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EFFECT OF LIGHT-EMITTING DIODE WAVELENGTHS ON THE QUALITY-INDEX OF MARKET-DISPLAYED TOMATOES

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Abstract. This study investigated the effects of light-emitting diode (LED) wavelengths as a postharvest pre-treatment to improve the physiological quality index and delay the deterioration of market-displayed tomatoes (Solanum lycopersicum). Tomatoes are highly perishable climacteric fruits characterized by rapid developmental and ripening processes, which cause significant economic losses within the postharvest supply chain, particularly at wholesaler and retailer outlets. To address this problem, fresh tomato samples were subjected to a 5-day pre-treatment phase inside a cooling chamber at a temperature of 5 degrees Celsius and 90% relative humidity under a 16/8-hour light/dark photoperiod. The administered treatments included white LED, 5Blue:1Red (5B:1R) LED, 5Red:1Blue (5R:1B) LED, and a control group kept in complete darkness. Following this phase, the tomatoes were transferred to simulated retail market environment conditions (24 degrees Celsius and 78% relative humidity) for a 24-day shelf display period, with data collection occurring every three days. The experimental results demonstrated that the 5B:1R LED pre-treatment was the most effective waveband for preserving the intrinsic qualities of the fruit. Compared to the control group, the 5B:1R LED successfully delayed fruit ripening and red color accumulation, showing a 19.9% decrease in the a-value and a 7.71% decrease in the L-value, while simultaneously boosting the accumulation of yellow-orange carotenoid pigments by increasing the b-value by 20.3%. Furthermore, this treatment maintained the highest physical integrity of the fruit, resulting in a 43.1% increase in flesh firmness over the control group. The 5B:1R LED also recorded the highest acidity level with an 8.7% increase over the control samples, which implies a stronger resistance against microbial and pathogenic attacks. Regarding sugar concentration, the 5R:1B LED performed best during short-term display, accelerating total soluble solids accumulation by 1.2% over the control within 12 days. However, for an extended display period of up to 18 days, the 5B:1R LED provided a more sustained increase in sugar concentrations due to its capacity to delay senescence. In conclusion, the application of a 5B:1R LED pre-treatment offers a highly effective and sustainable technique to enhance the postharvest shelf life of tomatoes, providing valuable practical benefits for producers and retailers to minimize commercial losses and boost economic growth.

Keywords: Tomato qualities index, light emitting diodes, postharvest management, shelf life, preservation technique.

Introduction. Formulation of the problem

Tomato's climacteric characteristics and short-shelf life have reduced its availability, contributing to economic loss. There is an urgent need for a preservation technique that can enhance the quality index of tomatoes and delay their deterioration until they are consumed.

Analysis of recent research and publications

Tomato (*Solanum lycopersicum*), a climacteric fruit, hastens to senescence due to its rapid developmental and ripening processes caused by a respiratory burst and spike in ethylene production, resulting in excessive losses. [1]. The production of ethylene increases during the postharvest stage, leading to the loss of firmness and colour changes in the fruit as they become highly perishable during the ripening process [2]. Respiration, an important indicator of the metabolic activity and freshness of tomatoes, also increases as tomatoes ripen, hastening their deterioration [3]. [4] highlighted the causes of postharvest losses in tomatoes to include an unfriendly environment during storage and marketability, poor postharvest handling methods, and infestations of microorganisms, pests, and insects, stressing that these factors pose challenges to the maintenance of the quality of tomatoes after harvest. [5] Characterize tomatoes at the postharvest supply chain, indicating that at wholesalers and retailers' outlets, a high percentage of losses are incurred, which point to economic loss and loss of health-promoting compounds. The highest percentage of these losses (27.3%) was due to a lack of good preservation methods to sustain the tomatoes throughout the marketable period This calls for the need to investigate the impact of postharvest treatment on tomatoes when they are displayed in the market.

Light is a source of energy essentially needed by plants because it helps in directing plant Phyto-morphology and Phyto-physiology. Some essential proteins in tomatoes, known as the photoreceptors, interact with light characteristics such as intensities, wavelengths, qualities, durations, and light direction, regulating their growth, development, and physiological processes [6]. The phytochrome photoreceptors, which absorb mainly red and/or far-red light operating in the regions of 620–750 nm wavelength, and the cryptochromes and phytotropins which respond to the blue spectrum of light (425–485 nm), aid in regulating essential physiological functions in plants [7]. Studies into the utilization of light-emitting diodes (LED) as a preservation method have shown potential for enhancing the physiological qualities of tomatoes. [8] reported on the effectiveness of LED light in reducing firmness loss by 30-35% and improving pigment redness by 27% when tomatoes are stored at 5 ºC. [9] admitted that one-hour exposure per day of tomatoes to LED enhances their organoleptic qualities by 30-60% under storage conditions. [10] 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). These studies emphasized the use of LED lighting for tomato preservation and post-harvest losses in general, but a comprehensive investigation specifically addressing the LED treatment of tomatoes for quality enhancement in a retail market setting is lacking, and this study intends to bridge the gap. Hence, it is hypothesized that the pre-treatment of tomatoes with specific LED wavelengths will enhance their physiological qualities when displayed in a retail market setting. The objective of this research is to investigate the effect of LED pre-treatment on tomato inherent qualities to identify which of the LED wavelengths will uphold these qualities in tomatoes after treatment and the duration of their retention in the retail market.

Materials and methods.

Experimental design

The experiment employed a design with replicates. The design permitted the comparison of the effects of the different LED wavelengths with no light treatment (control) on the tomato's physiological quality parameters. The light treatments were regulated in a 16/8 light/dark photoperiod. Each treatment was fixed to a rectangular multi-layer rack with a dimension of 120 × 35 × 30 cm, displaying the tomato samples (Fig. 1). The rack consists of four layers where each treatment was administered. Each layer was divided into six units (A-F), and the intensity of the light treatments was measured at three data points from each unit (Points 1, 2, and 3) with a light meter (Spectrum Technologies Inc., 3415F USA) to ascertain whether there were significant differences in light intensity distribution across the layer. Each unit comprised 30 tomato samples, of which three were withdrawn from each experimental unit, accumulating to 12 samples from each treatment on each day of data collection. The experiment consisted of two phases: the pre-treatment phase, where the tomatoes were pretreated with the different light treatments for five days, and the shelf display phase, where the tomatoes were displayed at market environmental conditions for 24 days. A temperature range of 5 ºC and 90% relative humidity were obtained inside the cooling chamber, where the treatments were administered using an Elitech data logger (Gsp-6 USA). This corresponds to the storing temperature used by [11].

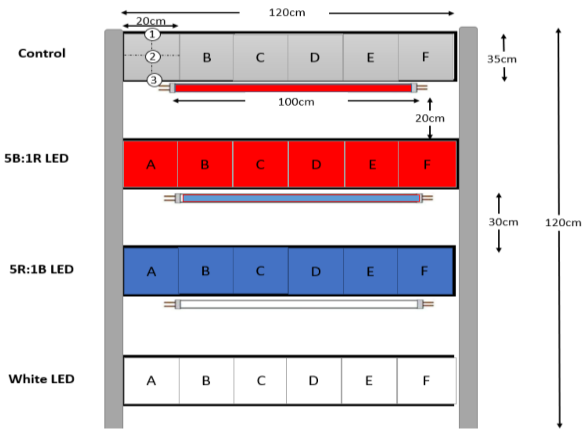

Fig. 1 The multi-layer rack for treatment of tomatoes with light-emitting diodes

The rack shows the different light treatments fixed in each layer. Layers 1–4 show the different treatments used; Layer 1 is the control with no light treatment, Layer 2 is the 5B:1R LED treatment, Layer 3 for 5R:1B LED treatment, and Layer 4 is the white LED treatment. The six units in each layer of the rack are represented by Units A to F. Points 1, 2, and 3 are the various points where the light intensity measurements are carried out at the center of each unit.

After treatment, the tomato samples were transferred to the market-displayed environment of 24 ºC and 78% relative humidity. This condition is an average measurable market environmental condition obtained by measuring various retailers' outlets where tomatoes are displayed for sale within Malaysia. The market-displayed environment was illuminated with two 100W white bulbs to replicate the market environment, and the intensity of the light was ensured to be uniform across the displayed tomatoes. Data collection was done before the treatment and every three days at the market.

Quality Parameters Measurement

Colour. Colour changes were measured with a 3nh NR-145 (China) colorimeter consisting of an 8-mm aperture where light from the colorimeter passed through to the surface of the tomato. The colorimeter was first calibrated with a standard colorimetric white tile to ensure the equipment produced accurate and reliable data. The L*, a*, and, b* components, representing the brightness, progression from green to red, and yellowness of tomatoes, were measured, respectively. The measurement was done at three points on the tomatoes one on the distal and two on the equatorial zones..

Firmness. The flesh firmness of each tomato was determined using a penetrometer (Tianpeng GY-1 12228, China) with a capacity of 15 kg cm and a plunger tip diameter of 3.5 mm. An average of three readings (one at the distal and two at the equatorial area) was taken from each tomato. The initial firmness reading was taken before treatment, and the final reading was taken on each data collection day. [11].

Total soluble solids. Total soluble solids were measured using a Brix meter (Atago PAL-BX/A3590, Tokyo, Japan). The tomato was sliced into three, and an average of three measurements was obtained, one from each of the sections of the sliced tomatoes.

pH value. Calibration of the pH meter (Extech, pH100 China) was done using the pH 4, 7, and 10 buffer solutions [12]. The pH measurement of the samples (Fig. 8) was obtained by squeezing out the juice in the tomatoes, and the pH meter electrode was inserted into the juice to read the values.

Statistical analysis. Data obtained from the study were subjected to statistical analysis using the R-programming software (4.3.3). Data collection from each day was subjected to the Shapiro-Wilk test to ascertain if it followed the Gaussian normal distribution curve. A one-way analysis of variance (ANOVA) was used to ascertain the significant differences of the main effect (LED treatments) on the qualities of tomatoes, and the Duncan multiple range test (DMRT) was employed for post hoc analysis on data that were normally distributed, while data that were not normally distributed, the Kruskal-Walli's rank sum test and the Bonferroni post hoc analysis method were employed to determine the significance differences. Descriptive statistics were also generated to compare the mean and the variability of the data obtained.

Results of the research and their discussion

Effect of LED pretreatment on the colour of tomatoes

L-value. The L-value measures the brightness or lightness of the tomato's colour, where higher values represent a more luminous colour (Fig. 2). The trend shows a marginal increase in the brightness of tomatoes from days 1-18. Figure 3 shows that the control samples maintained a brighter colour more than samples from other treatments from days 1-21 as it shows a significant difference from other treatments, however on days 18 and 21, 5R:1B LED samples showed no significant difference with the control indicating that it luminosity increased to the level of the control samples. On the 24th day of data collection, the brightness of tomato samples was relatively the same and no significant differences were obtained. Tomatoes with LED treatments lag behind the control samples with 3.5%, 8.3%, and 7.5% for 5R:1B, 5B:1R, and white LEDs respectively.

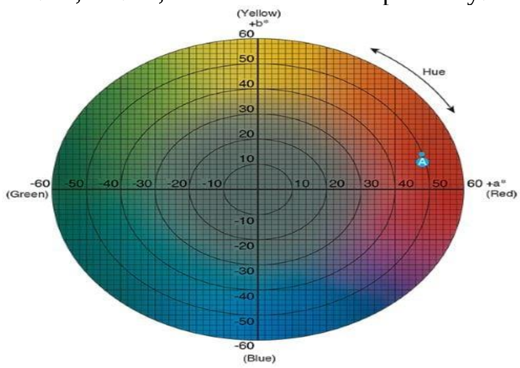

Fig.2 Changes in colour and brightness for L, a*, and b* colour parameters

The a-value shows the changes in tomato colour from green to red (Fig. 2), as an increase in the a-value implies the accumulation of redder colour. A 9.8%, 19.9%, and 13.8% decrease in red colour accumulation was obtained for 5R:1B, 5B:1R, and white LEDs respectively when compared to the control (tomatoes kept in darkness), indicating that these treatments inhibit red colour accumulation in tomatoes, while 5B:1R LED was the most effective treatment. Fig. 4 reveals that the control sample showed significant differences with the other three light treatments from Days 1-15, while no significant differences were obtained in the three light treatments for the first 15 days. Day 18 showed that 5B:1R and white LEDs exhibited a lower a-value as compared to other treatments, and while there was no significant difference between them, they were significantly different from the control and 5R:1B LEDs. However, no significant difference was obtained between the control and the 5R:1B LED. Days 21 and 24 displayed only 5B:1R LED, significantly different from other treatments with lower a-value.

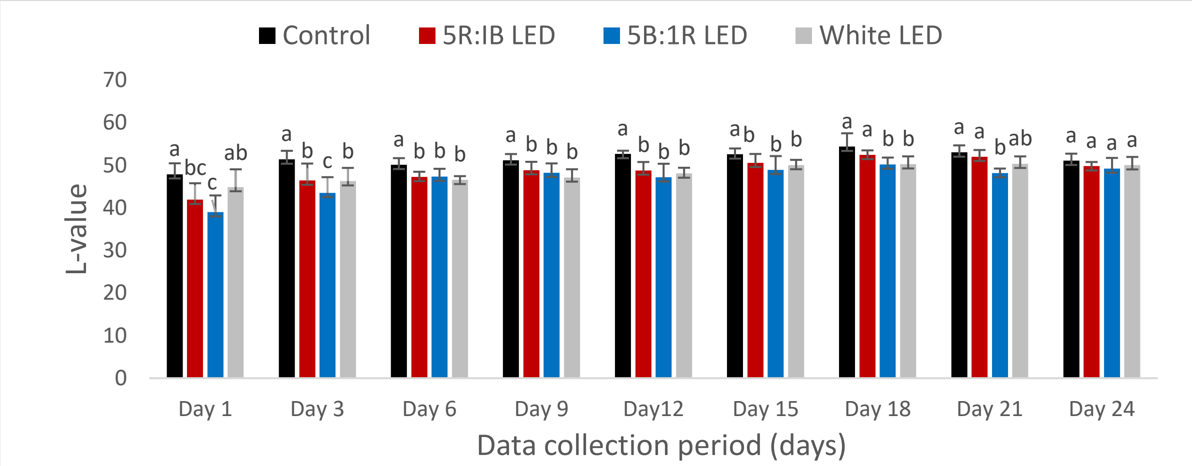

Fig. 3 Effect of different light spectra on the L-value of tomatoes

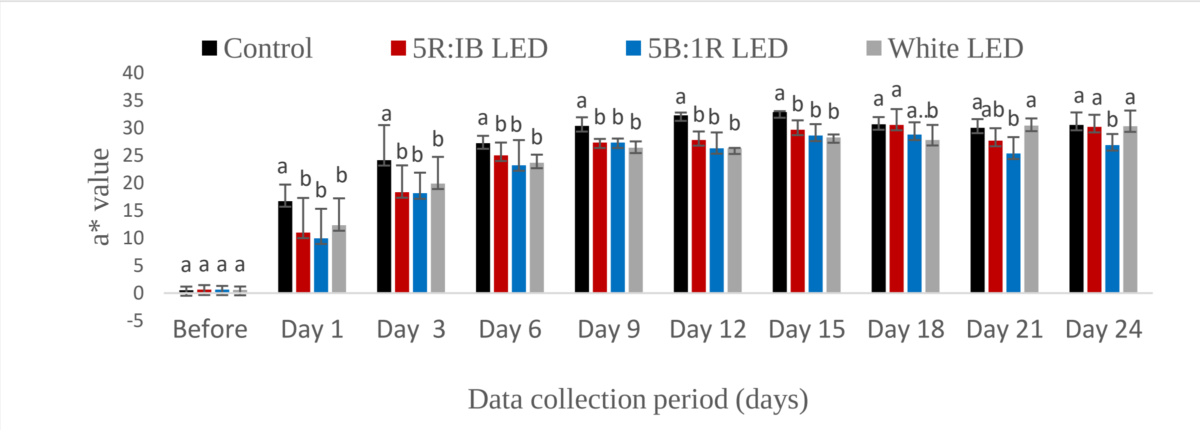

Fig. 4 Effect of different light spectra on the a-value of tomatoes

The b-value indicates the accumulation of yellow-orange pigments in tomatoes, which corresponds to the accumulation of other types of carotenoids except lycopene. An 8.4, 20.3 and 5.8% increase was obtained for 5R:1B, 5B:1R, and white LEDs respectively over the control, indicating that LED treatment increases the yellow-orange colour in tomatoes but 5B:1R LED is the most effective treatment. Figure 5 shows a progressive increase in b-value across all the treatments within the first fifteen days; . On Days 18-24, a reduction in b-value was observed in all the treatments, while white LED measured up to the value of 5B:1R LED on the 21st and 24th days. Analysis conducted showed that no significant differences were obtained between the three light treatments and the control on the 1st and 3rd days. Further analysis revealed that 5B:1R and 5R:1B LEDs showed significant differences with the control and white LEDs from Days 6 to 15. On Day 18, only 5B:1R LED showed a significant difference with other treatments, while Day 21 showed no significant difference between the control and 5R:1B LED,

Effect of LED pretreatment on tomato firmness

The trend for tomato firmness on the market displayed environment after pretreatment showed a slow decrease within the first three days, a sharp decrease from Days 6 to 15, and an infinitesimal decrease from the 18th to the 24th day (Fig 6). Firmness increases of 18.3, 43.1 and 31.4% for 5R:1B, 5B:1R, and white LEDs treated tomatoes were obtained over the non-treated tomatoes (control). This indicates that LED enhances the firmness of tomatoes after pretreatment, in market-displayed conditions, and 5B:1R LED is the most effective LED treatment. Statistical analysis showed that no significant difference was obtained in tomato fruit firmness within the first three days after treatment. However, from Days 6-18, tomatoes under the 5B:1R LED showed a significant difference over the control and other treatments and retained the highest firmness during the period.

pH is an essential measurement parameter in tomatoes because it measures the acidity level which provides essential information needed for quality assessment, such as the tomato's ability to resist microbial and pathogenic attack. An increase of 4.2, 8.7, and 0.64% in acidity level were obtained for tomatoes pretreated with 5R:1B. 5B:1R, and white LEDs respectively over the control samples. This indicates that tomatoes pretreated with these LEDs increase the acidity of tomatoes as tomatoes ripen in the market-displayed environment. Fig. 7 indicates that 5B:1R LED shows significant differences over other treatments from days 1-6. On Day 9, the tomatoes under LED treatments showed no significant differences from each other but were significantly different from the control. However, further reduction in pH value as ripening progresses revealed that tomatoes under 5B:1R LED recorded the lowest pH value in subsequent days of pH measurement which implies higher acidity.

Effect of LED pretreatment on tomatoes' total soluble solids

The result for data collected for total soluble solids (Fig. 8) revealed that the tomatoes under control and white LED maintained a high mean value from Days 1 to 9, however, on Day 12, tomatoes under 5R:1B LED reached their maximum sugar concentration accumulation and increased more than other treatments. The increase in sugar concentration continued for 5B:1R LED until it climaxed on the 18th day of data collection. An increase of 1.2 and 0.2% were obtained over the non-treated tomato samples for 5R:1B and 5B:1R LEDs respectively, while white LED recorded a 6.1% decrease in total soluble solid over the non-treated tomato samples. This implies that only 5R:1B LED had the potential of a slight increase in sugar concentration when compared to the control (non-treated samples).

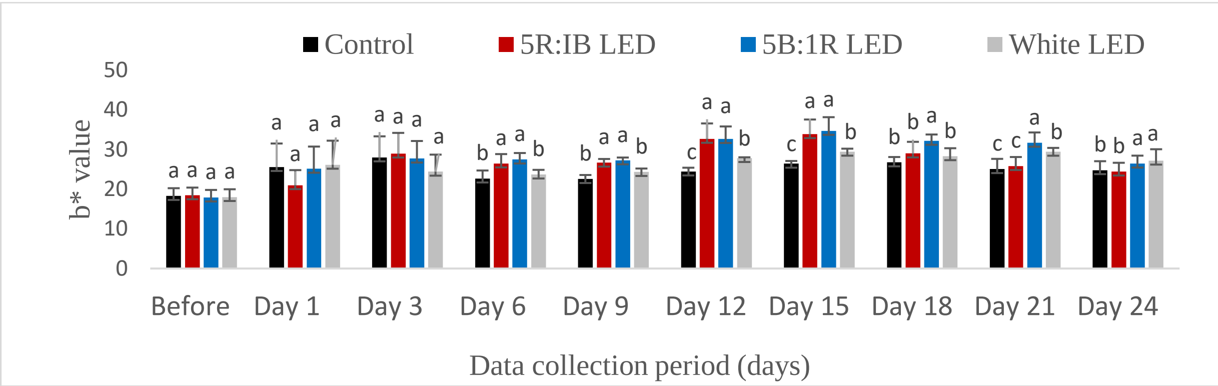

Fig. 5 Effect of different light spectra on the b-value of tomatoes

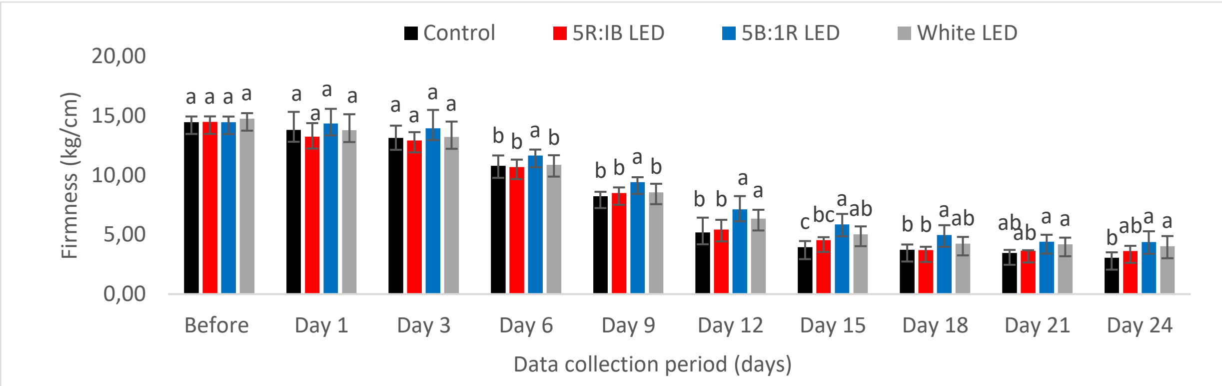

Fig. 6 Effect of different light spectra on the firmness of tomatoes

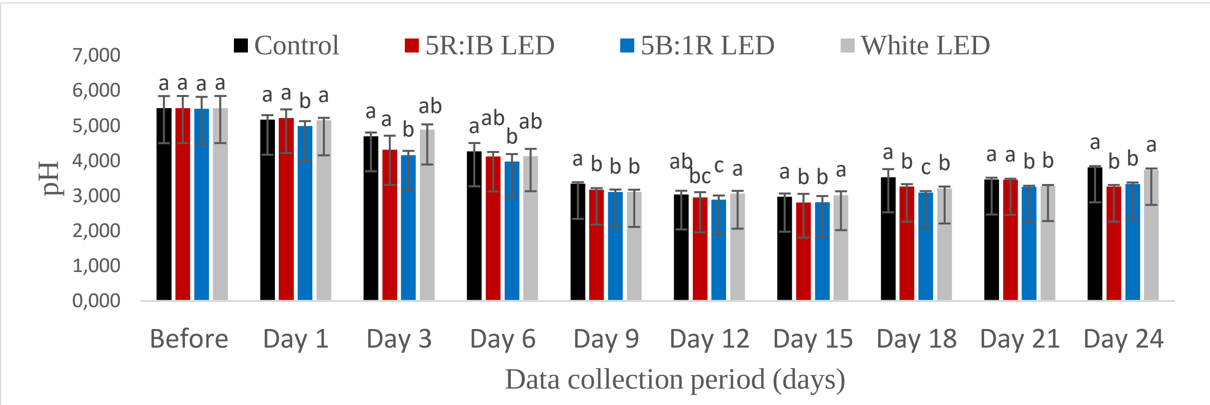

Fig. 7 Effect of different light spectra on the pH in tomatoes

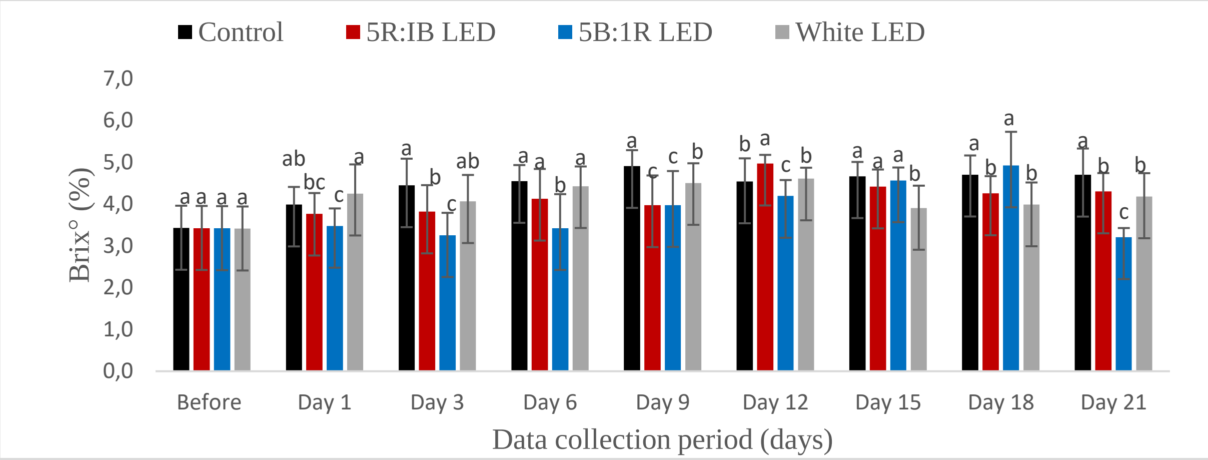

Fig. 8 Effect of different light spectra on the total soluble solids in tomatoes

No significant difference was obtained between tomatoes under the control and white LED within the first six days of the data collection, as white LED shows a decline in soluble solids when compared to the control samples. However, on Day 9, 5B:1R and 5R:1B LEDs were significantly different from the control and white LED. Day 12 revealed that tomatoes under 5R:1B LED were significantly different from other treatments with the highest mean value, but no significant difference was obtained with the control and white LED. On Day 15, only tomatoes under white LED showed a significant difference with other treatments, while on Day 18, the control and 5B:1R LED showed no significant difference between them, but they were significantly different from white and 5R:1B LED.

Effect of LED pretreatment on Tomatoes' colour changes in the retail market

The luminosity of tomatoes as reflected in Figure 2 indicates that an increase in ripening results in more brightness in the colour of tomatoes. Tomatoes treated with LEDs had less brightness compared to the control (tomatoes in a dark environment) with 3.5%, 8.3%, and 7.5% decreases in brightness obtained for 5R:1B, 5B:1R, and white LEDs respectively. This shows that LED treatment delays the ripening of tomatoes, and 5B:1R LED is the most effective LED treatment in brightness control. Since the brightness of colour in tomatoes implies the degradation of chlorophyll (green colour) and the accumulation of carotenoids (yellow-red colour) [13; 14], this implies that LED treatments on tomatoes can delay the degradation of chlorophyll and the accumulation of carotenoids, leading to a decrease in the brightness of tomatoes, hence extending the shelf life of tomatoes and delaying the onset of senescence.

The a-value serves as digital information depicting the increase in the red colour accumulation in tomatoes.[15]. The control produced the highest average output on each day of the data collection. With a decreasing percentage of 9.8, 19.9 and 13.8% for 5R:1B, 5B: IR, and white LEDs respectively over the control, this shows that LEDs can inhibit red colour accumulation in tomatoes, delaying the degradation of chlorophyll which elongates the shelf life of tomatoes and delays the senescence. Tomato samples subjected to 5B:1R LED had the highest percentage decrease in redness of tomatoes (19.9%), this implies that 5B:1R LED is the most effective LED treatment in inhibiting red colour accumulation in tomatoes. [16] admitted that blue light, when absorbed by the cryptochrome receptor, can suppress the expression of genes for ethylene biosynthesis, hence delaying the onset of ripening. The effectiveness of 5B:1R LED in reducing the brightness of tomatoes (L-value) and delaying red colour accumulation (a-value) is an indication that the treatment can delay ripening in tomatoes thereby extending their shelf life.

The b-value is used to quantify the intensity of the yellow-orange colour in tomatoes, which indicates the accumulation of beta-carotene, xanthophyll, and other types of carotenoids except lycopene. [17]. At these phases, tomato colour changes from yellow to pink, pink to orange, and orange to light red. The percentage increase in b-value for LED-treated tomatoes over the non-treated tomatoes are 8.4, 20.3, and 5.8% for 5R:1B, 5B:1R, and white LEDs respectively. Figure 2 shows that the higher the b-value the more the yellow colour increase in tomatoes. This indicates that 5B:1R LED with the highest b-value is the most effective LED treatment for the accumulation of yellow-orange colour in tomatoes.

An inverse correlation (Fig. 9) is established between a-value and b-value with 5B:1R LED treatment being the most effective treatment in both colour parameters in tomatoes. A correlation coefficient of 91.7% shows that a* and b* values are highly correlated and establishes that a decrease in a-value results in an increase in b-value in tomatoes treated with 5B:1R LED. This implies that as the treatment inhibits red colour development in tomatoes, it promotes the development of yellow colour which implies the accumulation of other carotenoids except for lycopene. The inhibition of red colour delays ripening in tomatoes which can hastily lead to senescence.

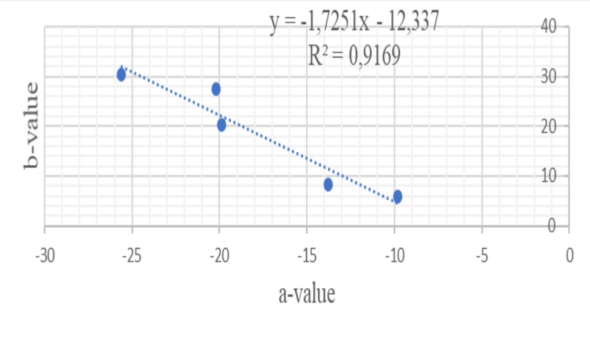

Fig. 9 Correlation of a* and b* values for 5B:1R LED-pretreated tomatoes

Poly-galacturonate (PG), pectin methyl esterase (PME), cellulase, and pectic lyase (PL) have been identified as the principal enzymes catalyzing cell wall disintegration and fruit firmness [18]. The silencing of these enzymes during ripening is the key to enhancing firmness in tomatoes. [19] admitted that light, when absorbed by the cryptochrome receptor, triggers the microribonuclear acid molecules to silence the gene expression for enzymes responsible for cell wall degradation. The cryptochrome receptor absorbed blue light from the visible light spectrum; hence, this affirms why blue/red LED (5B:1R) enhanced the firmness of tomatoes more than other treatments in this study. This shows that pre-treating tomatoes with these treatments can improve the firmness of tomatoes in a market-displayed environment.

Effect of LED pretreatment on the pH of tomatoes

The observed trend in the pH of tomatoes in figure10 which showed a decrease in pH value, can be explained by the ripening process and the changes in organic acids and sugars. During the early stage of ripening (Days 1-6), the exponential decrease is due to the conversion of organic acids, such as citric acid, into sugars, increasing acidity as ripening progresses. [20], which is an indication of delayed ripening and the strengthening of tomatoes against microbial attack. In the mid-stage of ripening (Days 6-15), the decrease in pH becomes marginal. This is due to a balance between the conversion of organic acids into sugars and the production of new organic acids during the ripening process. During this period, the rate of pH change slows down. During the late stage of ripening (Days 15-21), there is a noticeable increase in pH. The gradual loss of organic acids, such as citric acid, which contribute to the acidity of the fruit as the tomato ripens further leads to a rise in the pH value (21). 5B:1R LED treatment had the highest increased acidity level when compared to other treatments, implying that the treatment can offer tomatoes high resistance against microbes and pathogens, leading to improved quality and extension of shelf life.

Effect of Different Light Spectrum on Total Soluble Solids in Tomatoes

The accumulation of total soluble solids in tomatoes is influenced by ripening, and since light-emitting diodes delay ripening, this has affected the performance of each treatment in terms of sugar accumulation. To determine the effect of treatments on total soluble solids, the peak of sugar concentration for each treatment was examined. The control reached its peak accumulation on Day 9 of the data collection, and a mean of 4.907 was obtained. The variability of the data obtained on Day 9 for all treatments was relatively the same. 5R:1B and white LEDs reached their maximum sugar accumulation on day 12, with average outputs of 4.966 and 4.611, respectively, while 5B:1R LED reached their peak accumulation on Day 18, and the mean value obtained was 4.922. This shows that 5R:1B LED had more influence in enhancing the total soluble solid, albeit with a shorter duration on tomato display in market environmental conditions (12 days). This is reflected in a 1.2% increase in total soluble solids over the control. [22] admitted that the phytochrome receptor, which absorbs red light, can activate the downstream signaling pathway, resulting in the upregulation of sink-and-starch biosynthesis enzymes, and the enzymes stimulate the sugar biosynthesis pathway, leading to an increase in sugar concentration. This attests to the outcome of an increase in sugar concentration for 5R:1B LED over other treatments since the phytochrome receptor absorbed red light from the visible light spectrum. Also, red light enhanced ripening in tomatoes, this attests to why a short duration is required for high sugar accumulation for tomatoes exposed to this treatment. However, with the extended time of tomatoes in the market environment, the 5B:1R LED enhanced the sugar concentration with a mean value of 4.922 (18 days). The delaying of ripening by 5B1R LED results in a longer duration of sugar accumulation for this treatment.

Conclusion

This study examined the impact of LED pretreatment on some tomatoes' intrinsic qualities when displayed on the market, assessing the impact of each LED wavelength on quality parameters. The study revealed that LED pre-treatments inhibit the red colour accumulation of tomatoes in the market environment, while for yellow to orange colour, which serves as an expression of diverse types of carotenoids in tomatoes, pre-treating tomatoes with 5B:1R LED significantly enhances the expression of these colour. Firmness, which is the strengthening of the cell wall turgor to delay its degradation, was significantly enhanced by 5B:1R LED and also gives tomatoes a higher acidity level as ripening progresses, thereby extending their shelf life. However, for sugar concentration, 5R:1B LED enhances its accumulation with a shorter period of tomato exposure in the market environment, whereas, for longer days of exposure, 5B:1R LED enhances sugar accumulation. Pre-treating tomatoes with 5B:1R LED favours the enhancement of tomatoes' intrinsic physiological qualities when transferred from the storage medium to the market environment. It is believed that tomato producers and retailers will find this study useful in enhancing the shelf life of the produce to improve economic growth and reduce losses during post-harvest management.

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