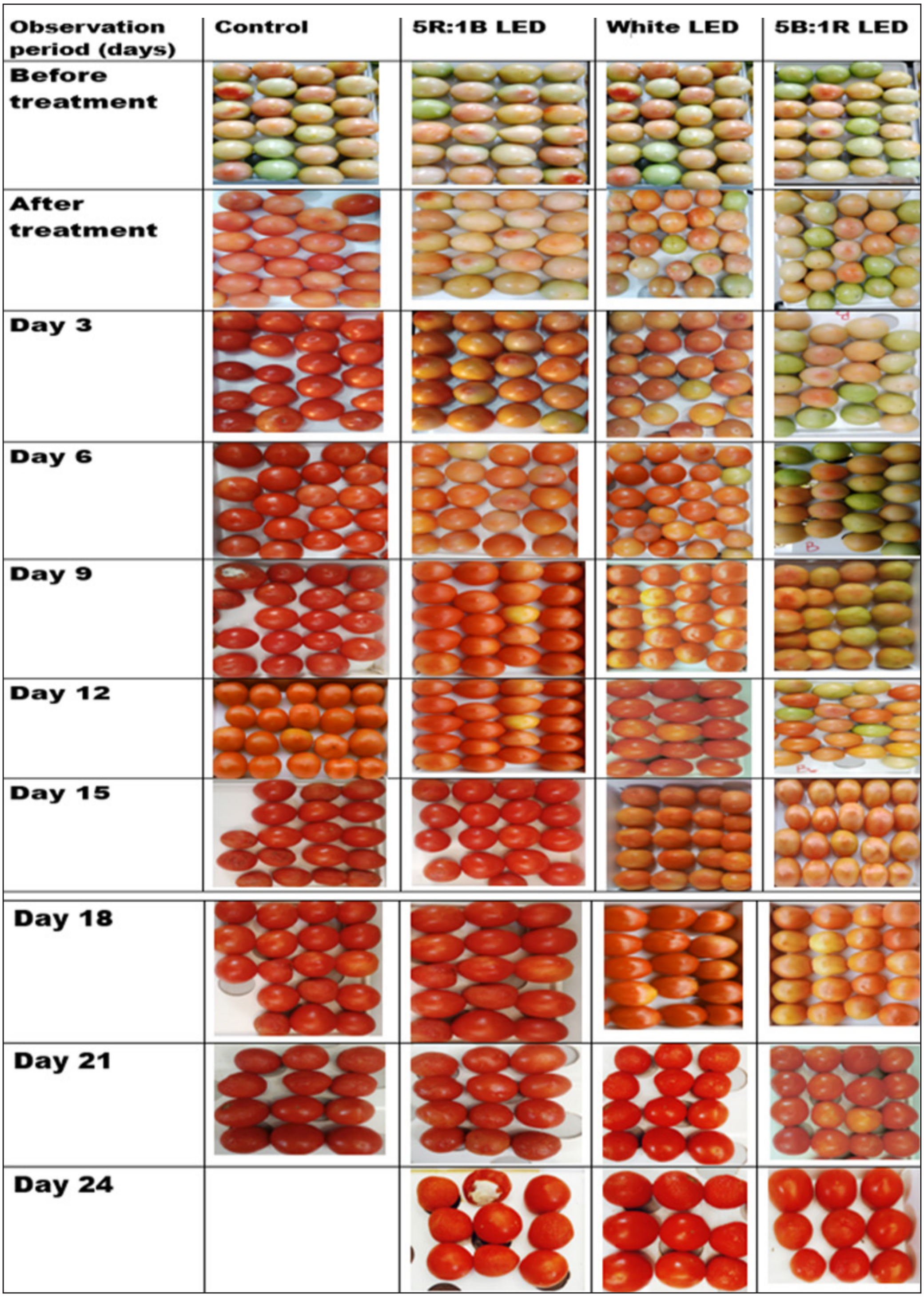

Figure 3. Visual changes in tomatoes pretreated with different LED wavelengths during the 24 days of market display

highest ΔE values with peak values of 67.962 on day 15, indicating that tomatoes without LED treatment may undergo accelerated colour changes due to ripening processes. This was closely followed by the 5R:1B LED treatment with a peak value of 66.892, which also promoted colour changes significantly, while the 5B:1R and white LEDs treatment showed less colour changes with peak values of 63.974 on day 18 and 62.903 on day 21. Significant differences were observed ($p<0.05$).

The colour of tomatoes depends on the concentration of various pigments, including chlorophyll, hydroxylated carotenoids, xanthophylls, carotene, and lycopene, as ripening progresses. (Khoo et al., 2011). Zhao et al. (2023) obtained less colour variation when treating tomatoes with high-voltage electrostatic fields. Nassarawa et al. (2022) reported on delayed ripening when treating grapefruit with red LED light. Blue light activates cryptochrome receptors through the absorption of photons by the flavin adenine dinucleotide (FAD) chromophore, which triggers conformational changes that cause the repression of ethylene biosynthesis and signalling, thereby delaying the onset of ripening (Xu et al., 2018). For this study, white and 5B:1R LEDs delayed changes in tomato colour.

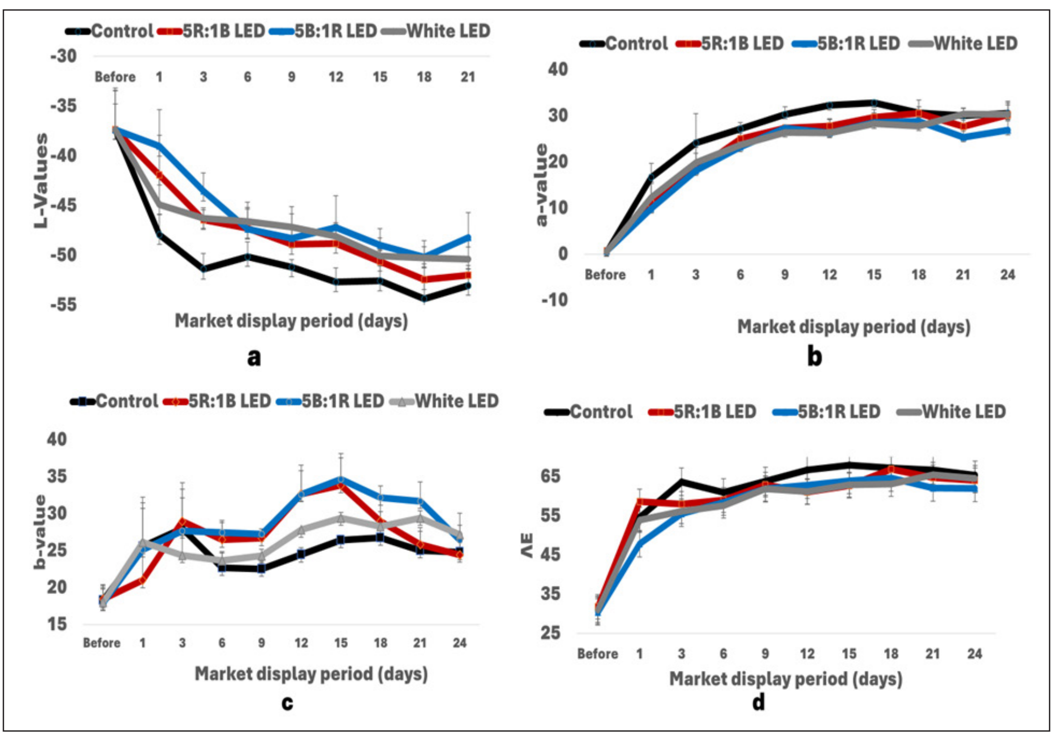

Figure 4. Changes in: a) lightness (L*), b) redness (a*), c) yellowness (b*) and d) colour change (ΔE) in tomatoes pretreated with LED wavelengths (white, 5R:1B, 5B:1R) and the control group at different display periods for 24 days

Effect of LED Pretreatment on the Firmness of Market-displayed Tomatoes

The firmness of the control specimen and different LED-treated specimens at various times was analysed (Figure 5). A downward trend in firmness was observed for all treatments. In the first interval (Days 1 - 3), relatively moderate declines were obtained. The second interval (Days 3 -15) was marked by significant reductions, especially in the Control and 5R:1B treatments, signifying increased deterioration. This shows that this period may be the critical period for firmness and stability when displayed in the market. During this period, the control lost 9.182 kg/m^2, 5R:1B LED lost 8.358 kg/m^2, 5B:1R LED lost 7.881kg/m^{2,} while white LED lost 8.177 kg/m^2. This shows that 5B:1R LED produces the lowest firmness loss during this critical period, signifying the effectiveness of the treatment in resisting firmness loss more than other treatments and the control. In the third interval (Days 15-21), the rate of losses decreased, but observable differences among treatments remained noticeable.

In comparison with the control, 18.3, 43.1, and 31.4 % increases in firmness for 5R:1B, 5B:1R, and white LEDs were obtained. Figure 5 shows that significant differences were observed for the different LED treatments and the control ($P < 0.05$). This indicates that the softening rate in tomatoes during market-displayed conditions was slower with LED-treated samples than with the control samples. This result is in line with the study of Nájera et al. (2018). Blue light-activated cryptochrome receptors stimulate the expression

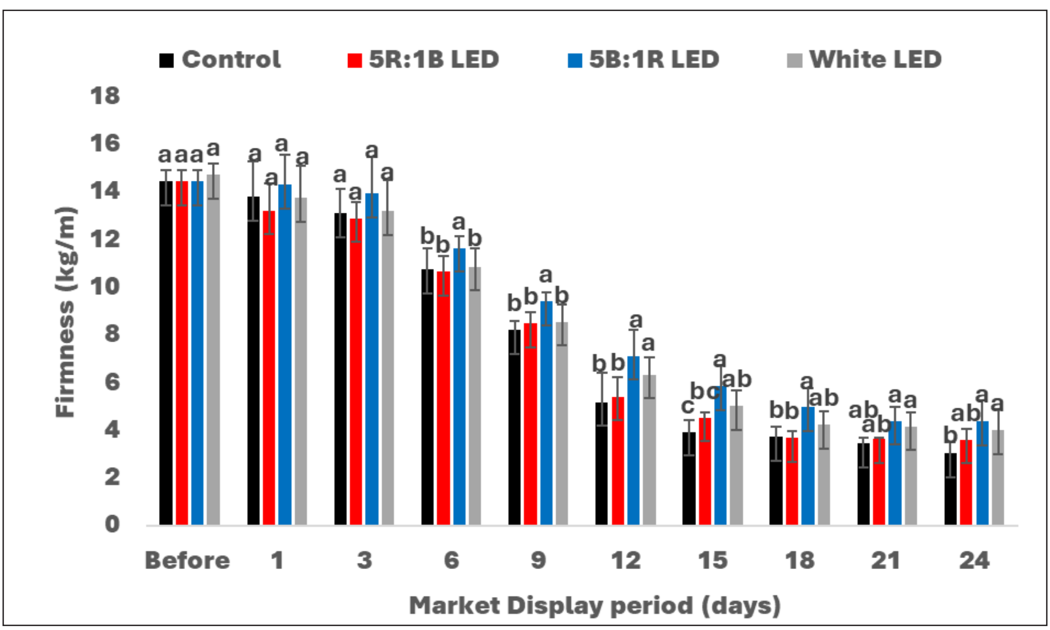

Figure 5. Changes in firmness of tomato pretreated with different LED wavelengths at different display times for 24 days with significant differences in the different display days (p<0.5)

of microRNAs, which in turn silence genes associated with the galacturonate pathway, and inhibit the activities of cell wall degradation enzymes, delaying starch hydrolysis (Wang et al., 2014; Wang et al., 2018).

Effect of LED Pretreatment on the pH of Market-displayed Tomatoes

The change in pH value is a vital indicator of tomato quality; lowering the pH value results in a slow respiration rate and enhanced quality in tomatoes. (Tigist et al., 2013). Figure 6 shows the pH curves of tomatoes pretreated with different LED wavelengths during market-displayed conditions. The trend shows a decrease from days 1-15, and the curves slightly increase from days 15-24 across all treatments. In comparison with the untreated tomatoes (control), 0.6, 0.5, and 0.1 units drop in pH were obtained relative to the control for 5R:1B. 5B:1R, and white LEDs on day 24 of display, signifying an increase in acid strength of LED-treated tomatoes over the control. Significant differences were observed from days 1-6 for the 5B:1R LED with other treatments. Studies have shown that citrate and malate acids are substrates used in respiration processes. They contribute to energy production during ripening (Batista-Silva et al., 2018), and an increase is always observed in the pH of tomatoes after harvest (Tolesa & Workneh, 2017). However, using LED during preservation and marketability, specifically 5B:1R LED, may maintain a low pH value by retaining organic acid in the fruits through suppression of the catabolic rate, preventing

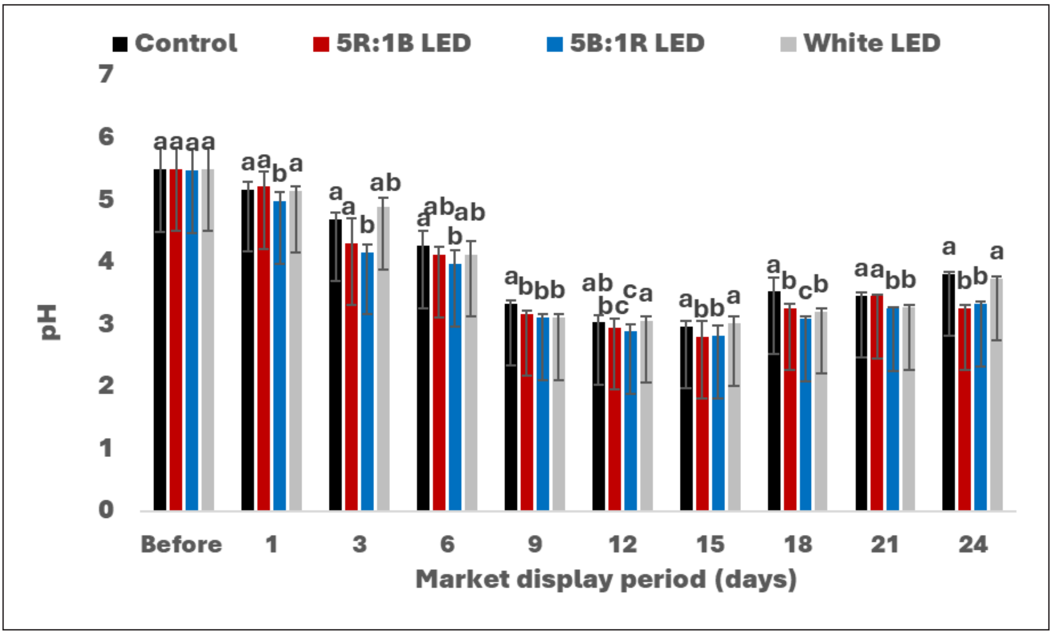

Figure 6. Changes in pH value of tomato pretreated with different LED wavelengths at different display times for 24 days with the significant differences obtained during the display period (p<0.5)

the breakdown of these acids and ensuring they remain in the fruit for an extended period (Wang et al., 2023).

Tomatoes free from microbial growth or defects influenced purchasing decisions in the market environment. Higher acidity prevents microbial growth in tomatoes since neutral or slightly alkaline conditions favour pathogens (Zheng et al., 2023). Therefore, increasing acidity in tomatoes through LED treatments can reduce microbial spoilage, extend shelf life, and reduce the risk of foodborne illnesses. The growing consumer demand for natural food products has intensified interest in natural preservation methods since synthetic methods are linked to health-threatening issues (Teshome et al., 2022). The increasing acidity with the LED treatment method replaces the need for synthetic preservatives, as it aligns with consumer demand, favouring minimal processed and organic products and offering an edge in a health-conscious market.

Effect of LED Pretreatment on Total Soluble Solid (TSS) Concentration of Market-displayed Tomatoes

The variation trend of TSS concentration in tomatoes pretreated with different LED wavelengths, with an increase in the market display time, is displayed in Figure 7. The TSS concentration in the untreated samples (control) reached its peak at 9 days with a value of 4.908% before decreasing gradually. The peak concentration of TSS for 5R:1B and white

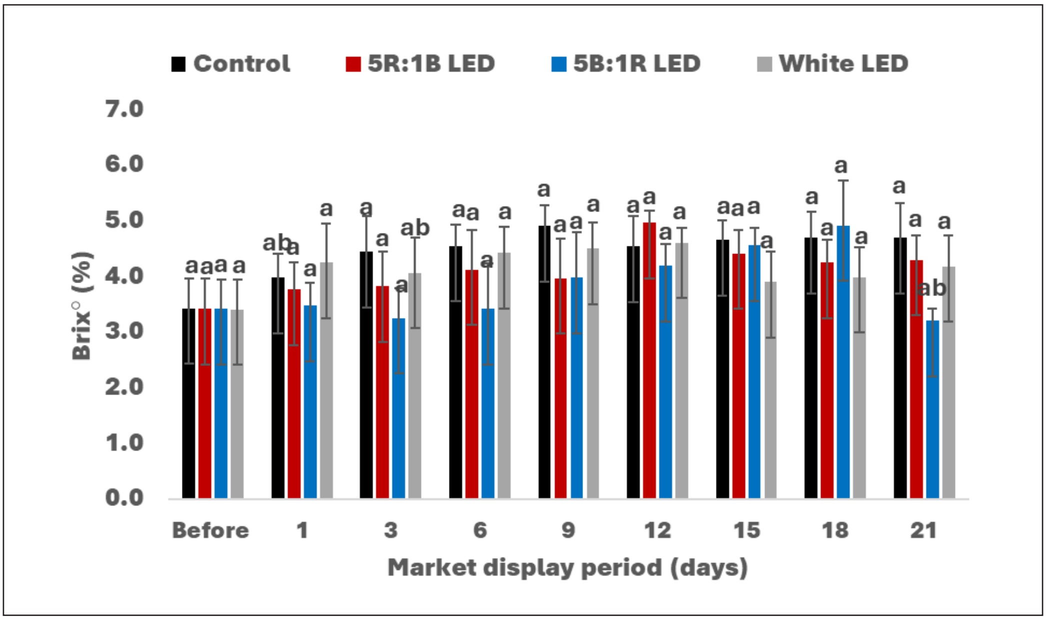

Figure 7. Changes in TSS of tomato pretreated with different LED wavelengths at different display times for 24 days with the significant differences obtained during the display period (p<0.5)

LED treatments occurred on the 12th day with values of 4.966 and 4.611 %, while the 5B:1R LED treatment attained its peak accumulation at 18 days with a value of 4.922%. The result shows that 5R:1B LED accumulated more TSS, though with a short duration (12 days), as compared to 5B:1R LED, with a value of 4.922%, but with a prolonged duration of market display (18 days). 5R:1B and 5B:1R LEDs recorded an increase of 1.2 and 0.2 % over the control, while the white LED lagged by 6.1%. Figure 7 reveals that 5B:1R LED treatment shows significant differences with other treatments from days 1-6, as it maintained a low brix value ($p<0.05$). The result of the study aligns with that of Xiang et al. (2021), with an increase of 4.86, 4.92, 4.98, and 5.08% for the treated groups, while the untreated group had a TSS of 4.76%. This study agrees with Nassarawa et al. (2022b) report on higher concentration of soluble solids in grapefruit when treated with red LED light over the control and blue LED Light.

Relationship between Acidity, Sugar Levels, and the Flavour Profile of Tomatoes

The flavour profile of tomatoes depends on the balance between sourness (acids) and sweetness (sugars). The soluble sugars contribute to sweetness, while organic acids contribute to their acidity, producing sourness (Li et al., 2023). It is a necessity to achieve a balance of these quality markers for enhanced flavour in tomatoes. An 8.7% increase in acid concentration produces a 0.2% increase in sugar level for 5B:1R LED, whereas a 4.2% increase in acidity level yields a 1.2% enhancement in sugar level for 5R:1B LED. The 5R:1B LED treatment produces a balanced flavour profile for LED-treated tomatoes.

Effect of LED Pretreatment on the Weight of Market-displayed Tomatoes

Weight loss in tomatoes is caused by transpiration, where water evaporates from the tomato, resulting in a weight reduction. Figure 8 shows that after treatment, the weight loss of tomato samples across the different treatments was relatively the same. On days 6-12, the control samples recorded more losses. On days 15-18, 5R:1B LED shows slightly higher losses than the control samples. Days 18-21 reveal a high percentage of losses for control, white and 5R:1B LEDs. Throughout the display period, the 5B:1R LED maintained a lower percentage of weight loss. 30% and 4,9% of weight were observed with 5B:1R and 5R:1B LEDs over the control at the end of the display period, indicating that these treatments significantly reduce weight loss in tomatoes during market display conditions. Significant differences were observed with 5B:1R LED over other treatment conditions.

Establishment of Regression Models on Tomato Market Quality Indicators

Functional regression models were used to obtain changes in the quality index of tomatoes in market-displayed conditions after pretreatment with varying LED wavelengths. The

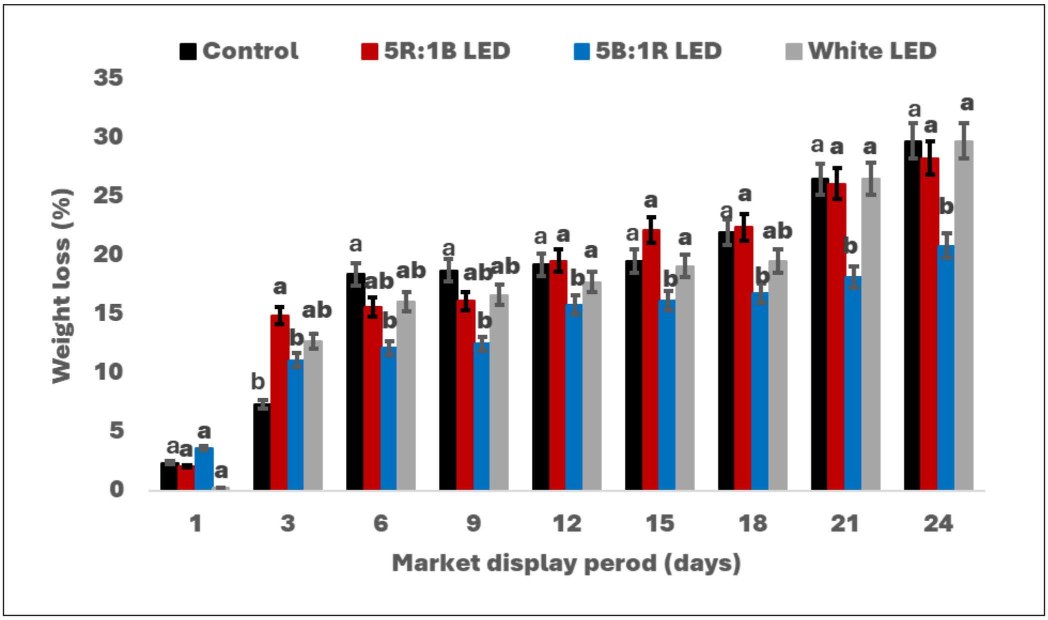

Figure 8. Changes in weight of tomato pretreated with different LED wavelengths at different display times for 24 days, with the significant differences obtained during the display period (p<0.5)

regression models were estimated based on R^2 values from the changes in tomato quality indices as a function of market display time (days) to obtain the variation curves of various quality indicators (Table 1). The model with the best R^2 value was chosen as the best model that fit the trend of each quality index. Evaluation of the models with the highest R^2 value involves metrics such as MAE and RMSE.

Regression Analysis on LED Pretreatment on the Colour of Market-displayed Tomatoes

The quadratic regression model had the highest R^2 values compared to other treatments on a-values (degree of redness), showing that the model explains a greater portion of the variance, which explains light inhibition of red colour accumulation in tomatoes (a-value), and the variances in colour distinction (ΔE). Table 2 reveals that the 5B:1R LED had the lowest MAE and RMSE values for both a* and ΔE, showing that the treatment model has higher reliability and accuracy and can also explain a larger portion of the variances than other treatment models. This aligns with the empirical results, affirming that 5B:1R LED delays ripening and also produces a model to describe the influence of LED on colour dynamics in tomatoes during market-displayed conditions.

Regression Model Analysis on LED Pretreatment on the Firmness of Market-displayed Tomatoes

The quadratic regression model produces the highest $R^{2,}$ indicating that the model best captures the data describing the dynamics of firmness in tomatoes. Adjusted R^2 values of 0.980, 0.975, 0.987, and 0.987 for the control, 5R:1B, 5B:1R and white LED, respectively, indicate that this model explains a greater portion of the variance for each treatment (Table 2). However, further metrics showed that the 5B:1R LED had the lowest MAE and RMSE values compared to other treatments, indicating that the magnitude of error between the predicted and the actual values is small compared to other treatments, and the accuracy is high.

Regression Model Analysis on LED Pretreatment on the pH of Market-displayed Tomatoes

pH, a measure of the acidity and alkalinity in tomatoes which serves as an important quality check shows that the pH data fitted into the quadratic regression model, as the model produces higher R^2 values compared to other regression models. Table 2 shows

Table 2
Model selection using the coefficient of determination

Treatment	Regression Models	R^2		R^2	R^2	R^2
		Colour		Firmness	pH	Weight loss
		a*	ΛE			
Control	Linear	0.518	0.426	0.900	0.423	0.861
	Log	0.856	-	0.902	0.704	0.877
	Power	0.817	-	0.743	0.723	0.862
	Quadratic	0.917	0.681	0.981	0.938	0.894
5R:1B LED	Linear	0.674	0.426	0.92	0.465	0.569
	Log	0.937	-	0.887	0.738	0.895
	Power	0.872	-	0.914	0.753	0.869
	Quadratic	0.960	0.592	0.976	0.906	0.901
5B:1R LED	Linear	0.775	0.515	0.935	0.501	0.877
	Log	0.919	-	0.899	0.802	0.900
	Power	0.913	-	0.764	0.826	0.912
	Quadratic	0.944	0.820	0.988	0.944	0.915
White LED	Linear	0.552	0.533	0.913	0.745	0.846
	Log	0.874	-	0.909	0.811	0.847
	Power	0.786	-	0.776	0.887	0.787
	Quadratic	0.910	0.699	0.988	0.958	0.858

that white LED had lower MAE and RMSE values, which indicate higher reliability and accuracy than other treatment models. Although the empirical data identify 5B:1R LED as the treatment that enhances firmness with a 43.1% increase in firmness over the control, the model shows that the treatment is more likely to produce a less accurate model with higher MAE and RMSE values.

Alternatively, the white LED had higher reliability and accuracy with higher predictive power than the 5B:1R LED and also performed well empirically with a 31.4% increase in firmness over the control. These differences between the empirical data and model output raise concerns about the relationship between empirical data and the model's predictive ability. Whereas 5B:1R LED can offer an immediate effect on pH, the modelling result suggests that white LED treatment may provide a more detailed framework for understanding pH dynamics across varying days of tomatoes in the market environment. This variation lies in the model's ability to capture the variability in the data more than the empirical observation shown in the average output. This highlights the essence of empirical measurements and modelling approaches in understanding the impact of LED treatments.

Regression Model Analysis on LED Pretreatment on the Weight of Market-displayed Tomatoes

The quadratic regression model produces the highest R^2 values, indicating that the model best captures the data describing the dynamics of weight loss in tomatoes. Table 3 shows that the 5B:1R LED had the lowest MAE and RMSE values compared to other treatments. This 5B:1R LED pretreatment produces less weight loss in tomatoes and can explain the changes in tomato weight across the market display period.

None of these models could describe the changes in the b-component of the colour variable and total soluble solids, as these variables were not included in the modelling.

With this study, the overall quality and flavour profile of tomatoes can be improved, making them more desirable to consumers. Retailers can manage inventory better, reducing the frequency of markdowns on unsold produce and improving overall profitability. This efficiency can also lead to better pricing strategies and reduced logistical costs. Conducting consumer preference studies will provide valuable insights into how LED treatments influence purchasing decisions and understanding consumer perceptions can inform targeted marketing strategies and product positioning in the marketplace.

Comparative Evaluation of the LED Treatment Method with other Tomato Preservation Methods

Comparing the effect of LEDs with other tomato preservation techniques, Paulsen et al. (2019) reported an 18 % reduction in red colouration and a 37 % increase in firmness on tomatoes preserved with modified atmosphere packaging (MAP). The coating technique

Table 3
Fitting model and parameters of quality indices of LED-treated tomato fruit during market display condition

Quality Indicators	Treatment	MAE	RMSE	Adjusted R^2	Fitting Equation
Colour (a*)	Control	1.893	1.376	0.917	$y = -0.062x^2 + 1.991x + 16.901$
	5R:1B	5.964	2.442	0.960	$y = -0.089x^2 + 2.707x + 9.980$
	White	3.030	1.741	0.910	$y = -0.073x^2 + 2.349x + 10.169$
	5B:1R	0.590	0.768	0.979	$y = -0.042x^2 + 1.663x + 13.421$
ΔE	Control	36.032	6.003	0.680	$y = -0.102x^2 + 3.212x + 45.505$
	5R:1B	36.627	6.052	0.591	$y = -0.073x^2 + 2.456x + 45.661$
	White	27.799	5.272	0.698	$y = -0.074x^2 + 2.583x + 43.266$
	5B:1R	18.856	4.342	0.819	$y = -0.105x^2 + 3.324x + 40.08$
Firmness	Control	0.328	0.573	0.980	$y = 0.024x^2 - 1.078x + 15.696$
	5R:1B	0.351	0.593	0.975	$y = 0.021x^2 - 1.001x + 15.141$
	White	0.180	0.425	0.987	$y = 0.021x^2 - 0.984x + 15.460$
	5B:1R	0.171	0.413	0.987	$y = -0.018x^2 - 0.924x + 16.0$
pH	Control	0.051	0.226	0.937	$y = 0.011x^2 - 0.320x + 5.541$
	5R:1B	0.051	0.226	0.905	$y = 0.001x^2 - 0.303x + 5.352$
	White	0.030	0.174	0.956	$y = 0.011x^2 - 0.343x + 5.623$
	5B:1R	1.751	1.323	0.943	$y = 0.009x^2 - 0.291x + 5.147$
Weight Loss	Control	87.893	9.375	0.897	$y = 0.211x^2 - 5.344x + 0.791$
	5R:1B	72.869	8.536	0.901	$y = -0.228x^2 + 4.916x + 1.203$
	White	83.830	9.156	0.858	$y = -0.144x^2 + 4.225x + 0.880$
	5B:1R	30.628	5.534	0.915	$y = -0.158x^2 + 3.297x + 2.634$

**Note.* The table shows the model evaluation metrics (MAE, RMSE, and R^2), and their equations

shows a 20 % decrease in red colouration, a 31.6 % increase in firmness, and an increase in pH from 4.4 with the control to 4.6 with chitosan coating (Venkatachalam et al., 2024). The result obtained from 5B:1R LED of 19.9 % red colour reduction, an increase in acid strength, a 43.1 % increase in firmness over the control, and a 30% weight loss reduction qualifies the LED treatment as a more reliable technique for the preservation of tomatoes to lengthen their shelf life and improve the quality**.** Additionally, it is cost-effective, compact, produces high efficiency, and its parameters can be regulated to suit the properties of any crop under investigation.

CONCLUSION

This study investigated the effects of LED pretreatment during storage on the postharvest quality of tomatoes during market display over 24 days, assessing key parameters including colour, firmness, total soluble solids (TSS), pH, and weight loss. The results demonstrate that 5B:1R LED pretreatment effectively delayed the progression of lightness and red colour development, moderated overall colour changes, preserved firmness, increased acid strength, and significantly reduced weight loss. In contrast, the 5R:1B LED configuration notably enhanced TSS content. The beneficial effects of the pretreatments were maintained for up to 15 days under market conditions before significant changes in ripening, firmness, and pH increase were observed. Regression analysis revealed that the dynamics of the quality indices followed nonlinear trends: quadratic models best described changes in the quality parameters. Overall, these findings highlight the potential of LED light pretreatments, particularly specific red-blue light ratios, as an effective postharvest strategy for maintaining tomato quality and extending shelf life in market environments. This research offers a foundation for the development of predictive models to monitor and optimise the quality of LED-treated tomatoes during retail display.

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