Scientific Research Publishing

Open Journal of Applied Sciences, 2026, 16(11), 4394-4434
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Effect of Full-Spectrum White Led Light Intensity on Pigment-Related Optical Responses, Ripening, and Postharvest Quality of Bananas (*Musa* spp.)

Arouna Khalil Fanny[1*], Laura Mihai[2], Banah Florent Degni[1], Yao Hervé Yao[1], Labile Lamah[1], Cissé Théodore Haba[1]

[1]Laboratoire d'Ingénierie Électronique, d'Électrique et de Systèmes Embarqués (LIEESE), Institut polytechnique national Félix Houphouët Boigny (INP-HB), Yamoussoukro, Côte d'Ivoire
[2]Center for Advanced Laser Technologies (CETAL), National Institute for Laser, Plasma and Radiation Physics (INFLPR), Magurele, Romania
Email: *arouna.fanny23@inphb.ci, *fannyarouna3@outlook.com

How to cite this paper: Fanny, A.K., Mihai, L., Degni, B.F., Yao, Y.H., Lamah, L. and Haba, C.T. (2026) Effect of Full-Spectrum White Led Light Intensity on Pigment-Related Optical Responses, Ripening, and Postharvest Quality of Bananas (*Musa* spp.). *Open Journal of Applied Sciences*, **16**, 4394-4434.
https://doi.org/10.4236/ojapps.2026.1611239

Received: September 23, 2026
Accepted: November 8, 2026
Published: November 11, 2026

Copyright © 2026 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/

Open Access

Abstract

Controlling postharvest ripening in bananas remains a major challenge for reducing food losses and improving storage strategies. This study evaluated three illumination levels (low, medium, and high) using a full-spectrum LED source during 14 days of storage. Fifteen banana fruits, with five fruits monitored within each illumination condition, were monitored through an integrated, non-destructive approach combining spectral reflectance, pigment-related spectral indices, digital colorimetry (RGB and CIELAB), mass variation, and correlation analysis. Results showed coherent temporal patterns across spectral, pigment-related, and colorimetric variables, consistent with the progression of ripening and associated changes in the optical properties of the fruit peel. The temporal dynamics of ripening-related optical responses differed among illumination conditions and depended on the parameter and ripening stage. Early spectral reflectance changes were more pronounced under low luminance, whereas some pigment-related spectral indices and yellowing-related color parameters exhibited distinct trajectories under medium and high luminance at intermediate stages. Despite these differences, the convergence of most parameters at later stages indicated that the observed differences among illumination conditions were mainly related to the timing and amplitude of ripening-related changes rather than to the overall final ripening trajectory. Weight loss reached approximately 34% - 37% after 14 days across conditions, with no significant luminance × time interaction. Moderate to

strong correlations among spectral indices, pigment-related variables, and colorimetric parameters highlighted coherent relationships among the measured optical characteristics during ripening. The integration of spectral indices with colorimetric and physiological measurements provides a useful non-destructive framework for monitoring banana maturity and ripening progression. Controlled light exposure may represent a potential approach for modulating ripening-related optical responses, although further studies combining different spectral compositions, replicated experimental units, and direct biochemical measurements are required to validate the underlying physiological mechanisms.

Keywords

Banana Ripening, Postharvest Management, Spectral Reflectance, Spectral Indices, Light Luminance, Non-Destructive Monitoring

1. Introduction

Postharvest ripening of bananas (*Musa* spp.) is a climacteric process and remains a major constraint for effective storage, quality maintenance, and loss reduction in tropical supply chains. This fruit plays a central nutritional and economic role in many tropical regions, yet it is highly perishable due to a sharp rise in respiration and ethylene production after harvest [1] [2]. Postharvest losses of bananas can be substantial along the supply chain, with reported losses during transportation and marketing ranging from 25% to 50%, particularly as a consequence of physiological deterioration, softening, mechanical damage, and inadequate postharvest handling and storage conditions [3].

During ripening, profound biochemical transformations occur, notably the progressive degradation of chlorophylls and the accumulation of carotenoids, which together drive the visible color transition from green to yellow that defines market maturity [4] [5]. Chlorophyll catabolism is a tightly regulated physiological process involving coordinated enzymatic pathways and hormonal signalling [6] [7], whereas carotenoid biosynthesis is controlled by complex metabolic networks that respond to developmental and environmental cues [8] [9]. Because these pigment changes directly affect the optical properties of the fruit peel, they provide a valuable basis for monitoring ripening progression.

Effective ripening management therefore depends not only on controlling environmental conditions but also on accurately tracking these physiological changes. However, conventional assessment methods such as destructive chemical analyses or mechanical testing are labor-intensive, time-consuming, and unsuitable for continuous monitoring. This limitation highlights the need for rapid, nondestructive approaches capable of providing rapid and repeated insights into fruit maturation.

Spectral reflectance techniques provide a non-destructive approach for assessing

biochemical and structural characteristics of plant tissues [10] [11]. Vegetation indices such as TCARI, NDVI, SIPI, and CRI have been widely investigated as spectral indicators associated with chlorophyll- and carotenoid-related variation because they exploit wavelength regions sensitive to pigment-related optical variation [12]-[14]. These optical metrics can be complemented by digital image-derived color parameters, including RGB and CIELAB coordinates, which provide quantitative descriptors of visual changes occurring during fruit ripening [15] [16]. Together, these approaches provide a complementary framework for monitoring and characterizing fruit maturation through non-destructive measurements.

Environmental factors strongly influence these postharvest processes. Temperature and humidity are well-known regulators of ripening kinetics and quality attributes [17] [18]. More recently, light has emerged as an important external signal that can modulate pigment metabolism, antioxidant systems, and gene expression involved in fruit maturation [19] [20]. In particular, light-emitting diodes (LEDs) have gained increasing attention in horticultural research because they provide precise control of spectral composition, intensity, and exposure duration, enabling targeted manipulation of physiological responses [21] [22]. Experimental studies have demonstrated that light treatments can influence carotenoid biosynthesis pathways, enhance the accumulation of nutritional compounds, and regulate ripening-related metabolism in fruits and vegetables [23] [24]. Specifically in bananas, visible light has been shown to affect ripening behavior and metabolic activity, suggesting that irradiance may act as a regulatory factor rather than merely a passive environmental condition [25] [26]. In this context, particular attention should be given to light luminance as a controllable factor. The present study therefore focuses specifically on the differences in ripening-related optical responses observed under different luminance levels while keeping the spectral composition of the light source constant.

Despite these advances, the combined relationships between controlled light luminance, spectral reflectance, pigment-related spectral indices, and visual attributes during banana postharvest ripening remain insufficiently documented. Most previous studies have focused either on biochemical measurements or on individual optical indicators, leaving gaps in our understanding of how different luminance levels may be associated with differences in the temporal evolution of pigment-related spectral responses and tissue optical properties during ripening.

In this context, the present study aims to characterize the postharvest ripening dynamics of dessert bananas under three luminance levels (low, medium, and high) using an integrative approach combining spectral reflectance, pigment-related spectral indices, digital colorimetry, and weight-loss analysis. By examining the relationships among these non-destructive measurements and their temporal evolution during storage, this work seeks to characterize whether different luminance levels are associated with differences in ripening-related optical responses and to assess the usefulness of spectral and colorimetric measurements as rapid, non-destructive indicators of banana maturity and quality.

2. Materials and Methods

2.1. Biological Material and Experimental Setup

A total of fifteen dessert banana fruits (*Musa* spp.) were used in this study, with five fruits monitored within each of three illumination conditions. The fruits were commercially sourced from Brazil and purchased from a retail market in Măgurele, Romania. The commercial packaging indicated Brazil as the country of origin; however, the specific cultivar could not be independently verified from the available product information and was therefore not assigned in this study.

The fruits were selected at the mature-green stage based on comparable external appearance and ripening stage. Fruits exhibiting visible mechanical damage, lesions, or signs of advanced ripening were excluded. Such selection criteria are commonly applied in postharvest studies to reduce variability associated with the initial physiological and physical condition of the fruit [27]. Prior to the experiment, all fruits were rinsed with potable water, air-dried at room temperature, individually identified, photographed, and weighed. Individual initial weights were recorded on Day 0 to document baseline variability among fruits and to provide reference values for subsequent calculations of weight changes and weight loss during storage (Table 1).

Table 1. Initial weight of individual banana fruits assigned to the three luminance treatments at Day 0.

Fruit	Treatment	Initial weight (g)
B01	High	221.701
B02	High	181.865
B03	High	212.434
B04	Low	188.328
B05	Medium	224.295
B06	Medium	254.755
B07	Low	216.544
B08	High	242.001
B09	Low	258.812
B10	Low	238.391
B11	Medium	220.545
B12	Medium	224.503
B13	Medium	191.693
B14	Low	201.679
B15	High	175.290

Baseline optical measurements were also performed on Day 0 (0 d). Reflectance spectra were obtained from radiance measurements acquired at the fruit surface, together with simultaneous measurements of the incident illumination. These initial measurements served as reference values for monitoring temporal changes in the optical, colorimetric, and physiological characteristics of the fruits throughout ripening. Reflectance spectroscopy and other non-destructive optical techniques have been used to monitor banana maturity and ripening without requiring destructive sampling [28] [29].

The experiment was conducted in three transparent plexiglass cubic chambers (Box 1, Box 2, and Box 3), each measuring 100 × 100 × 100 cm (length × width × height). Each chamber was assigned to a single luminance condition, such that each luminance level was implemented in one independent chamber. Illumination was provided by full-spectrum white light-emitting diodes (LEDs; SF2000 Pro, Spider Farmer, China), mounted on the ceiling of each chamber at approximately 60-70 cm above the fruit surface. The spectral emission of the LED light source was experimentally characterized using a VIS-NIR spectrometer (QE65000, Ocean Optics, USA), and the corresponding emission spectrum is presented in **Figure 1**.

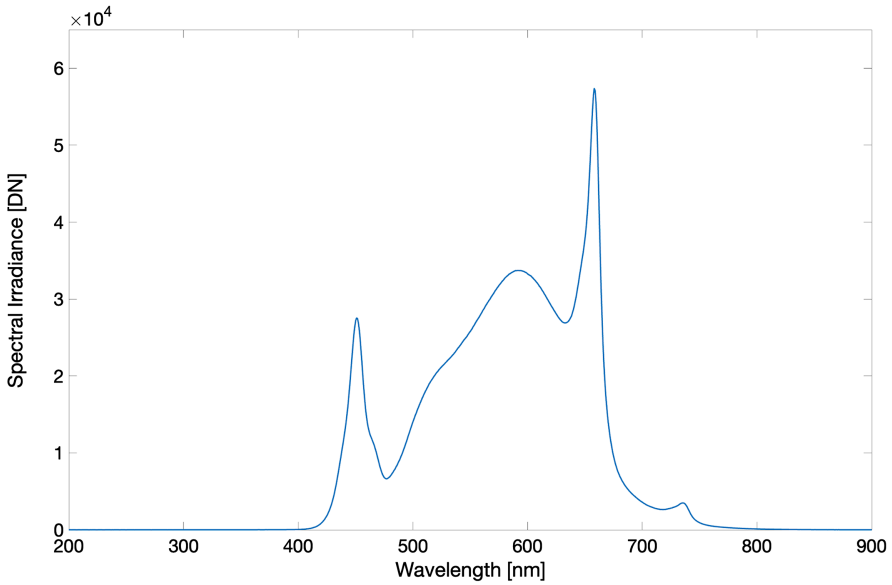


Figure 1. Experimentally measured spectral emission of the LED-based light source, obtained using a QE65000 spectrometer.

Three luminance levels were established by adjusting the dimming settings of the LED lamps and subsequently characterized by direct photometric measurements at fruit height using an L203 Photometer (Irradian Ltd., UK). Five measurements were performed at evenly distributed positions within the fruit sampling area of each chamber, and the mean value was used to characterize the photometric light level under each illumination condition. The measured values were 374.48, 662.26, and 1894.68 cd·m^{-2} for the low-, medium-, and high-luminance conditions, respectively. These photometric measurements were used to charac-

terize the light level at fruit height and were distinct from the radiometric measurements subsequently used for spectral reflectance determination.

Storage temperature was maintained at approximately 22˚C using a controlled climate and ventilation system providing continuous air circulation. Mean temperatures recorded in the three chambers were 22.01˚C ± 0.04˚C in Box 1, 22.03˚C ± 0.05˚C in Box 2, and 22.05˚C ± 0.04˚C in Box 3, respectively. Temperature is an important environmental factor affecting banana ripening and postharvest physiological processes. Storage temperatures around 20˚C have been reported for postharvest handling of bananas, while controlled temperatures between approximately 20˚C and 22˚C have also been used in studies investigating light-induced responses during banana ripening [27] [30]. The same environmental conditions were maintained across the three chambers to minimize temperature-related variation among the light treatments**.** Relative humidity was also monitored in each chamber using an ENS160 sensor coupled with an AHT2x module; however, continuous measurements over the entire 14-day experimental period were not available because of an interruption in the data-acquisition system.

Each illumination condition was applied continuously for 24 h per day over 14 days. The same individual fruits within each chamber were followed longitudinally throughout the storage period. Measurements were performed at regular intervals on Days 0, 4, 6, 8, 10, 12, and 14. At each measurement time, spectral and colorimetric characteristics, pigment-related spectral indices, and physiological parameters were recorded to characterize the temporal evolution of the fruits during ripening. Repeated non-destructive measurements of the same fruit can provide complementary information on ripening dynamics while avoiding the loss of the experimental unit associated with destructive sampling [28] [29].

2.2. Optical Measurements and Data Processing

To obtain reflectance spectra throughout the treatment period, both the irradiance of the light source and the radiance from each banana sample were measured using a spectrometer system comprising a QE65000 spectrometer (Ocean Optics, USA) coupled to a Piccolo Doppio optical fibre system (NERC, UK). This system enables sequential measurements of radiance and irradiance over the spectral range 200 nm - 900 nm, with spectral resolution better than 1 nm. Prior to spectral acquisition, the system underwent spectral and radiometric calibration in accordance with the internal protocols of the Optical Metrology Laboratory (CETAL, INFLPR, Romania). Spectral calibration was performed using four gas-discharge lamps following the protocol described by Mihai *et al.* (2018) [31], and the corrected wavelengths scale was applied to all raw data. The resulting datasets were exported and processed using MATLAB. For each measurement session and sample, 10 individual scans were acquired and averaged. The recorded signals were corrected for dark noise, normalised to the integration time, and converted into physical units using the instrument-specific radiometric calibration coefficients. Radiometric calibration of each fore-optics configuration was performed using

laboratory radiance and irradiance standards, traceable to NIST.

Spectral reflectance was calculated as the ratio of upwelling radiance to downwelling irradiance:

$$R(\lambda) = \pi \frac{L_{SI}(\lambda)}{E_{SI}(\lambda)} \tag{1}$$

where

$$L_{SI}(\lambda) = \frac{\underline{S}_{lg}(\lambda) - \underline{S}_{dk}(\lambda)}{t_{int}} \cdot C_L(\lambda) \tag{2}$$

$$E_{SI}(\lambda) = \frac{\underline{S}_{lg}(\lambda) - \underline{S}_{dk}(\lambda)}{t_{int}} \cdot C_E(\lambda) \tag{3}$$

where $\underline{S}_{lg}(\lambda)$ is mean light signal recorded by the spectrometer at wavelength λ (digital numbers, DN); $\underline{S}_{dk}(\lambda)$ is mean dark signal measured with the detector closed, accounting for electronic offset and sensor noise; t_{int} is integration time (ms); $C_E(\lambda)$ and $C_L(\lambda)$ are the irradiance and radiance calibration coefficient, respectively. $E_{SI}(\lambda)$ represents the calibrated spectral irradiance incident on the fruit surface, and $L_{SI}(\lambda)$ represents the calibrated spectral radiance reflected by the fruit surface. $R(\lambda)$ corresponds to the hemispherical-directional reflectance factor of the fruit surface at wavelength λ.

Image acquisition was performed using a smartphone camera (*Xiaomi Note* 14 *Pro*, *Xiaomi*, *China*). Photographs were captured at the same sampling times as spectral reflectance measurements to ensure direct temporal correspondence between the spectroscopic and colorimetric datasets. All images were acquired under controlled and uniform lighting conditions, while maintaining a constant distance between the camera and the fruit surface and a fixed acquisition angle to ensure measurements reproducibility. Multiple images were recorded for each fruit to obtain representative surface color information.

Image processing was performed in MATLAB. For each image, a central region of interest (ROI) was selected to avoid border effects, reflections, and shadows. Mean pixel intensities of the red (*R*), green (*G*), and blue (*B*) channels were extracted from the ROI. From these primary values, normalized RGB components and colorimetric parameters in the CIELAB space (L^*, a^*, b^*), as well as the total color difference (ΔE), were calculated. The mathematical definitions, physical interpretations, and references for all color indices are summarized in **Table 2**.

2.3. Weight Loss Measurement

To assess the evolution of fruit weight loss throughout the experiment, the mass of each sample was measured at regular intervals. Measurements were performed using an LPWG-723i precision electronic balance (*VWR International*, *Italy*) with a readability of ±0.001 g. Weighing was conducted prior to the start of the experiment and subsequently every two days. Fruits were weighed individually, and the resulting values were used to calculate relative weight loss with respect to the initial mass of each fruit, according to the following equation [35]:

$$W(\%) = \frac{W_0 - W_t}{W_0} \times 100 \quad (4)$$

where:

W_0 is initial fruit mass (g), W_t is fruit mass at time t (g), $W(\%)$ represents weight loss expressed as percentage.

Table 2. Definition of RGB-derived and CIELAB color indices used for color analysis.

Category	Index	Formula/Definition	Physical Meaning	Reference
Normalized RGB	r	$r = R/(R+G+B)$	Relative red intensity	[32]
	g	$g = G/(R+G+B)$	Relative green intensity	[32]
	b	$b = B/(R+G+B)$	Relative blue intensity	[32]
CIELab Parameters	L^*	Lightness component	Luminosity of surface	[33]
	a^*	Green-red axis	Chlorophyll degradation/reddening	[33]
	b^*	Blue-yellow axis	Carotenoid accumulation	[33]
	ΔE	$\sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$	Global color change	[34]

2.4. Calculation of Spectral Reflectance Indices

Spectral reflectance measurements were used to derive several pigment-related indices associated with the dynamics of chlorophyll and carotenoid. Reflectance values at specific wavelengths (R(λ)) were extracted from calibrated spectra and used to calculate a set of established spectral indices sensitive to chlorophyll and carotenoid content. Chlorophyll-related indices included TCARI, Chlorophyll Index (Chl I), NDVI, PSSRa, and PSSRb. Carotenoid-related indices comprised SIPI, CRI1-like, and CRI2-like, while anthocyanin-related indices included ARI1 and ARI2. These indices were selected for their sensitivity to pigment concentration, relative independence from structural noise, and extensive validation in prior optical and physiological studies.

The mathematical expressions, physiological interpretations, and bibliographic references for all reflectance indices used in this study are summarized in Table 3.

2.5. Statistical Analysis

All statistical analyses were performed using R version 4.5.0. Because measurements were repeatedly collected from the same fruits throughout the 14-day storage period, the data were analyzed using linear mixed-effects models (LMMs) to account for the non-independence of repeated observations. For each response variable, luminance level (low, medium, and high), storage time (0, 4, 6, 8, 10, 12, and 14 days), and their interaction (luminance × storage time) were included as fixed effects, while fruit identity was included as a random effect. Because each luminance level was implemented in a single chamber, luminance was not independently replicated at the chamber level; therefore, between-luminance comparisons were inter-

preted cautiously and primarily as descriptive differences in temporal trajectories.

Table 3. Definition of pigment-related indices with corresponding bibliography.

Index	Formula	Used for	Reference
TCARI (Transformed Chlorophyll Absorption in Reflectance Index)	$3\cdot(R_{700}-R_{670})-0.2\cdot(R_{700}-R_{500})\cdot\frac{R_{700}}{R_{670}}$	Chlorophyll content (canopy sensitive)	[12]
SIPI (Structural Insensitive Pigment Index)	$\frac{R_{800}-R_{455}}{R_{800}-R_{680}}$	Carotenoid: Chlorophyll ratio	[14]
CRI1-like (Carotenoid Reflectance Index 1)	$\frac{1}{R_{510}}-\frac{1}{R_{550}}$	Carotenoid content	[13]
CRI2-like (Carotenoid Reflectance Index 2)	$\frac{1}{R_{510}}-\frac{1}{R_{700}}$	Carotenoid content (less chlorophyll influence)	[13]
Chl I (Chlorophyll Index)	$\frac{R_{750}-R_{705}}{R_{750}-R_{705}}$	Chlorophyll content	[36] [37]
NDVI (Normalised Difference Vegetation Index)	$\frac{R_{NIR}-R_{RED}}{R_{NIR}-R_{RED}}$	chlorophyll content and photosynthetic activity	[38]
PSSRa (Pigment Specific Simple Ratio for Chlorophyll a)	$\frac{R_{800}}{R_{680}}$	Chlorophyll a content	[39]
PSSRb (Pigment Specific Simple Ratio for Chlorophyll b)	$\frac{R_{800}}{R_{635}}$	Chlorophyll b content	[39]
ARI 1 (Anthocyanin Reflectance Index 1)	$\frac{1}{R_{550}}-\frac{1}{R_{700}}$	estimation of anthocyanin accumulation	[40]
ARI 2 (Anthocyanin Reflectance Index 2)	$\frac{800}{R_{550}}-\frac{800}{R_{700}}$	estimation of anthocyanin accumulation	[41]

The significance of the fixed effects was assessed from the fitted mixed-effects models. Particular attention was given to the luminance × storage time interaction, which was used to characterize whether the temporal evolution of the measured parameters differed among the applied luminance conditions. When significant effects or interactions were detected, estimated marginal means (EMMs) [42] were calculated and pairwise comparisons among luminance conditions were performed separately for each storage day using the emmeans procedure, with appropriate multiplicity adjustment. Because each luminance condition was represented by a single chamber, these between-condition comparisons were interpreted cautiously and were not considered evidence of a generalized treatment effect beyond the experimental chambers.

Model assumptions were evaluated by examining the distribution of residuals and their variance structure. Residual normality was assessed using the Shapiro-Wilk test [43], while the homogeneity of residual variance was examined using graphical diagnostics and, where appropriate, the Levene test [44]. When the assumptions of the linear mixed-effects model were not adequately satisfied, an appropriate alternative model or transformation was considered.

Statistical significance was defined at $P < 0.05$, while values of $0.05 \le P < 0.10$ were considered indicative of marginal trends. For pairwise comparisons performed within each storage day, different lowercase letters were used to indicate statistically significant differences among luminance treatments ($P < 0.05$). Estimated marginal means are reported as mean ± standard error (SE).

3. Results and Discussions

3.1. Spectral Reflectance Dynamics during Storage

The absolute spectral reflectance of bananas was measured over the 350-900 nm wavelength range following the methodology described in Section 2.2 and is presented in **Figures 2(A)-(C)**. Spectral regions below 400 nm and above 800 nm were excluded from the plots due to increased instrument noise. Relative reflectance differences (%) defined as $\frac{R_{0d} - R_{xd}}{R_{0d}} \times 100$, where R_{0d} represents the initial reflectance and R_{xd} corresponds to reflectance at the subsequent measurement days (4 - 14 d). These relative differences are shown in **Figures 2(D)-(F)** to highlight temporal changes in spectral features. Higher percentage values indicate greater reductions in reflectance relative to day 0.

Across all three boxes, the spectra underwent pronounced changes during storage, particularly in the visible region. The reflectance response around 650 - 680 nm changed markedly during storage, with a decrease in reflectance from Day 0 to later stages of ripening. This spectral evolution reflects changes in the optical properties of the fruit peel during ripening and may be associated with pigment-related and tissue structural changes. Similar spectral changes have been reported during fruit ripening, and Seifert *et al.* (2014) [45] demonstrated that changes in the chlorophyll absorption region can provide non-destructive information on fruit ripeness. These observations therefore support the use of the measured reflectance profiles as indicators of ripening-associated optical changes. However, because pigment concentrations were not directly quantified in the present experiment, the spectral response should not be interpreted as a direct measurement of chlorophyll degradation.

Changes were also observed in the 420-500 nm region, together with progressive modifications of the visible reflectance profile. Such changes are compatible with alterations in pigment-related optical properties during ripening. In banana, Galal *et al.* (2022) [29] demonstrated that visible, NIR and combined spectral reflectance indices could be associated with chlorophyll, carotenoids and other biochemical quality parameters when calibrated against reference measurements. Thus, the changes observed here provide evidence of a modification of pigment-related spectral responses,

but do not by themselves establish a quantitative change in pigment concentration.

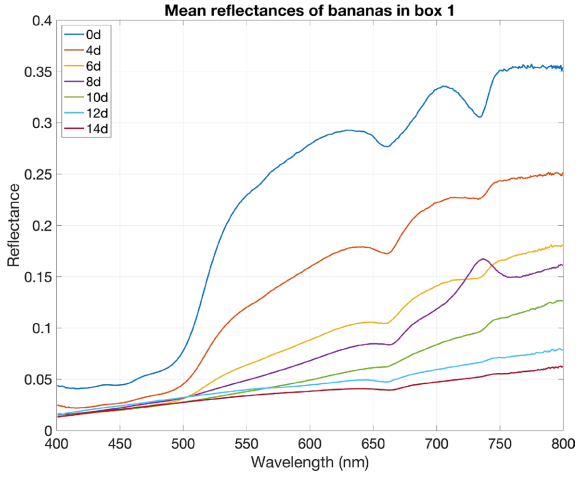
The evolution toward the red-edge/NIR region (approximately 700 nm - 800 nm) also differed with storage time. These changes are likely to reflect modifications in the optical properties of the fruit surface during ripening, in addition to pigment-related effects. The present results are therefore consistent with the ability of Vis-NIR measurements to capture multiple aspects of fruit maturation rather than a single biochemical component. This is important when interpreting the subsequent spectral indices, since their response can integrate pigment-related and structural optical effects.

The relative reflectance profiles revealed a distinct temporal response to the three luminance levels. Box 1 (low luminance) showed the largest early changes, reaching approximately 48% in the 400 - 550 nm region and about 25% above 550 nm at the early stages, with differences increasing to approximately 86% after 14 days. Box 3 (high luminance) exhibited a weaker initial response, with differences of approximately 8% - 28% at day 4, but reached a similar magnitude of change above 550 nm by day 14. Box 2 (medium luminance) showed intermediate changes, ranging from approximately 24% - 43% during the intermediate stages and reaching approximately 82% at day 14. Thus, the three treatments followed a similar overall spectral trajectory but differed in the timing and magnitude of their early changes. The relative reflectance profiles revealed distinct temporal patterns among the three luminance conditions. Box 1 (low luminance) showed the largest early changes, reaching approximately 48% in the 400 - 550 nm region and about 25% above 550 nm at the early stages, with differences increasing to approximately 86% after 14 days. Box 3 (high luminance) exhibited a weaker initial response, with differences of approximately 8% - 28% at Day 4, but reached a similar magnitude of change above 550 nm by Day 14. Box 2 (medium luminance) showed intermediate changes, ranging from approximately 24% - 43% during the intermediate stages and reaching approximately 82% at Day 14. Thus, the three luminance conditions followed a similar overall spectral trajectory but differed in the timing and magnitude of their early changes. Given the experimental design, these differences are interpreted as descriptive differences in temporal spectral trajectories rather than as evidence of a generalized causal effect of luminance on ripening kinetics.

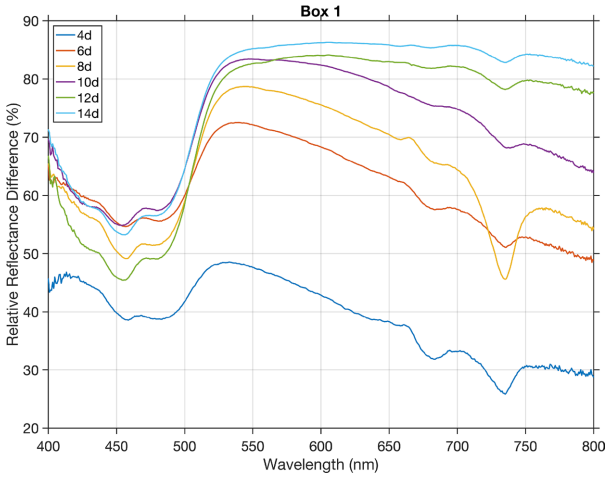
This treatment-dependent temporal response is consistent with previous work showing that postharvest illumination can modify banana ripening. Huang *et al*. (2018) [46] reported effects of LED irradiation on postharvest banana ripening and nutritional quality, while Zhou *et al*. (2023) [26], using direct measurements of chlorophyll and carotenoids, showed that red LED illumination altered the progression of banana ripening. However, those studies used specific LED treatments and, in the case of Zhou *et al*. (2023) [26] direct biochemical measurements. Our results therefore extend the optical perspective by showing that different luminance conditions were associated with distinct temporal spectral trajectories under controlled postharvest conditions.

Representative images of three of the five bananas monitored in each chamber are shown in **Figure 2(G)**. Fruits from Box 2 appeared to undergo a comparatively

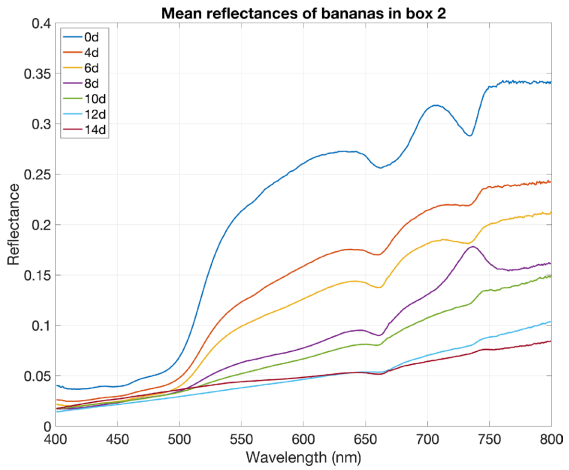
slower visible color transition. This observation is qualitatively consistent with the intermediate spectral evolution observed under medium luminance; however, the photographs are presented as representative observations and were not considered an independent statistical endpoint.



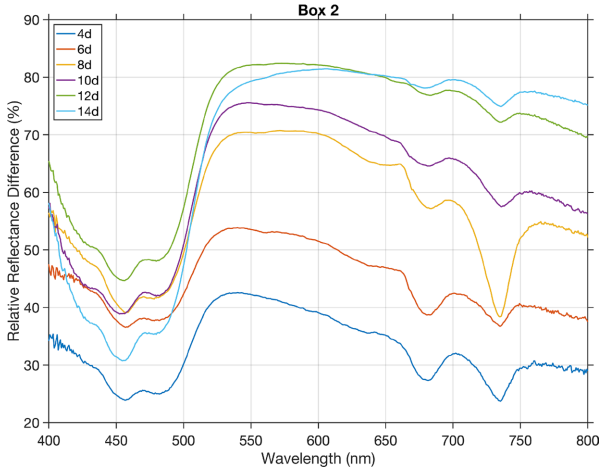
(A)



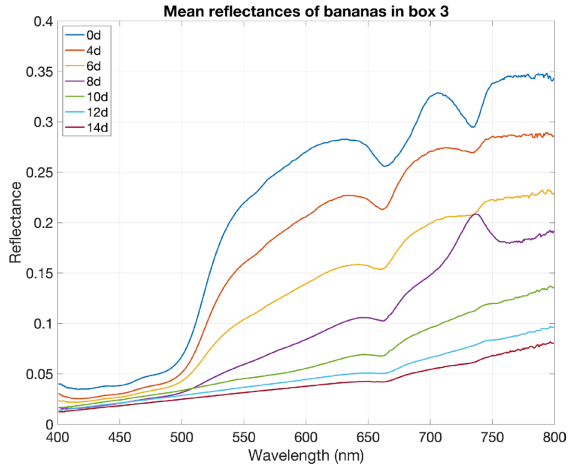
(D)



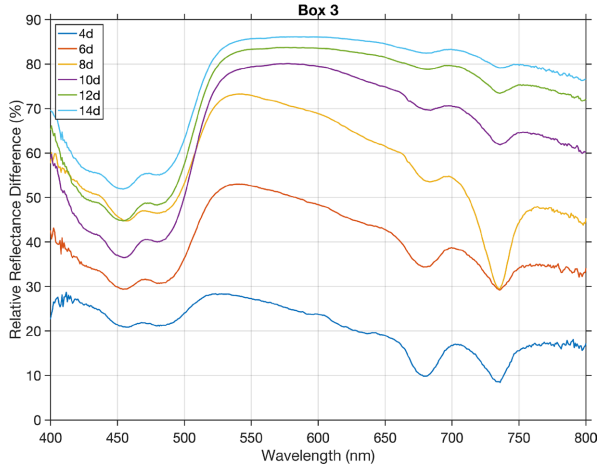
(B)



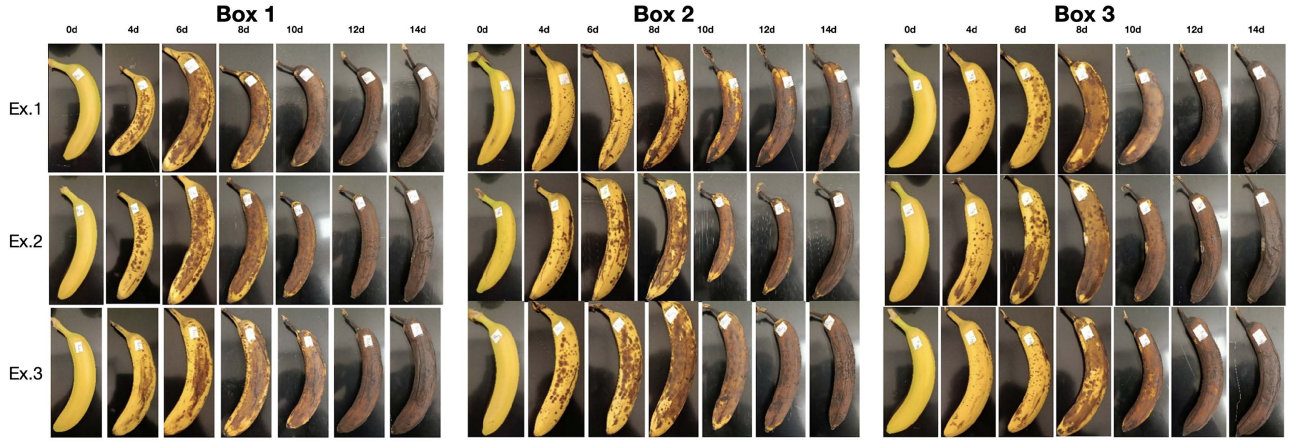
(E)



(C)



(F)



(G)

Figure 2. (A)-(C) Changes of banana reflectance spectra (350 - 900 nm) in time, and the (D)-(F) emphasis of reflectance difference in percentages from the 0d (0d-xd)/0d under three light luminance levels (a-low, b-medium and c-high). (G) The visual evolution of the fruit from Day 0 to Day 14, three sample examples from each box (Ex.1, Ex.2, Ex.3).

Overall, the spectral measurements revealed a common ripening-related trajectory across luminance conditions, accompanied by differences in the timing and magnitude of spectral changes. Given the experimental design, these differences are interpreted primarily as treatment-associated temporal patterns rather than as evidence of a generalized causal effect of luminance on ripening. Importantly, the present spectral data support associations with pigment-related and structural changes but do not establish direct biochemical changes; such relationships would require complementary chemical measurements.

3.2. Evolution of Pigment Related Spectral Indices

3.2.1. Chlorophyll-Related Indices

Chlorophyll-related spectral indices showed marked temporal changes during banana storage, with distinct responses among the luminance treatments (**Figure 3**). TCARI decreased sharply during the first stages of storage in all treatments, from approximately 0.09 - 0.11 at day 0 to values below 0.05 by day 6, followed by a more gradual decline toward day 14. The reduction was approximately 65%, 62%, and 72% under low, medium, and high luminance, respectively, between day 0 and day 6. The mixed-effects analysis indicated a significant luminance × time interaction ($P < 0.001$; **Table 4**), indicating that the temporal trajectory of TCARI differed among the applied luminance conditions. However, the treatment differences were limited to specific sampling times: at day 0, the high-luminance treatment showed a significantly higher TCARI than the medium-luminance treatment, whereas no significant differences were detected among treatments at the subsequent sampling days. Thus, the temporal pattern of TCARI differed among the applied luminance conditions without producing a persistent separation among treatments.

The Chlorophyll Index (Chl I) followed a different trajectory, increasing from

day 0 to approximately day 10 and subsequently declining toward day 14. The interaction between luminance and storage time was significant ($P < 0.001$; **Table 4**). Treatment differences were detected at days 4, 6, and 12, but not at days 0, 8, 10, or 14. At day 6, the medium-luminance treatment showed the highest Chl I value, whereas at day 12 it showed the lowest value. The transient increase in Chl I should therefore not be interpreted as an increase in chlorophyll concentration. Reflectance-based indices can be influenced by pigment absorption as well as by changes in tissue optical properties, including scattering. This is particularly relevant for banana, for which spectral reflectance indices have been shown to provide indirect estimates of chlorophyll and other biochemical parameters when calibrated against reference measurements [29].

PSSRa and PSSRb exhibited broadly similar temporal trajectories, increasing during the first part of storage and reaching their highest values between days 10 and 12 before declining toward day 14 (**Figure 3**). For both indices, the luminance × time interaction was significant ($P < 0.001$; **Table 4**). Medium luminance produced significantly higher values than high luminance at day 6 for both PSSRa and PSSRb and remained higher than low luminance at days 8 and 10. However, this response was not maintained throughout storage: at day 12, the medium-luminance treatment showed significantly lower values than the low- and high-luminance treatments, while no differences remained at day 14. The response therefore suggests a transient treatment-dependent modulation rather than a consistent enhancement of chlorophyll-related spectral indices under medium luminance.

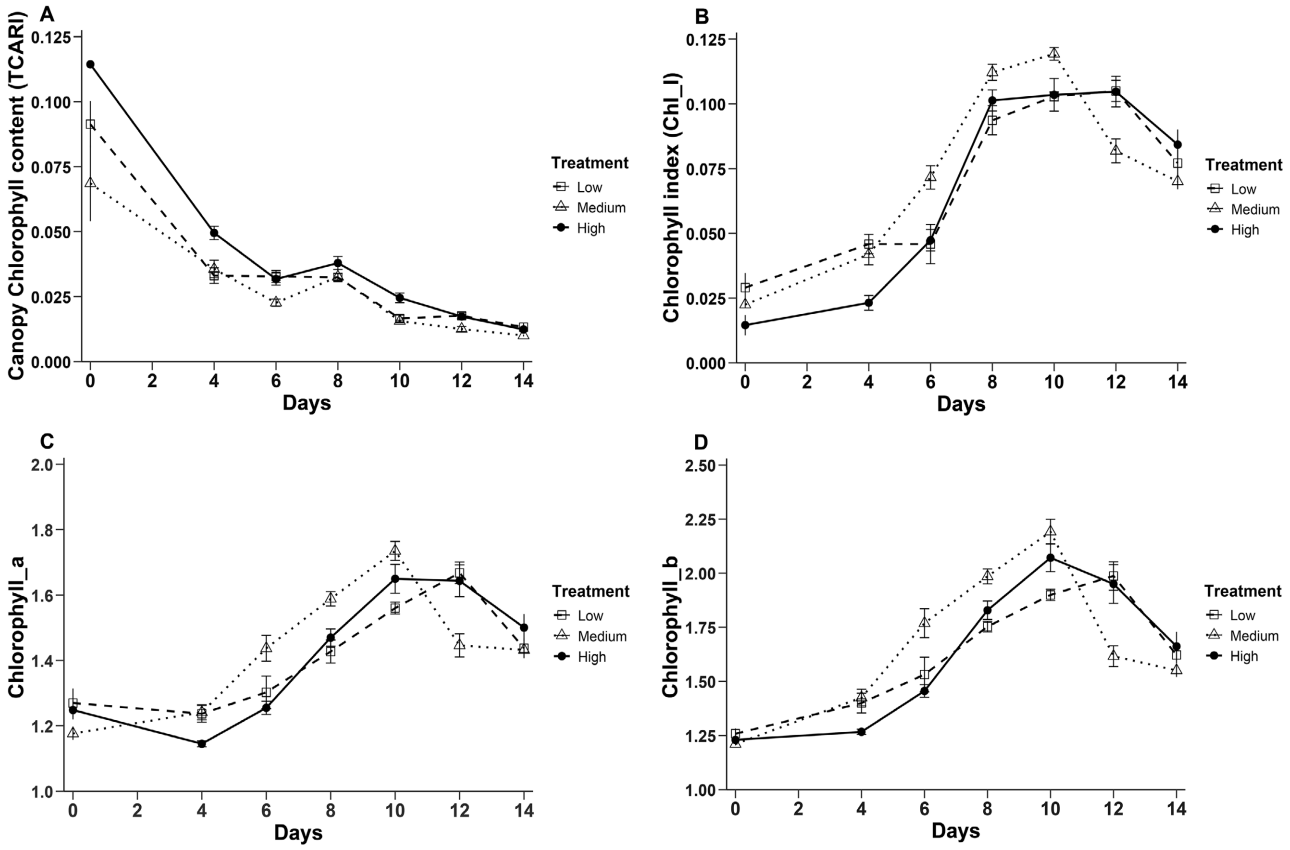
NDVI also exhibited a non-linear temporal pattern, with a slight change during the early storage period followed by an increase toward days 10 - 12 and a subsequent decline by day 14. The luminance × time interaction was significant ($P < 0.001$; **Table 4**), with significant treatment differences detected at days 6 and 12. At day 6, the medium-luminance treatment showed the highest NDVI, whereas at day 12 it showed the lowest value. No significant differences were observed at days 0, 4, 8, 10, or 14. Similar work has demonstrated that NDVI-type measurements can provide information related to chlorophyll status and fruit maturity, although their response reflects optical properties rather than chlorophyll concentration alone [47].

Taken together, the four chlorophyll-related indices did not exhibit identical responses to luminance. TCARI showed a rapid decline, whereas Chl I, PSSRa, PSSRb, and NDVI displayed transient increases followed by declines. These contrasting trajectories are not contradictory because the indices are based on different spectral formulations and therefore respond differently to changes in reflectance. The common feature was the significant luminance × time interaction for all indices, indicating that the temporal evolution of the spectral responses differed among the applied luminance conditions rather than showing a uniform pattern throughout storage.

The early decline in TCARI is compatible with the progressive modification of

chlorophyll-related optical features during banana ripening. However, spectral indices should be interpreted as indirect indicators of pigment-related changes, particularly in the absence of direct pigment quantification. Galal *et al*. (2022) [29] similarly demonstrated the potential of spectral reflectance indices to estimate chlorophyll-related biochemical parameters in banana, but their approach was validated using chemical measurements of chlorophyll a and b. In contrast, direct measurements reported by Zhou *et al*. (2023) [26] showed that red LED illumination could modify chlorophyll degradation and carotenoid accumulation during postharvest banana ripening. The present results therefore indicate that the spectral expression of ripening differed among the applied luminance conditions, but they do not by themselves demonstrate changes in chlorophyll concentration or degradation rates.

Overall, the results indicate that the timing and magnitude of chlorophyll-related spectral responses differed among the applied luminance conditions, with the strongest treatment differences occurring at intermediate stages of storage and largely disappearing by day 14. This convergence suggests that the observed treatment-associated differences were predominantly transient, superimposed on a common ripening trajectory. The results therefore support the use of these indices for non-destructive monitoring of ripening dynamics, while direct biochemical measurements would be required to establish their quantitative relationship with chlorophyll content.



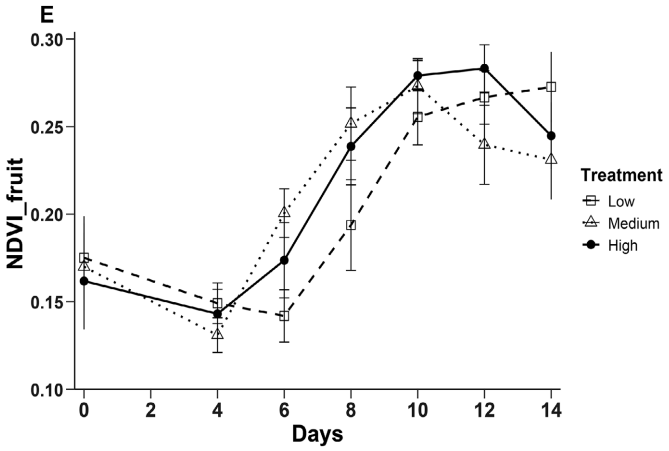


Figure 3. Evolution of chlorophyll pigments during the experimental period under different levels of light: TCARI (A), Chlorophyll Index (B), PSSRa (C), PSSRb (D), chlorophyll b/total chlorophyll ratio (E). The curves represent pigment variations over 14 days under the light treatments (Low, Medium, High), with standard deviations indicated.

Table 4. Estimated marginal means of chlorophyll-related spectral indices during banana ripening under different light luminance levels. Values are estimated marginal means ± standard errors (EMM ± SE). Different lowercase letters within the same storage day indicate significant differences among luminance treatments based on multiplicity-adjusted pairwise comparisons ($P < 0.05$). The P and F-values correspond to the luminance × storage time interaction from the linear mixed-effects model. $P < 0.05$ was considered statistically significant, whereas $0.05 \leq P < 0.10$ indicated a marginal trend.

Index	Day	Low	Medium	High	P Luminance × Time	F-value_Luminance × Time
Chl I	0	0.0290 ± 0.0056^{a}	0.0224 ± 0.0056^{a}	0.0145 ± 0.0056^{a}	**<0.001**	5.2221
	4	0.0458 ± 0.0056^{b}	0.0419 ± 0.0056^{ab}	0.0232 ± 0.0056^{a}		
	6	0.0458 ± 0.0056^{a}	0.0716 ± 0.0056^{b}	0.0473 ± 0.0056^{a}		
	8	0.0936 ± 0.0056^{a}	0.1121 ± 0.0056^{a}	0.1013 ± 0.0056^{a}		
	10	0.1029 ± 0.0056^{a}	0.1177 ± 0.0059^{a}	0.1035 ± 0.0056^{a}		
	12	0.1050 ± 0.0056^{a}	0.0818 ± 0.0056^{b}	0.1047 ± 0.0056^{a}		
	14	0.0771 ± 0.0056^{a}	0.0700 ± 0.0056^{a}	0.0843 ± 0.0056^{a}		
PSSRa	0	1.2698 ± 0.0399^{a}	1.1763 ± 0.0399^{a}	1.2484 ± 0.0399^{a}	**<0.001**	6.6209
	4	1.2369 ± 0.0399^{a}	1.2413 ± 0.0399^{a}	1.1450 ± 0.0399^{a}		
	6	1.3024 ± 0.0399^{ab}	1.4369 ± 0.0399^{b}	1.2549 ± 0.0399^{a}		
	8	1.4271 ± 0.0399^{a}	1.5883 ± 0.0399^{b}	1.4698 ± 0.0399^{ab}		
	10	1.5599 ± 0.0399^{a}	1.7229 ± 0.0423^{b}	1.6496 ± 0.0399^{ab}		
	12	1.6678 ± 0.0399^{a}	1.4460 ± 0.0399^{b}	1.6434 ± 0.0399^{a}		
	14	1.4372 ± 0.0399^{a}	1.4320 ± 0.0399^{a}	1.5005 ± 0.0399^{a}		

Continued

	0	1.2583 ± 0.0582[a]	1.2107 ± 0.0582[a]	1.2298 ± 0.0582[a]	**<0.001**	6.4458
	4	1.3998 ± 0.0582[a]	1.4251 ± 0.0582[a]	1.2669 ± 0.0582[a]		
	6	1.5320 ± 0.0582[a]	1.7690 ± 0.0582[b]	1.4556 ± 0.0582[a]		
PSSRb	8	1.7529 ± 0.0582[a]	1.9853 ± 0.0582[b]	1.8287 ± 0.0582[ab]		
	10	1.8996 ± 0.0582[a]	2.1762 ± 0.0628[b]	2.0713 ± 0.0582[ab]		
	12	1.9872 ± 0.0582[a]	1.6166 ± 0.0582[b]	1.9501 ± 0.0582[a]		
	14	1.6221 ± 0.0582[a]	1.5508 ± 0.0582[a]	1.6619 ± 0.0582[a]		
	0	0.1371 ± 0.0149[a]	0.1063 ± 0.0149[a]	0.1431 ± 0.0149[a]	**<0.001**	6.0888
	4	0.1449 ± 0.0149[a]	0.1519 ± 0.0149[a]	0.1144 ± 0.0149[a]		
	6	0.1771 ± 0.0149[ab]	0.2272 ± 0.0149[b]	0.1570 ± 0.0149[a]		
NDVI	8	0.2332 ± 0.0149[a]	0.2914 ± 0.0149[a]	0.2519 ± 0.0149[a]		
	10	0.2552 ± 0.0149[a]	0.3058 ± 0.0158[a]	0.3000 ± 0.0149[a]		
	12	0.2956 ± 0.0149[a]	0.2178 ± 0.0149[b]	0.2890 ± 0.0149[a]		
	14	0.2131 ± 0.0149[a]	0.2131 ± 0.0149[a]	0.2463 ± 0.0149[a]		

3.2.2. Carotenoid-Related Indices

Carotenoid-related spectral indices exhibited distinct temporal patterns during banana storage, with differences in the magnitude and timing of responses among luminance treatments (**Figure 4**). Because these indices were derived from spectral reflectance rather than from direct biochemical quantification, the observed variations are interpreted as carotenoid-related spectral responses rather than direct evidence of changes in carotenoid concentration or biosynthesis. This distinction is particularly important because reflectance in the visible region is influenced by overlapping absorption by chlorophylls and carotenoids, as well as by tissue optical properties [13].

SIPI (**Figure 4(A)**) showed an overall decline during storage, although its temporal trajectory differed among luminance treatments. Under high luminance, SIPI increased from day 0 to day 4, reaching the highest value among treatments at this stage, before decreasing progressively toward day 14. SIPI was originally developed as a structure-insensitive pigment index and has been related to the carotenoid-to-chlorophyll *a* ratio through spectral reflectance measurements [14]. However, its interpretation remains indirect because the index integrates the spectral effects of multiple pigments and tissue optical properties [48].

The significant luminance × storage-time interaction for SIPI ($P < 0.001$; **Table 5**) indicates that its temporal evolution differed among the applied luminance

conditions. Pairwise comparisons showed a significant treatment effect at day 4, when the high-luminance treatment exhibited a higher SIPI value than the low- and medium-luminance treatments. No significant differences were detected among treatments at the other storage dates. The subsequent convergence of SIPI values therefore suggests a reduction in treatment-dependent spectral differences as ripening progressed rather than sustained differences in pigment composition.

CRI1 (**Figure 4(B)**) increased from day 0 to the intermediate stages of storage and subsequently declined toward day 14. The maximum response occurred around day 6 under medium luminance, whereas the high-luminance treatment reached its maximum around day 8. CRI1 is based on reciprocal reflectance in the 510-550 nm region, where reflectance is sensitive to carotenoid-related absorption but is also affected by chlorophylls [13]. Consequently, changes in CRI1 can provide information on carotenoid-related spectral variation, but should not be interpreted as a direct measurement of carotenoid concentration in the absence of biochemical validation.

The luminance × storage-time interaction for CRI1 was marginal ($P = 0.0938$; **Table 5**), indicating a tendency toward treatment-dependent temporal variation but not a statistically significant interaction at the 5% level. Moreover, no significant pairwise differences among luminance treatments were detected at individual storage dates. The differences observed in the timing and magnitude of the CRI1 response should therefore be considered descriptive trends rather than evidence of statistically confirmed differences in carotenoid content.

A similar temporal evolution was observed for CRI2 (**Figure 4(C)**), with values increasing during the first part of storage, reaching maximum values between days 8 and 10, and subsequently declining toward day 14. The medium-luminance treatment exhibited the highest response around days 6 - 10, whereas the high-luminance treatment also showed a pronounced response during the intermediate stages. CRI2, like CRI1, uses reciprocal reflectance around 510 nm combined with a reference wavelength less sensitive to carotenoid absorption, and was developed for nondestructive assessment of carotenoid-related spectral variation [49].

The significant luminance × storage-time interaction for CRI2 ($P = 0.0093$; **Table 5**) confirms that the temporal evolution of this index differed among treatments. At day 6, the medium-luminance treatment exhibited a significantly higher value than the high-luminance treatment, whereas the low-luminance treatment was intermediate. No significant differences among treatments were detected at the remaining storage dates. Thus, the effect of luminance on CRI2 was transient and concentrated during the intermediate phase of storage, rather than being maintained throughout ripening.

The temporal evolution observed for these indices is consistent with previous spectroscopic observations of banana ripening. Ringer and Blanke (2021) [28] reported pronounced changes in banana reflectance during ripening, particularly around the chlorophyll-associated absorption feature near 679 nm and a second feature around 494 nm, with progressive flattening of the reflectance spectra as

ripening advanced. These observations support the use of spectral measurements for monitoring nondestructive changes during banana maturation.

Overall, SIPI, CRI1 and CRI2 revealed substantial temporal changes during banana storage, particularly during the intermediate stages of ripening. The significant luminance × time interactions observed for SIPI and CRI2 indicate that the timing and magnitude of carotenoid-related spectral responses differed among the applied luminance conditions, whereas the marginal interaction observed for CRI1 suggests a weaker treatment effect. Importantly, these spectral responses should not be equated directly with carotenoid accumulation or biosynthesis because no complementary biochemical determination of carotenoid concentration was performed. Instead, the results indicate that the optical signatures associated with pigment evolution differed among the luminance conditions. The progressive convergence of the indices toward the end of storage further suggests that treatment-dependent differences became less pronounced as ripening advanced. These findings support the potential of hyperspectral measurements and spectral indices for non-destructive monitoring of pigment-related changes, while highlighting the need for pigment extraction and chromatographic or spectrophotometric analyses to establish direct biochemical relationships.

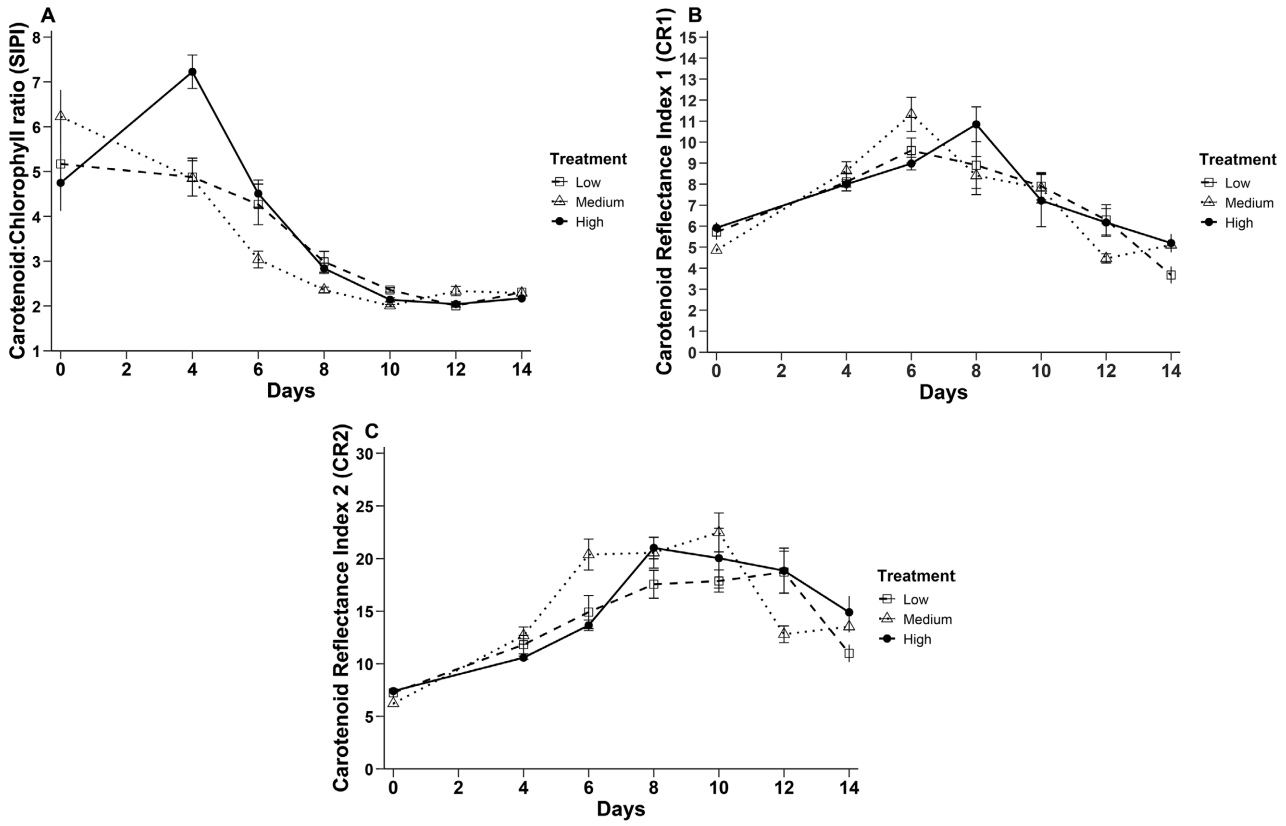


Figure 4. Evolution of carotenoid-related indices during maturation under different levels of light luminance: (A) SIPI (Structure Insensitive Pigment Index); (B) CRI1 (Carotenoid Reflectance Index 1); (C) CRI2 (Carotenoid Reflectance Index 2). The curves illustrate the progressive accumulation of carotenoid pigments over 14 days under the light treatments (Low, Medium, High), with standard deviations indicated.

Table 5. Estimated marginal means of carotenoid-related spectral indices during banana ripening under different light luminance levels. Values are estimated marginal means ± standard errors (EMM ± SE). Different lowercase letters within the same storage day indicate significant differences among luminance treatments based on multiplicity-adjusted pairwise comparisons ($P < 0.05$). The P and F-values correspond to the luminance × storage time interaction from the linear mixed-effects model. $P < 0.05$ was considered statistically significant, whereas $0.05 \leq P < 0.10$ indicated a marginal trend.

Index	Day	Low	Medium	High	P (L × T)	*F* (L × T)
SIPI	0	5.1698 ± 0.4915^{a}	6.2271 ± 0.4915^{a}	4.7479 ± 0.4915^{a}	**<0.001**	**3.6915**
	4	4.8769 ± 0.4915^{a}	4.8451 ± 0.4915^{a}	7.2252 ± 0.4915^{b}		
	6	4.2674 ± 0.4915^{a}	3.0389 ± 0.4915^{a}	4.5065 ± 0.4915^{a}		
	8	2.9859 ± 0.4915^{a}	2.3586 ± 0.4915^{a}	2.8383 ± 0.4915^{a}		
	10	2.3594 ± 0.4915^{a}	2.0412 ± 0.5135^{a}	2.1397 ± 0.4915^{a}		
	12	2.0036 ± 0.4915^{a}	2.3326 ± 0.4915^{a}	2.0414 ± 0.4915^{a}		
	14	2.3068 ± 0.4915^{a}	2.2902 ± 0.4915^{a}	2.1705 ± 0.4915^{a}		
CRI1	0	5.7184 ± 0.7797^{a}	4.8615 ± 0.7797^{a}	5.9186 ± 0.7797^{a}	**0.0938**	**1.6638**
	4	8.1028 ± 0.7797^{a}	8.6353 ± 0.7797^{a}	7.9919 ± 0.7797^{a}		
	6	9.5982 ± 0.7797^{a}	11.3228 ± 0.7797^{a}	8.9794 ± 0.7797^{a}		
	8	8.9024 ± 0.7797^{a}	8.4065 ± 0.7797^{a}	10.8464 ± 0.7797^{a}		
	10	7.9000 ± 0.7797^{a}	7.7588 ± 0.8664^{a}	7.2199 ± 0.7797^{a}		
	12	6.2977 ± 0.7797^{a}	4.4641 ± 0.7797^{a}	6.1719 ± 0.7797^{a}		
	14	3.6722 ± 0.7797^{a}	5.1048 ± 0.7797^{a}	5.1941 ± 0.7797^{a}		
CRI2	0	7.2417 ± 1.6180^{a}	6.2179 ± 1.6180^{a}	7.4031 ± 1.6180^{a}	**0.0093**	**2.4689**
	4	11.8129 ± 1.6180^{a}	12.6827 ± 1.6180^{a}	10.5729 ± 1.6180^{a}		
	6	14.9054 ± 1.6180^{ab}	20.3711 ± 1.6180^{a}	13.6523 ± 1.6180^{b}		
	8	17.5492 ± 1.6180^{a}	20.5491 ± 1.6180^{a}	21.0089 ± 1.6180^{a}		
	10	17.8585 ± 1.6180^{a}	22.2764 ± 1.7943^{a}	20.0304 ± 1.6180^{a}		
	12	18.7031 ± 1.6180^{a}	12.8029 ± 1.6180^{a}	18.8410 ± 1.6180^{a}		
	14	10.9938 ± 1.6180^{a}	13.5226 ± 1.6180^{a}	14.8880 ± 1.6180^{a}		

3.2.3. Anthocyanin-Related Spectral Indices

Anthocyanin-related spectral indices (ARI1 and ARI2) exhibited marked temporal changes during banana storage, although their trajectories differed among luminance treatments (Figure 5). Both indices increased progressively during the first part of storage, reached maximum values around days 8 - 10, and subsequently declined toward day 14. This general temporal pattern indicates substantial changes in the spectral response of the fruit peel during ripening.

ARI1 increased from approximately 1.4 - 1.5 at day 0 to maximum values between 12 and 15 around days 8 - 10, depending on the treatment. The medium-

luminance treatment showed the highest value at day 10 (14.54 ± 1.08), whereas low and high luminance reached 9.96 ± 0.98 and 12.81 ± 0.98, respectively. Significant differences among treatments were detected at days 6, 10 and 12 (**Table 6**). At day 6, the medium-luminance treatment exhibited a higher ARI1 value than the low- and high-luminance treatments, while at day 10 it remained significantly higher than the low treatment. At day 12, the medium-luminance treatment showed a significantly lower value than both low and high luminance. By day 14, the differences were no longer significant.

ARI2 followed a broadly similar trajectory, increasing from approximately 0.5 at day 0 to maximum values between 1.8 and 2.0 around days 8-10 before declining markedly at the end of storage. Significant treatment differences were observed at days 6, 8 and 12. At day 6, the medium-luminance treatment displayed a higher value than both low and high luminance. At day 8, both medium and high luminance produced higher ARI2 values than low luminance, whereas at day 12 the medium treatment showed a significantly lower value than the low- and high-luminance treatments. No significant differences were detected at days 0, 4, 10 or 14.

The ARI was originally developed from visible reflectance measurements to provide a nondestructive indication of anthocyanin-related variation, exploiting the strong influence of anthocyanins around the green spectral region and using longer wavelengths to reduce the contribution of chlorophyll and other optical effects [50]. Subsequent work has emphasized that such indices are indirect optical proxies whose response can also be affected by pigment interactions, tissue structure and scattering properties. Consequently, the increases observed here should be interpreted as changes in anthocyanin-related spectral response rather than direct evidence of anthocyanin accumulation [51].

This distinction is particularly important for banana peel. Anthocyanins have been chemically identified in some banana cultivars, particularly red-peeled bananas, whereas the yellow coloration characteristic of most cultivated bananas is primarily associated with carotenoid accumulation rather than anthocyanins. Nevertheless, recent chemical analyses of banana fruit have reported changes in anthocyanin concentrations during ripening, including increases in both peel and pulp, demonstrating that anthocyanin metabolism can contribute to ripening-related pigment changes even when it is not the dominant determinant of peel colour.

In the present experiment, the transient increase in ARI1 and ARI2 therefore suggests a ripening-associated modification of the spectral region sensitive to anthocyanin-related pigments, with the magnitude and timing of this response being influenced by luminance. The stronger intermediate responses observed under medium luminance, particularly for ARI1 at day 10 and ARI2 at days 6-8, may indicate that this treatment modified the timing of pigment-related spectral changes. However, because anthocyanin concentrations were not determined chemically, these differences cannot be attributed exclusively to changes

in anthocyanin content. Changes in chlorophyll, carotenoids, epidermal structure, tissue scattering and other optical properties may also contribute to the observed indices. This caution is consistent with the broader use of spectral indices as nondestructive indicators of fruit maturity, which generally requires biochemical validation when specific pigment concentrations are to be inferred [52] [53].

The decline in both indices after days 10 - 12 further indicates that the spectral response associated with these wavelengths did not continue to increase throughout ripening. Rather than interpreting this decrease as a direct loss of anthocyanins, it is more appropriate to consider it as evidence of a transition in the optical properties of the peel during the late stages of ripening. Such a transition occurs concomitantly with the well-established degradation of chlorophyll and changes in carotenoid composition during banana ripening [28].

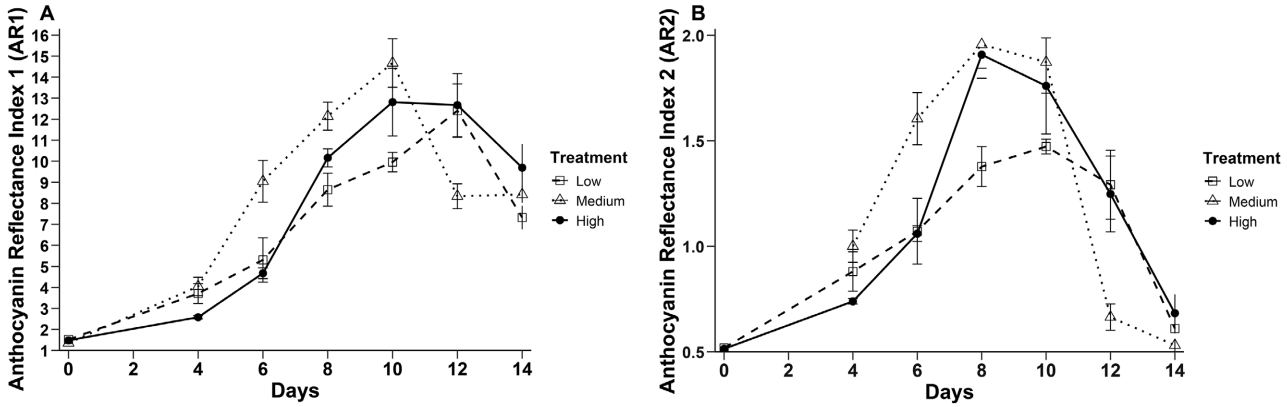


Figure 5. Evolution of anthocyanin-related indices during maturation under different levels of light luminance: (A) ARI1 (Anthocyanin Reflectance Index 1); (B) ARI2 (Anthocyanin Reflectance Index 2). The curves illustrate the trends over 14 days according to the light treatments applied (low, medium, high), with indication of standard deviations.

Table 6. Estimated marginal means of anthocyanin-related indices during banana ripening under different light luminance levels. Values are estimated marginal means ± standard errors (EMM ± SE). Different lowercase letters within the same storage day indicate significant differences among luminance treatments based on multiplicity-adjusted pairwise comparisons ($P < 0.05$). The P and F-values correspond to the luminance × storage time interaction from the linear mixed-effects model. $P < 0.05$ was considered statistically significant, whereas $0.05 \leq P < 0.10$ indicated a marginal trend.

Index	Day	Low	Medium	High	P (L × T)	*F* (L × T)
	0	1.5233 ± 0.9847^{a}	1.3564 ± 0.9847^{a}	1.4845 ± 0.9847^{a}	**<0.001**	**3.5549**
	4	3.7101 ± 0.9847^{a}	4.0474 ± 0.9847^{a}	2.5810 ± 0.9847^{a}		
	6	5.3072 ± 0.9847^{b}	9.0483 ± 0.9847^{a}	4.6730 ± 0.9847^{b}		
ARI1	8	8.6468 ± 0.9847^{a}	12.1426 ± 0.9847^{a}	10.1625 ± 0.9847^{a}		
	10	9.9585 ± 0.9847^{a}	14.5379 ± 1.0832^{b}	12.8106 ± 0.9847^{ab}		
	12	12.4055 ± 0.9847^{b}	8.3389 ± 0.9847^{a}	12.6691 ± 0.9847^{b}		
	14	7.3216 ± 0.9847^{a}	8.4178 ± 0.9847^{a}	9.6939 ± 0.9847^{a}		

Continued

	0	0.5180 ± 0.1311[a]	0.4793 ± 0.1311[a]	0.5138 ± 0.1311[a]	**<0.001**	**4.0325**
	4	0.8804 ± 0.1311[a]	1.0003 ± 0.1311[a]	0.7388 ± 0.1311[a]		
	6	1.0710 ± 0.1311[b]	1.6045 ± 0.1311[a]	1.0600 ± 0.1311[b]		
ARI2	8	1.3773 ± 0.1311[a]	1.9556 ± 0.1311[b]	1.9074 ± 0.1311[b]		
	10	1.4725 ± 0.1311[a]	1.8733 ± 0.1455[a]	1.7599 ± 0.1311[a]		
	12	1.2916 ± 0.1311[b]	0.6642 ± 0.1311[a]	1.2474 ± 0.1311[b]		
	14	0.6100 ± 0.1311[a]	0.5308 ± 0.1311[a]	0.6826 ± 0.1311[a]		

Overall, ARI1 and ARI2 revealed distinct temporal changes in the banana peel spectral response, with the strongest responses occurring during intermediate ripening stages and treatment-dependent differences being most evident during this period. These indices therefore provide useful nondestructive markers of ripening-related pigment and optical changes, but their interpretation as quantitative indicators of anthocyanin accumulation should remain cautious in the absence of direct biochemical measurements.

3.2.4. Evolution of Colorimetric Parameters

The RGB and CIELAB parameters showed marked temporal changes during storage, whereas the magnitude and timing of these changes varied according to the luminance treatment (**Figure 6**, **Table 7**). These colorimetric responses are consistent with the progressive transition of banana peel during ripening, which involves chlorophyll degradation, the emergence of yellow-brown coloration, and associated changes in surface optical properties. Such color changes are widely recognized as practical indicators of banana ripening and quality, while previous studies have also demonstrated that light treatments can modulate pigment degradation and peel coloration [26] [46] [54].

The *R* component decreased markedly from day 0 to day 14 under all luminance treatments, with the greatest reduction occurring during the first 8 days. Mean values decreased from 158.9, 164.2, and 164.3 at day 0 to 96.5, 94.0, and 95.3 at day 14 under low, medium, and high luminance, respectively. Although the luminance × time interaction was significant (P = 0.0029; $F = 2.86$), no significant differences among treatments were detected at any individual storage day. This indicates that luminance modified the temporal response without producing a consistent separation among treatments at specific sampling dates. The progressive decrease in *R* is compatible with the general loss of the initial green coloration and the transition toward yellow and brown tones during banana ripening, reflecting the combined effects of chlorophyll degradation and changes in the optical properties of the peel [46].

A similar temporal pattern was observed for the *G* component, which declined substantially throughout storage. Values decreased from approximately 134 - 138

at day 0 to about 82 at day 14. The luminance × time interaction was highly significant ($P < 0.001$; $F = 3.47$), although treatment differences were detected only at day 8, when the medium-luminance treatment showed a higher G value than the low-luminance treatment. The absence of systematic differences at the other sampling dates suggests that luminance affected the kinetics of the color transition rather than establishing a persistent treatment-specific color response. The parallel decreases in R and G are consistent with the progressive alteration of the green component of banana peel during ripening and agree with previous observations of light-associated modulation of banana coloration [26] [46].

The B component differed from R and G by exhibiting a non-monotonic response. It decreased from approximately 61 - 66 at day 0 to 47 - 51 by days 6 - 8, followed by a marked increase toward days 10 - 14, reaching approximately 72 - 74 at the end of storage. The luminance × time interaction was significant ($P = 0.0057$; $F = 2.64$), but significant differences among luminance treatments were observed only at day 8, when the medium-luminance treatment presented a higher value than the low-luminance treatment. The increase in B during the later stages should not be interpreted as the formation of blue pigments. Rather, it likely reflects changes in the surface and internal optical properties of the peel associated with ripening, including modifications in tissue structure, texture, scattering, and reflection. The distinct trajectory of B compared with R and G therefore indicates that RGB responses are influenced not only by pigment composition but also by structural changes occurring during ripening.

The CIELAB lightness parameter (L^*) followed a pattern broadly similar to the RGB components, decreasing strongly from day 0 to day 14. Mean L^* values declined from 143 - 148 initially to approximately 90 at the end of storage. The luminance × time interaction was significant ($P < 0.001$; $F = 3.40$), with a significant treatment difference at day 8, when medium luminance resulted in a higher L^* value than low luminance. The decrease in L^* indicates a progressive reduction in perceived lightness as ripening advanced, consistent with the development of darker and more heterogeneous peel coloration. Importantly, the similarity between the L^* and RGB trajectories suggests that the overall loss of initial peel brightness was largely associated with the temporal progression of ripening rather than with a sustained effect of luminance intensity.

In contrast, a^* and b^* exhibited relatively limited treatment-related variation. The luminance × time interaction was not significant for either parameter (a^*: $P = 0.4647$, $F = 0.99$; b^*: $P = 0.1197$, $F = 1.57$). Although both parameters varied during storage, no significant differences among luminance treatments were detected at any sampling date. The absence of a significant interaction indicates that luminance did not substantially modify the temporal trajectories of these two CIELAB coordinates. This result is important because it demonstrates that not all colorimetric dimensions were equally sensitive to the imposed light conditions, despite the pronounced changes observed in RGB values and L*.

The total color difference (ΔE) showed the clearest overall deterioration of color

similarity relative to the initial state. ΔE increased sharply from approximately 6-8 at day 0 to 18 - 25 at day 4 and 29 - 41 at day 6, followed by further increases and stabilization at high values toward the end of storage. The luminance × time interaction was significant (P = 0.0016; $F = 3.06$). Treatment differences were observed at days 6 and 8: at day 6, the medium-luminance treatment exhibited a higher ΔE than the high-luminance treatment, whereas at day 8 the low-luminance treatment showed a higher value than the medium-luminance treatment. No significant differences were detected at days 10, 12, or 14. Thus, luminance influenced the magnitude of color divergence mainly during intermediate ripening stages, while the treatments converged toward similarly large color differences at the end of storage.

The evolution of ΔE integrates the changes occurring across the different color dimensions and therefore provides a complementary measure of the overall visual transformation of the peel. Its strong increase coincided with the progressive changes in R, G, B, and L^*, particularly during the transition from the early to intermediate stages of ripening. The late increase in B, together with the continued changes in the other color components, may have contributed to the high ΔE values observed at the final stages. This relationship highlights that ΔE should be interpreted as a global optical response rather than as a direct indicator of a single pigment. Similar approaches have been used to characterize fruit ripening and color deterioration, while studies on banana under controlled light conditions have shown that illumination can modify the kinetics of peel color development [26] [46] [54].

Overall, the colorimetric results reveal a strong temporal component in banana peel color evolution, whereas the effect of luminance was more limited and stage-dependent. The significant luminance × time interactions observed for R, G, B, L^*, and ΔE indicate that light intensity influenced the kinetics of color change, but the absence of persistent treatment differences at most sampling dates indicates that luminance did not override the intrinsic progression of ripening. Conversely, the lack of significant interactions for a^* and b^* suggests that these parameters were comparatively insensitive to the imposed luminance conditions. This pattern is consistent with the spectral-index results presented above, where treatment effects were also most apparent during intermediate stages before diminishing as ripening progressed.

From an applied perspective, the combination of RGB and CIELAB parameters provides a relatively simple and nondestructive approach for monitoring banana ripening. In particular, ΔE and L^*, together with selected RGB parameters, captured substantial changes in peel appearance without requiring the more complex instrumentation associated with spectroscopic measurements. These measurements could therefore serve as complementary low-cost indicators for monitoring postharvest quality, while spectral indices provide more specific information on pigment-related changes. The combined use of both approaches may be particularly valuable for developing practical monitoring systems in which detailed spectroscopic characterization is complemented by rapid image-based assessment.

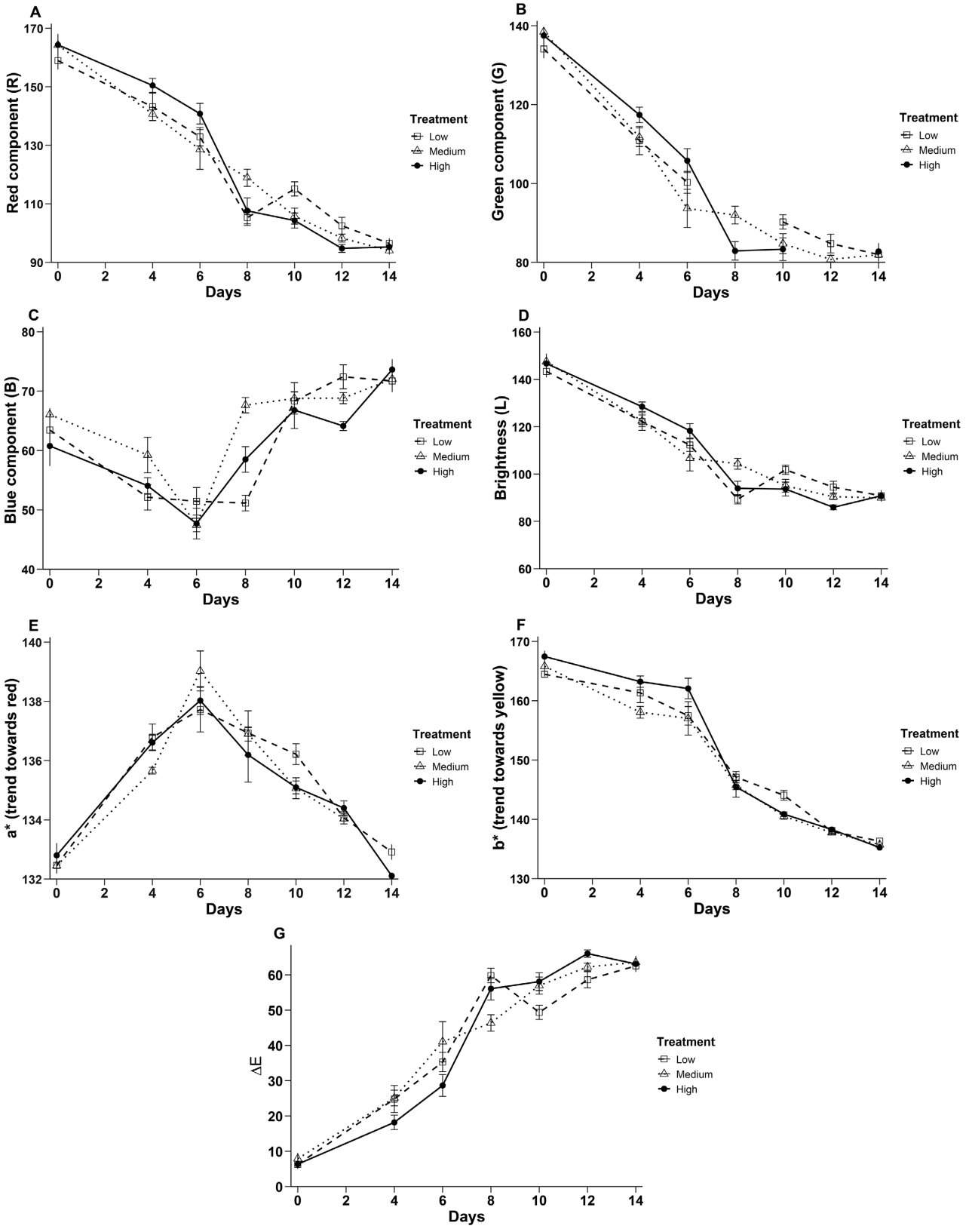


Figure 6. Evolution of colorimetric parameters during the experimental period under different levels of light: Red component (A), Green component (B), Blue component (C), Brightness L (D), a (E), b (F), and ΔE (G). The curves represent variations over 14 days under the light treatments (Low, Medium, High), with standard deviations indicated.

Table 7. Estimated marginal means of colorimetric parameters during banana ripening under different light luminance levels. Values are estimated marginal means ± standard errors (EMM ± SE). Different lowercase letters within the same storage day indicate significant differences among luminance treatments based on multiplicity-adjusted pairwise comparisons ($P < 0.05$). The P and F-values correspond to the luminance × storage time interaction from the linear mixed-effects model. $P < 0.05$ was considered statistically significant, whereas $0.05 \leq P < 0.10$ indicated a marginal trend.

Parameter	Day	Low	Medium	High	P (L × T)	*F* (L × T)
R	0	158.9311 ± 3.9853^{a}	164.2342 ± 3.9853^{a}	164.3391 ± 3.9853^{a}	**0.0029**	**2.8603**
	4	143.1563 ± 3.9853^{a}	140.7074 ± 3.9853^{a}	150.4590 ± 3.9853^{a}		
	6	132.9057 ± 3.9853^{a}	128.5954 ± 3.9853^{a}	140.8076 ± 3.9853^{a}		
	8	105.2622 ± 3.9853^{a}	118.9075 ± 3.9853^{a}	107.5941 ± 3.9853^{a}		
	10	115.0939 ± 3.9853^{a}	104.2460 ± 4.3379^{a}	104.2817 ± 3.9853^{a}		
	12	102.4977 ± 3.9853^{a}	98.2902 ± 3.9853^{a}	94.7438 ± 3.9853^{a}		
	14	96.4507 ± 3.9853^{a}	94.0210 ± 3.9853^{a}	95.2712 ± 3.9853^{a}		
G	0	134.1039 ± 3.0865^{a}	138.4655 ± 3.0865^{a}	137.5079 ± 3.0865^{a}	**<0.001**	**3.4666**
	4	110.8831 ± 3.0865^{a}	111.7492 ± 3.0865^{a}	117.4015 ± 3.0865^{a}		
	6	100.3013 ± 3.0865^{a}	93.6868 ± 3.0865^{a}	105.7924 ± 3.0865^{a}		
	8	78.7135 ± 3.0865^{a}	91.9854 ± 3.0865^{b}	82.9067 ± 3.0865^{ab}		
	10	90.2513 ± 3.0865^{a}	83.7610 ± 3.3618^{a}	83.3229 ± 3.0865^{a}		
	12	84.7686 ± 3.0865^{a}	80.7529 ± 3.0865^{a}	76.5466 ± 3.0865^{a}		
	14	81.9824 ± 3.0865^{a}	81.9463 ± 3.0865^{a}	82.7838 ± 3.0865^{a}		
B	0	63.4427 ± 2.4846^{a}	66.0628 ± 2.4846^{a}	60.7649 ± 2.4846^{a}	**0.0057**	**2.6359**
	4	52.1229 ± 2.4846^{a}	59.2361 ± 2.4846^{a}	54.0674 ± 2.4846^{a}		
	6	51.4484 ± 2.4846^{a}	47.4592 ± 2.4846^{a}	47.7002 ± 2.4846^{a}		
	8	51.1529 ± 2.4846^{a}	67.6358 ± 2.4846^{b}	58.4976 ± 2.4846^{a}		
	10	68.3301 ± 2.4846^{a}	68.8713 ± 2.7689^{a}	66.8012 ± 2.4846^{a}		
	12	72.4176 ± 2.4846^{a}	68.8259 ± 2.4846^{a}	64.1331 ± 2.4846^{a}		
	14	71.7096 ± 2.4846^{a}	72.0241 ± 2.4846^{a}	73.6252 ± 2.4846^{a}		
*L**	0	143.3595 ± 3.3138^{a}	147.5437 ± 3.3138^{a}	146.6716 ± 3.3138^{a}	**<0.001**	**3.3958**
	4	122.1967 ± 3.3138^{a}	122.4839 ± 3.3138^{a}	128.4591 ± 3.3138^{a}		
	6	112.2329 ± 3.3138^{a}	106.7075 ± 3.3138^{a}	118.2869 ± 3.3138^{a}		
	8	89.3173 ± 3.3138^{a}	104.3563 ± 3.3138^{b}	93.9339 ± 3.3138^{ab}		
	10	101.7992 ± 3.3138^{a}	93.9221 ± 3.6106^{a}	93.6511 ± 3.3138^{a}		
	12	94.4332 ± 3.3138^{a}	90.3904 ± 3.3138^{a}	85.9209 ± 3.3138^{a}		
	14	90.8304 ± 3.3138^{a}	89.9478 ± 3.3138^{a}	90.7888 ± 3.3138^{a}		

Continued

	0	164.4566 ± 1.4120[a]	165.8070 ± 1.4120[a]	167.4537 ± 1.4120[a]	**0.4647**	**0.9926**
	4	161.3187 ± 1.4120[a]	158.0549 ± 1.4120[a]	163.2166 ± 1.4120[a]		
	6	157.4612 ± 1.4120[a]	157.0165 ± 1.4120[a]	162.0552 ± 1.4120[a]		
a^*	8	147.1147 ± 1.4120[a]	145.7662 ± 1.4120[a]	145.4650 ± 1.4120[a]		
	10	144.0523 ± 1.4120[a]	140.1852 ± 1.5630[a]	140.8795 ± 1.4120[a]		
	12	137.9725 ± 1.4120[a]	137.7613 ± 1.4120[a]	138.2817 ± 1.4120[a]		
	14	136.3158 ± 1.4120[a]	135.7146 ± 1.4120[a]	135.2457 ± 1.4120[a]		
	0	132.4625 ± 0.5339[a]	132.4509 ± 0.5339[a]	132.8003 ± 0.5339[a]	**0.1197**	**1.5723**
	4	136.7865 ± 0.5339[a]	135.6586 ± 0.5339[a]	136.6071 ± 0.5339[a]		
	6	137.7218 ± 0.5339[a]	139.0254 ± 0.5339[a]	138.0283 ± 0.5339[a]		
b^*	8	136.9299 ± 0.5339[a]	136.8964 ± 0.5339[a]	136.1930 ± 0.5339[a]		
	10	136.2168 ± 0.5339[a]	135.0262 ± 0.5963[a]	135.0957 ± 0.5339[a]		
	12	134.0683 ± 0.5339[a]	134.0396 ± 0.5339[a]	134.3975 ± 0.5339[a]		
	14	132.9140 ± 0.5339[a]	131.8951 ± 0.5339[a]	132.1091 ± 0.5339[a]		
	0	6.2955 ± 3.1078[a]	7.8984 ± 3.1078[a]	6.3330 ± 3.1078[a]	**0.0016**	**3.0626**
	4	24.8088 ± 3.1078[a]	25.1177 ± 3.1078[a]	18.1835 ± 3.1078[a]		
	6	35.2686 ± 3.1078[ab]	41.0464 ± 3.1078[a]	28.6443 ± 3.1078[b]		
ΔE	8	59.7937 ± 3.1078[a]	46.3641 ± 3.1078[b]	56.0669 ± 3.1078[ab]		
	10	49.3602 ± 3.1078[a]	57.7147 ± 3.4256[a]	58.0779 ± 3.1078[a]		
	12	58.5962 ± 3.1078[a]	62.2292 ± 3.1078[a]	66.0304 ± 3.1078[a]		
	14	62.5300 ± 3.1078[a]	63.5487 ± 3.1078[a]	63.0796 ± 3.1078[a]		

3.3. Changes in Fruit Weight and Weight Loss during Storage

Fruit weight decreased progressively throughout the 14-day storage period under all three luminance levels (Table 8, Figures 7(A)-(C)). At day 0, the estimated marginal mean fruit mass was 220.75 ± 9.87 g under low luminance, 223.16 ± 9.87 g under medium luminance, and 206.66 ± 9.87 g under high luminance. By day 14, these values had decreased to 140.69 ± 9.87 g, 146.57 ± 9.87 g, and 130.75 ± 9.87 g, respectively. Despite these numerical differences, the luminance × storage-time interaction was not significant (P = 0.9975, F = 0.2112), and no significant differences among luminance treatments were detected at any storage day. Thus, the progressive decline in fruit weight occurred similarly under the three luminance conditions.

A comparable pattern was observed for absolute weight loss, which increased progressively throughout storage. At day 14, cumulative weight loss reached 80.06 ± 3.17 g under low luminance, 76.58 ± 3.17 g under medium luminance, and 75.91 ± 3.17 g under high luminance. As expected from its direct mathematical relation-

ship with fruit weight, absolute weight loss showed the same luminance × storage-time statistics (P = 0.9975, $F = 0.2112$). This absence of a significant interaction indicates that luminance intensity did not significantly modify the temporal pattern of absolute weight loss.

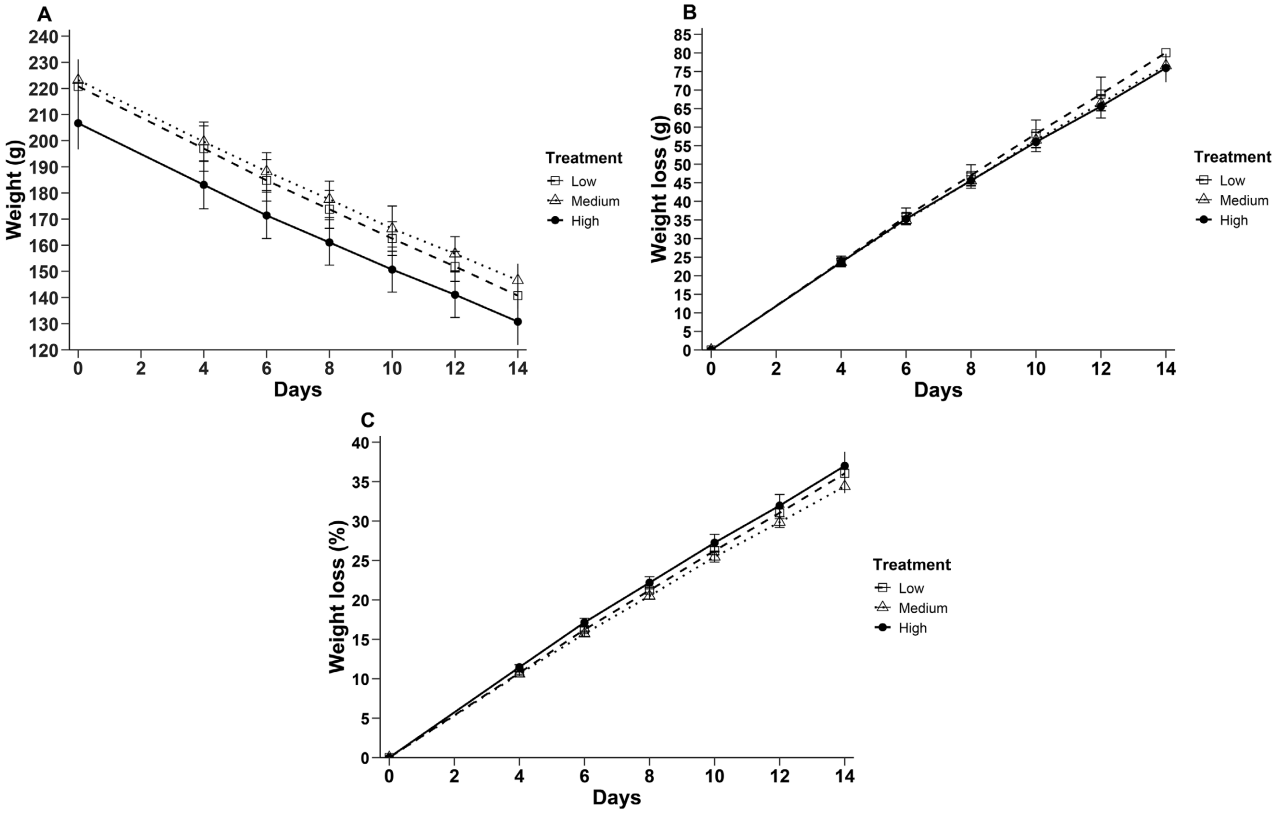


Figure 7. Evolution of weight and weight loss of bananas during ripening under different levels of light luminance: gross weight (A), absolute weight loss (B), relative weight loss (%) (C). The curves illustrate the trends over 14 days according to the light treatments applied (low, medium, high), with indication of standard deviations.

Table 8. Estimated marginal means of Weight parameters during banana ripening under different light luminance levels. Values are estimated marginal means ± standard errors (EMM ± SE). Different lowercase letters within the same storage day indicate significant differences among luminance treatments based on multiplicity-adjusted pairwise comparisons (P < 0.05). The P and F-values correspond to the luminance × storage time interaction from the linear mixed-effects model. P < 0.05 was considered statistically significant, whereas 0.05 ≤ P < 0.10 indicated a marginal trend.

Parameter	Day	Low	Medium	High	P (L × T)	F (L × T)
Weight (g)	0	220.7508 ± 9.8705[a]	223.1582 ± 9.8705[a]	206.6582 ± 9.8705[a]	**0.9975**	**0.2112**
	4	196.9564 ± 9.8705[a]	199.5728 ± 9.8705[a]	183.0724 ± 9.8705[a]		
	6	184.7920 ± 9.8705[a]	188.1998 ± 9.8705[a]	171.3876 ± 9.8705[a]		
	8	173.7370 ± 9.8705[a]	177.5678 ± 9.8705[a]	161.0572 ± 9.8705[a]		
	10	162.5370 ± 9.8705[a]	166.7159 ± 9.9193[a]	150.6676 ± 9.8705[a]		
	12	151.8518 ± 9.8705[a]	156.7144 ± 9.8705[a]	141.0548 ± 9.8705[a]		
	14	140.6894 ± 9.8705[a]	146.5734 ± 9.8705[a]	130.7466 ± 9.8705[a]		

Continued

Weight loss (g)	0	0.0000 ± 3.1746[a]	0.0000 ± 3.1746[a]	0.0000 ± 3.1746[a]	**0.9975**	**0.2112**
	4	23.7944 ± 3.1746[a]	23.5854 ± 3.1746[a]	23.5858 ± 3.1746[a]		
	6	35.9588 ± 3.1746[a]	34.9584 ± 3.1746[a]	35.2706 ± 3.1746[a]		
	8	47.0138 ± 3.1746[a]	45.5904 ± 3.1746[a]	45.6010 ± 3.1746[a]		
	10	58.2138 ± 3.1746[a]	56.4468 ± 3.3216[a]	55.9906 ± 3.1746[a]		
	12	68.8990 ± 3.1746[a]	66.4438 ± 3.1746[a]	65.6034 ± 3.1746[a]		
	14	80.0614 ± 3.1746[a]	76.5848 ± 3.1746[a]	75.9116 ± 3.1746[a]		
Weight loss (%)	0	0.0000 ± 0.9112[a]	0.0000 ± 0.9112[a]	0.0000 ± 0.9112[a]	**0.8477**	**0.5844**
	4	10.7381 ± 0.9112[a]	10.6039 ± 0.9112[a]	11.4543 ± 0.9112[a]		
	6	16.2228 ± 0.9112[a]	15.7050 ± 0.9112[a]	17.1415 ± 0.9112[a]		
	8	21.2093 ± 0.9112[a]	20.4814 ± 0.9112[a]	22.1750 ± 0.9112[a]		
	10	26.2443 ± 0.9112[a]	25.3771 ± 0.9635[a]	27.2517 ± 0.9112[a]		
	12	31.0394 ± 0.9112[a]	29.8568 ± 0.9112[a]	31.9573 ± 0.9112[a]		
	14	36.0454 ± 0.9112[a]	34.3995 ± 0.9112[a]	37.0025 ± 0.9112[a]		

When expressed relative to initial fruit weight, cumulative weight loss reached 36.05 ± 0.91%, 34.40 ± 0.91%, and 37.00 ± 0.91% under low, medium, and high luminance, respectively, after 14 days. Although the high-luminance treatment exhibited the numerically greatest relative weight loss, followed by low and medium luminance, the luminance × storage-time interaction remained non-significant (P = 0.8477, $F = 0.5844$). Therefore, these numerical differences should not be interpreted as evidence that high luminance accelerated mass loss.

The progressive loss of weight observed across all treatments is consistent with the physiological processes associated with postharvest storage, particularly water loss through transpiration and continued metabolic activity. However, the magnitude of weight loss observed in the present experiment was relatively high compared with values reported under other banana storage conditions. Elbagoury *et al*. (2022) [55] reported cumulative weight losses of approximately 19.37% - 20.03% after 20 days in "Grand Nain" bananas stored under controlled conditions, whereas Aruwajoye *et al*. (2024) [56] reported a maximum weight loss of 17.95% after 12 days at 25˚C in untreated bananas. In the present study, relative weight loss reached 34.40% - 37.00% after only 14 days. This greater magnitude may reflect differences in experimental conditions, including moisture availability, environmental exposure, cultivar characteristics, and the absence of protective postharvest coatings or packaging in the present experimental system.

Overall, the absence of a significant luminance × storage-time interaction, together with the similar temporal trends observed among treatments, indicates that weight loss was predominantly governed by intrinsic postharvest physiological

processes rather than by luminance intensity. The relatively high cumulative loss compared with values reported under coated or more humidity-controlled conditions also highlights the importance of water-vapor management in maintaining banana quality during storage. These findings suggest that, under the conditions tested, modifying luminance intensity alone was insufficient to substantially alter the water-loss dynamics of the fruit.

3.4. Relationships between Spectral Indices, Pigments and Color Parameters

Correlation matrices calculated separately for each luminance level are presented in **Figures 8(A)-(C)**. Overall, the correlation structures showed similar patterns across the three luminance treatments, although differences in correlation strength were observed for some variable pairs. Such clustering of spectral indices is expected because indices derived from similar spectral features tend to respond to common biochemical and optical changes during postharvest ripening [29].

Under low luminance (**Figure 8(A)**), fruit weight showed strong negative correlations with both absolute and relative weight loss, while the two weight-loss parameters were strongly positively correlated. This pattern is expected because the progressive loss of water and dry matter is directly reflected in the decrease in fruit weight. Among the pigment-related variables, carotenoid-related indices, including CRI1, CRI2, ARI1, ARI2, and SIPI, generally exhibited moderate to strong positive correlations with one another, indicating a similar response to changes in carotenoid-related optical properties during ripening. Likewise, chlorophyll-related indices, including TCARI, Chl-a, Chl-b, and the Chl-Index, formed a distinct group characterized by strong positive correlations. In contrast, chlorophyll-related indices generally showed negative associations with several carotenoid-related indices, reflecting the opposite trends commonly associated with chlorophyll degradation and carotenoid accumulation during banana ripening [57]. The color parameters also showed relationships with several pigment indices, indicating that changes in surface color occurred concurrently with changes in pigment-related spectral responses.

Under medium luminance (**Figure 8(B)**), the overall correlation structure remained comparable to that observed under low luminance. Strong associations persisted among weight-related variables, while chlorophyll- and carotenoid-related indices continued to form relatively distinct correlation clusters. Some relationships between pigment indices and color parameters (R, G, B, L^*, a^*, and b^*) appeared stronger under medium luminance than under low luminance. This closer association may indicate a greater correspondence between pigment-related spectral responses and visible color changes under moderate illumination. However, these correlations should be interpreted as associations between variables evolving simultaneously during ripening rather than as evidence of a direct causal effect of luminance on pigment accumulation or degradation. The observed relationships are therefore more appropriately considered as reflecting the con-

current evolution of biochemical and optical properties during postharvest maturation.

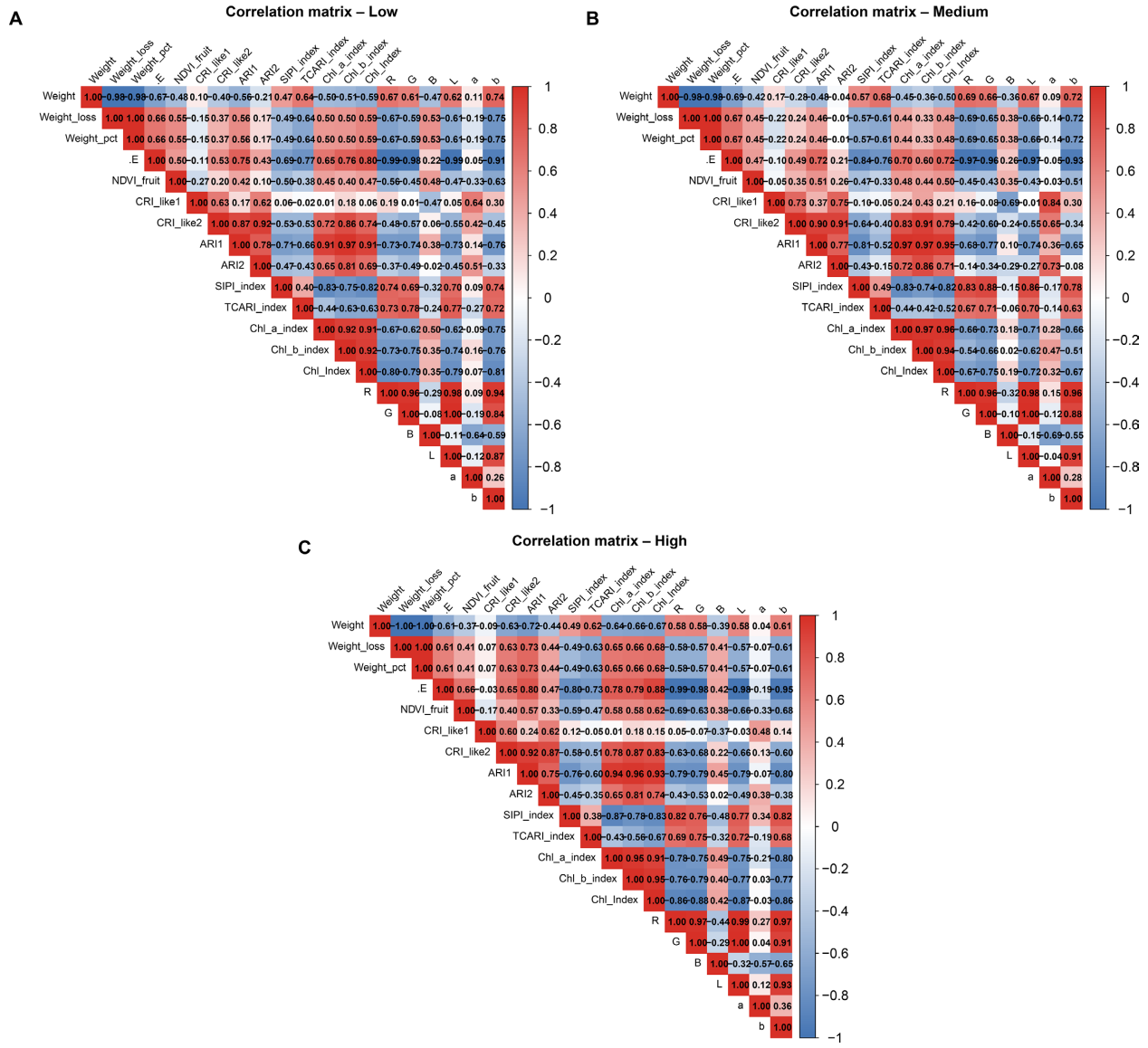


Figure 8. Correlation matrices showing the relationships between spectral, pigment-related, colorimetric, and physiological variables measured during banana ripening under three LED luminance levels: (A) low, (B) medium, and (C) high. Pearson correlation coefficients illustrate the relationships between spectral indices, chlorophyll parameters (Chl a, Chl b, Chl tot), carotenoids (*α*, *β*, *γ*, total), colorimetric components (L*, a*, b*, R, G, B), fruit mass, and overall colorimetric variation (ΔE). Colors indicate the strength and direction of correlations (positive correlations in red and negative correlations in blue).

Under high luminance (Figure 8(C)), the global correlation structure was also preserved. Fruit weight remained strongly and negatively associated with both weight-loss parameters, whereas the carotenoid- and chlorophyll-related indices maintained their respective correlation clusters. Moderate to strong associations were also observed between several pigment indices and colorimetric parameters, indicating the concurrent evolution of biochemical and visual characteristics dur-

ing ripening. Nevertheless, the similarity of the overall correlation patterns across luminance treatments suggests that the main relationships among weight, pigment indices, and color parameters were relatively stable despite differences in luminance level.

Overall, the correlation analysis revealed three main functional groups of variables: weight and weight-loss parameters, pigment-related spectral indices, and colorimetric parameters. The strong associations within the chlorophyll- and carotenoid-related indices confirm that indices targeting similar pigment characteristics provide coherent information on pigment dynamics. Meanwhile, the relationships between pigment indices and RGB/CIELAB parameters demonstrate that spectral and colorimetric measurements capture complementary aspects of the ripening process. Importantly, the consistency of the correlation structure across luminance treatments suggests that these relationships primarily reflect the underlying physiological progression of ripening rather than a treatment-specific effect of luminance. From an applied perspective, the observed associations also support the potential use of simple RGB/CIELAB measurements as complementary, low-cost indicators for monitoring postharvest changes alongside spectroscopic measurements.

The correlation patterns observed under higher luminance levels were comparable to those observed under lower luminance levels, suggesting that luminance primarily modulates the strength rather than the nature of these associations. Similar observations have been reported in studies investigating light-induced modulation of pigment dynamics and color development [46] [56].

Overall, the correlation analysis confirms that spectral indices cluster according to their biochemical pathways, with carotenoid-related indices strongly intercorrelated and chlorophyll indices forming a distinct, tightly linked group. Negative associations between chlorophyll and carotenoid indices reflect the coordinated biochemical transition occurring during ripening. While luminance intensity slightly influences the strength of correlations particularly between pigment indices and colorimetric parameters the overall structure remains stable across treatments. These findings highlight the robustness of spectral indices as reliable, non-destructive indicators of postharvest ripening dynamics.

3.5. Strengths, Limitations and Perspectives

A major strength of this study lies in the integration of spectral, colorimetric, physiological, and statistical analyses to provide a multidimensional assessment of banana ripening under different luminance levels. In particular, the consistent relationships observed between pigment-related spectral indices and conventional RGB/CIELAB color parameters provide an internal cross-validation of the optical measurements and support the reliability of the observed ripening patterns. The combination of complementary indicators therefore provides a more comprehensive interpretation of postharvest changes than would be possible from a single measurement approach. This multidimensional framework

is consistent with recent developments in postharvest monitoring, where the integration of spectral and visual measurements can improve the assessment of fruit maturity and quality [29].

Despite these strengths, several limitations should be acknowledged. First, the experiment investigated luminance intensity while maintaining a single spectral composition of the LED source. Consequently, the present results cannot distinguish the effects of luminance from those associated with wavelength distribution. Light quality is known to influence pigment metabolism and gene expression [24] [58], and previous studies have shown that different LED spectra, including red, blue, and combined light, can differentially affect pigment metabolism, ripening kinetics, and fruit quality [44] [57]. Second, the pigment-related spectral indices used in this study provide indirect estimates of pigment dynamics and were not complemented by direct biochemical quantification of chlorophyll and carotenoid concentrations. Biochemical measurements would therefore be valuable for further validating the relationships observed between spectral indices and pigment evolution. Third, the experiment was conducted using a single banana type, which limits the extent to which the findings can be generalized to other cultivars or banana genotypes with different physiological and pigment characteristics. Finally, environmental conditions, particularly relative humidity, were not independently controlled as experimental factors. This may be relevant because humidity, together with temperature and fruit physiological activity, can influence water loss and therefore weight loss during storage.

These limitations do not undermine the main findings but rather define the scope within which they should be interpreted. In particular, the results demonstrate the response of banana fruit to different luminance intensities under the specific spectral and environmental conditions used in this experiment. The observed correlations should therefore be interpreted as associations between simultaneously evolving variables rather than as evidence of direct causal effects of luminance on pigment accumulation, degradation, or weight loss.

Building on the strengths and limitations identified above, future research should investigate the combined effects of spectral composition and luminance intensity, including monochromatic and mixed LED spectra. Direct biochemical measurements of chlorophyll and carotenoids should also be incorporated to validate the spectral indices and strengthen their physiological interpretation. Further experiments should include different banana cultivars and a larger range of environmental conditions, particularly controlled temperature and relative humidity, to determine whether the response to light is consistent across genotypes and storage environments. Such a combined approach could contribute to the development of optimized, fruit-specific postharvest lighting protocols designed to maintain quality, extend shelf life, and reduce postharvest losses in tropical fruit supply chains.

4. Conclusions

This study aimed to evaluate whether different light luminance levels could mod-

ulate the postharvest ripening dynamics of banana fruit using spectral, colorimetric, and physiological measurements. The results demonstrate that light luminance can influence the temporal dynamics of ripening-related optical changes, while the overall progression of ripening remained largely governed by the intrinsic physiology of the fruit. Across all treatments, spectral reflectance, pigment-related spectral indices, colorimetric parameters, and fruit weight exhibited temporal patterns consistent with climacteric ripening. The coordinated changes in chlorophyll- and carotenoid-related indices further indicate that spectral measurements can effectively track optical changes associated with pigment transitions during ripening, although these indices should be considered indirect proxies rather than direct measurements of pigment concentration.

The influence of luminance was most apparent during the intermediate stages of storage. Higher luminance was generally associated with earlier changes in pigment-related spectral responses and color parameters, whereas lower luminance tended to maintain green-related optical characteristics for longer. However, the convergence of most parameters at later stages indicates that luminance primarily affected the timing of ripening-related optical changes rather than the final ripening trajectory. These findings therefore support the interpretation of luminance as a potential modulator of ripening kinetics rather than as a factor determining the final developmental outcome.

In contrast, fruit weight declined progressively under all treatments, with relative weight loss reaching approximately 34% - 37% after 14 days, but without a significant luminance × time interaction. This indicates that, under the experimental conditions, luminance alone did not measurably modify the temporal progression of fruit weight loss. Correlation analysis further revealed coherent associations among spectral indices, pigment-related variables, and colorimetric parameters, supporting their complementary use for non-destructive monitoring of ripening. These correlations should nevertheless be interpreted as associations between simultaneously evolving variables rather than as evidence of direct causal relationships between luminance and pigment accumulation or degradation.

Overall, the integration of spectral indices, colorimetric parameters, and physiological measurements provides a useful non-destructive framework for monitoring banana maturity and quality during storage. The observed effects of luminance were transient and parameter-dependent, highlighting the importance of considering both light intensity and storage time when evaluating light-based postharvest strategies. The present findings should be interpreted within the experimental scope of the study, particularly the use of a single spectral composition and banana type and the absence of direct biochemical validation of pigment-related indices. Future studies should therefore investigate wavelength-specific and combined spectral effects, dynamic lighting regimes, and interactions with temperature and relative humidity, together with direct biochemical measurements, to develop more precise light-based strategies for postharvest management of tropical fruits.

Highlights

- Integrated spectral, colorimetric, and physiological data enable non-destructive monitoring of banana ripening
- Pigment-related spectral indices capture changes associated with chlorophyll and carotenoid dynamics
- Light luminance modulates ripening kinetics without substantially altering the final ripening trajectory
- Weight loss reached approximately 34% - 37% after 14 days across luminance treatments
- Moderate to strong correlations link spectral indices, pigment-related variables, and colorimetric parameters.

Acknowledgements

The author gratefully acknowledges the Agence Universitaire de la Francophonie (AUF) for financial support through the Eugène Ionesco Mobility Fellowship, which enabled a research stay in Romania and facilitated the experimental work and collaboration with the host institution. The author from INFLPR would like to acknowledge the support of National Interest Infrastructure facility IOSIN - CETAL at INFLPR and from the Ministry of Scientific Research, Innovation; Digitalization Nucleu Programme-LAPLAS VII, No. 30 N/2023.

Data Availability

Data will be made available on request.

Declaration on the Use of AI

We, the authors of this article, declare that artificial intelligence was used solely for grammar correction and text formatting tasks. No scientific content, data, or interpretation was generated or modified by AI. All analyses, results, and discussions presented in this manuscript are entirely the work of the authors.

Author Contributions

Arouna Khalil Fanny: conceptualization, data curation, writing—original draft, writing—review & editing, formal analysis, investigation, methodology, software, visualization, resources. Laura Mihai: supervision, methodology, formal analysis, visualisation, project administration, writing—review & editing, resources. Banah Florent Degni: conceptualization, methodology, project administration, writing—review & editing, supervision, validation. Yao Hervé Yao: methodology, formal analysis, software. Labile Lamah: methodology, writing—review & editing. Cissé Théodore Haba: conceptualization, project administration, writing—review & editing, supervision, validation, resources.

Conflicts of Interest

The authors declare that they have no known competing financial interests or per-

sonal relationships that could have influenced the work reported in this paper.

References

[1] Seymour, G.B., Taylor, J.E. and Tucker, G.A. (1993) Biochemistry of Fruit Ripening. Springer.

[2] Cho, B. and Koseki, S. (2021) Determination of Banana Quality Indices during the Ripening Process at Different Temperatures Using Smartphone Images and an Artificial Neural Network. *Scientia Horticulturae*, **288**, Article ID: 110382. https://doi.org/10.1016/j.scienta.2021.110382

[3] Al-Dairi, M., Pathare, P.B., Al-Yahyai, R., Jayasuriya, H. and Al-Attabi, Z. (2023) Postharvest Quality, Technologies, and Strategies to Reduce Losses along the Supply Chain of Banana: A Review. *Trends in Food Science & Technology*, **134**, 177-191. https://doi.org/10.1016/j.tifs.2023.03.003

[4] Merzlyak, M.N., Gitelson, A.A., Chivkunova, O.B. and Rakitin, V.Y. (1999) Non-Destructive Optical Detection of Pigment Changes during Leaf Senescence and Fruit Ripening. *Physiologia Plantarum*, **106**, 135-141. https://doi.org/10.1034/j.1399-3054.1999.106119.x

[5] Lichtenthaler, H.K., Buschmann, C. and Knapp, M. (2005) How to Correctly Determine the Different Chlorophyll Fluorescence Parameters and the Chlorophyll Fluorescence Decrease Ratio R_{Fd} of Leaves with the PAM Fluorometer. *Photosynthetica*, **43**, 379-393. https://doi.org/10.1007/s11099-005-0062-6

[6] Hörtensteiner, S. (2006) Chlorophyll Degradation during Senescence. *Annual Review of Plant Biology*, **57**, 55-77. https://doi.org/10.1146/annurev.arplant.57.032905.105212

[7] Zhu, X., Chen, J., Qiu, K. and Kuai, B. (2017) Phytohormone and Light Regulation of Chlorophyll Degradation. *Frontiers in Plant Science*, **8**, Article 1911. https://doi.org/10.3389/fpls.2017.01911

[8] Nisar, N., Li, L., Lu, S., Khin, N. and Pogson, B. (2015) Carotenoid Metabolism in Plants. *Molecular Plant*, **8**, 68-82. https://doi.org/10.1016/j.molp.2014.12.007

[9] Sun, T., Tadmor, Y. and Li, L. (2020) Pathways for Carotenoid Biosynthesis, Degradation, and Storage. In: Rodríguez-Concepción, M. and Welsch, R., Eds., *Plant and Food Carotenoids*, Springer, 3-23. https://doi.org/10.1007/978-1-4939-9952-1_1

[10] Gitelson, A.A., Gritz, Y. and Merzlyak, M.N. (2003) Relationships between Leaf Chlorophyll Content and Spectral Reflectance and Algorithms for Non-Destructive Chlorophyll Assessment in Higher Plant Leaves. *Journal of Plant Physiology*, **160**, 271-282. https://doi.org/10.1078/0176-1617-00887

[11] Richardson, A.D., Duigan, S.P. and Berlyn, G.P. (2002) An Evaluation of Noninvasive Methods to Estimate Foliar Chlorophyll Content. *New Phytologist*, **153**, 185-194. https://doi.org/10.1046/j.0028-646x.2001.00289.x

[12] Haboudane, D., Miller, J.R., Tremblay, N., Zarco-Tejada, P.J. and Dextraze, L. (2002) Integrated Narrow-Band Vegetation Indices for Prediction of Crop Chlorophyll Content for Application to Precision Agriculture. *Remote Sensing of Environment*, **81**, 416-426. https://doi.org/10.1016/s0034-4257(02)00018-4

[13] Gitelson, A.A., Zur, Y., Chivkunova, O.B. and Merzlyak, M.N. (2002) Assessing Carotenoid Content in Plant Leaves with Reflectance Spectroscopy. *Photochemistry and Photobiology*, **75**, 272-281. https://doi.org/10.1562/0031-8655(2002)075<0272:accipl>2.0.co;2

[14] Penuelas, J., Frederic, B. and Filella, I. (1995) Semi-Empirical Indices to Assess Ca-

rotenoids/Chlorophyll—A Ratio from Leaf Spectral Reflectance. *Photosynthetica*, **31**, 221-230.

[15] McLaren, K. (1976) XIII—The Development of the CIE 1976 (L* A* B*) Uniform Colour Space and Colour-Difference Formula. *Journal of the Society of Dyers and Colourists*, **92**, 338-341. https://doi.org/10.1111/j.1478-4408.1976.tb03301.x

[16] Acharya, U.K., Subedi, P.P., Walsh, K.B. and McGlasson, W.B. (2016) Estimation of Fruit Maturation and Ripening Using Spectral Indices. *Acta Horticulturae*, No. 1119, 265-272. https://doi.org/10.17660/actahortic.2016.1119.37

[17] El-Ramady, H.R., Domokos-Szabolcsy, É., Abdalla, N.A., Taha, H.S. and Fári, M. (2015) Postharvest Management of Fruits and Vegetables Storage. In: Lichtfouse, E., Ed., *Sustainable Agriculture Reviews*, Springer, 65-152. https://doi.org/10.1007/978-3-319-09132-7_2

[18] Kassab, N.A., El-Bahnasawy, A.H. and Fouda, T.Z. (2025) Effect of Environmental Conditions on Banana Ripening Models to Sustaining Optimal Ripening and Product Quality. *Journal of Sustainable Agricultural and Environmental Sciences*, **4**, 25-32. https://doi.org/10.21608/jsaes.2025.348123.1122

[19] Llorente, B., Martinez-Garcia, J.F., Stange, C. and Rodriguez-Concepcion, M. (2017) Illuminating Colors: Regulation of Carotenoid Biosynthesis and Accumulation by Light. *Current Opinion in Plant Biology*, **37**, 49-55. https://doi.org/10.1016/j.pbi.2017.03.011

[20] Do, V.G., Lee, Y., Kweon, H. and Kim, S. (2022) Light Induces Carotenoid Biosynthesis-Related Gene Expression, Accumulation of Pigment Content, and Expression of the Small Heat Shock Protein in Apple Fruit. *International Journal of Molecular Sciences*, **23**, Article 6153. https://doi.org/10.3390/ijms23116153

[21] Massa, G.D., Kim, H., Wheeler, R.M. and Mitchell, C.A. (2008) Plant Productivity in Response to LED Lighting. *HortScience*, **43**, 1951-1956. https://doi.org/10.21273/hortsci.43.7.1951

[22] Bantis, F., Smirnakou, S., Ouzounis, T., Koukounaras, A., Ntagkas, N. and Radoglou, K. (2018) Current Status and Recent Achievements in the Field of Horticulture with the Use of Light-Emitting Diodes (LEDs). *Scientia Horticulturae*, **235**, 437-451. https://doi.org/10.1016/j.scienta.2018.02.058

[23] Ma, G., Zhang, L., Setiawan, C.K., Yamawaki, K., Asai, T., Nishikawa, F., *et al*. (2014) Effect of Red and Blue LED Light Irradiation on Ascorbate Content and Expression of Genes Related to Ascorbate Metabolism in Postharvest Broccoli. *Postharvest Biology and Technology*, **94**, 97-103. https://doi.org/10.1016/j.postharvbio.2014.03.010

[24] Frede, K., Winkelmann, S., Busse, L. and Baldermann, S. (2023) The Effect of LED Light Quality on the Carotenoid Metabolism and Related Gene Expression in the Genus Brassica. *BMC Plant Biology*, **23**, Article No. 328. https://doi.org/10.1186/s12870-023-04326-4

[25] Özdemir, İ.S. (2016) Effect of Light Treatment on the Ripening of Banana Fruit during Postharvest Handling. *Fruits*, **71**, 115-122. https://doi.org/10.1051/fruits/2015052

[26] Zhou, X., Cheng, J., Sun, J., Guo, S., Guo, X., Chen, Q., *et al*. (2023) Effect of Red Visible Lighting on Postharvest Ripening of Bananas via the Regulation of Energy Metabolism. *Horticulturae*, **9**, Article 840. https://doi.org/10.3390/horticulturae9070840

[27] Bantayehu, M. and Alemayehu, M. (2024) Stability of Fruit Ripening Traits of Banana (*Musa Species*) across Postharvest Environments. *Heliyon*, **10**, e37143. https://doi.org/10.1016/j.heliyon.2024.e37143

[28] Ringer, T. and Blanke, M. (2021) Non-Invasive, Real Time *In-Situ* Techniques to Determine the Ripening Stage of Banana. *Journal of Food Measurement and Characterization*, **15**, 4426-4437. https://doi.org/10.1007/s11694-021-01009-2

[29] Galal, H., Elsayed, S., Allam, A. and Farouk, M. (2022) Indirect Quantitative Analysis of Biochemical Parameters in Banana Using Spectral Reflectance Indices Combined with Machine Learning Modeling. *Horticulturae*, **8**, Article 438. https://doi.org/10.3390/horticulturae8050438

[30] Zhang, Y., Butelli, E. and Martin, C. (2014) Engineering Anthocyanin Biosynthesis in Plants. *Current Opinion in Plant Biology*, **19**, 81-90. https://doi.org/10.1016/j.pbi.2014.05.011

[31] Mihai, L., Mac Arthur, A., Hueni, A., Robinson, I. and Sporea, D. (2018) Optimized Spectrometers Characterization Procedure for near Ground Support of ESA FLEX Observations: Part 1 Spectral Calibration and Characterisation. *Remote Sensing*, **10**, Article 289. https://doi.org/10.3390/rs10020289

[32] Ohta, Y., Kanade, T. and Sakai, T. (1980) Color Information for Region Segmentation. *Computer Graphics and Image Processing*, **13**, 222-241. https://doi.org/10.1016/0146-664x(80)90047-7

[33] Goodman, T.M. (2012) International Standards for Colour. In: Best, J., Ed., *Colour Design*, Elsevier, 417-452. https://doi.org/10.1016/b978-0-08-101270-3.00018-7

[34] Sharma, G., Wu, W. and Dalal, E.N. (2005) The CIEDE2000 Color-Difference Formula: Implementation Notes, Supplementary Test Data, and Mathematical Observations. *Color Research & Application*, **30**, 21-30. https://doi.org/10.1002/col.20070

[35] Mirani, B.N., Chattha, S.H., Soomro, S.A., Wagan, B., Dahri, I.A., Khan, Z.A., *et al*. (2022) Effect of Post-Harvest Treatments on Quality Characteristics of Carrots during Storage. *RADS Journal of Biological Research & Applied Sciences*, **13**, 168-174. https://doi.org/10.37962/jbas.v13i2.543

[36] Gitelson, A. and Merzlyak, M.N. (1994) Spectral Reflectance Changes Associated with Autumn Senescence of *Aesculus hippocastanum* L. and *Acer platanoides* L. Leaves. Spectral Features and Relation to Chlorophyll Estimation. *Journal of Plant Physiology*, **143**, 286-292. https://doi.org/10.1016/s0176-1617(11)81633-0

[37] Mänd, P. (2026) 5.2 Chlorophyll and Carotenoid Content—ClimEx Handbook. https://climexhandbook.w.uib.no/2019/11/03/chlorophyll-and-carotenoid-content/

[38] Gitelson, A.A. (2004) Wide Dynamic Range Vegetation Index for Remote Quantification of Biophysical Characteristics of Vegetation. *Journal of Plant Physiology*, **161**, 165-173. https://doi.org/10.1078/0176-1617-01176

[39] Blackburn, G.A. (1998) Spectral Indices for Estimating Photosynthetic Pigment Concentrations: A Test Using Senescent Tree Leaves. *International Journal of Remote Sensing*, **19**, 657-675. https://doi.org/10.1080/014311698215919

[40] Gitelson, A.A., Merzlyak, M.N., Zur, Y., Stark, R. and Gritz, U. (2001) Non-Destructive and Remote Sensing Techniques for Estimation of Vegetation Status.

[41] Merzlyak, M.N., Solovchenko, A.E. and Gitelson, A.A. (2003) Reflectance Spectral Features and Non-Destructive Estimation of Chlorophyll, Carotenoid and Anthocyanin Content in Apple Fruit. *Postharvest Biology and Technology*, **27**, 197-211. https://doi.org/10.1016/S0925-5214(02)00066-2

[42] Searle, S.R., Speed, F.M. and Milliken, G.A. (1980) Population Marginal Means in the Linear Model: An Alternative to Least Squares Means. *The American Statistician*, **34**, 216-221. https://doi.org/10.1080/00031305.1980.10483031

[43] Shapiro, S.S. and Wilk, M.B. (1965) An Analysis of Variance Test for Normality

(Complete Samples). *Biometrika*, **52**, 591-611. https://doi.org/10.2307/2333709

[44] Brown, M.B. and Forsythe, A.B. (1974) Robust Tests for the Equality of Variances. *Journal of the American Statistical Association*, **69**, 364-367. https://doi.org/10.1080/01621459.1974.10482955

[45] Seifert, B., Pflanz, M. and Zude, M. (2014) Spectral Shift as Advanced Index for Fruit Chlorophyll Breakdown. *Food and Bioprocess Technology*, **7**, 2050-2059. https://doi.org/10.1007/s11947-013-1218-1

[46] Huang, J., Xu, F. and Zhou, W. (2018) Effect of LED Irradiation on the Ripening and Nutritional Quality of Postharvest Banana Fruit. *Journal of the Science of Food and Agriculture*, **98**, 5486-5493. https://doi.org/10.1002/jsfa.9093

[47] Tsoulias, N., Saha, K.K. and Zude-Sasse, M. (2023) *In-Situ* Fruit Analysis by Means of LiDAR 3D Point Cloud of Normalized Difference Vegetation Index (NDVI). *Computers and Electronics in Agriculture*, **205**, Article ID: 107611. https://doi.org/10.1016/j.compag.2022.107611

[48] Zhou, X., Huang, W., Zhang, J., Kong, W., Casa, R. and Huang, Y. (2019) A Novel Combined Spectral Index for Estimating the Ratio of Carotenoid to Chlorophyll Content to Monitor Crop Physiological and Phenological Status. *International Journal of Applied Earth Observation and Geoinformation*, **76**, 128-142. https://doi.org/10.1016/j.jag.2018.10.012

[49] Moriya, É.A.S., Imai, N.N., Tommaselli, A.M.G., Honkavaara, E. and Rosalen, D.L. (2023) Design of Vegetation Index for Identifying the Mosaic Virus in Sugarcane Plantation: A Brazilian Case Study. *Agronomy*, **13**, Article 1542. https://doi.org/10.3390/agronomy13061542

[50] Gitelson, A.A., Merzlyak, M.N. and Chivkunova, O.B. (2001) Optical Properties and Nondestructive Estimation of Anthocyanin Content in Plant Leaves. *Photochemistry and Photobiology*, **74**, 38-45. https://doi.org/10.1562/0031-8655(2001)074<0038:opaneo>2.0.co;2

[51] Gitelson, A.A., Chivkunova, O.B. and Merzlyak, M.N. (2009) Nondestructive Estimation of Anthocyanins and Chlorophylls in Anthocyanic Leaves. *American Journal of Botany*, **96**, 1861-1868. https://doi.org/10.3732/ajb.0800395

[52] Anjali, Jena, A., Bamola, A., Mishra, S., Jain, I., Pathak, N., *et al.* (2024) State-of-the-Art Non-Destructive Approaches for Maturity Index Determination in Fruits and Vegetables: Principles, Applications, and Future Directions. *Food Production, Processing and Nutrition*, **6**, Article No. 56. https://doi.org/10.1186/s43014-023-00205-5

[53] Li, B., Lecourt, J. and Bishop, G. (2018) Advances in Non-Destructive Early Assessment of Fruit Ripeness towards Defining Optimal Time of Harvest and Yield Prediction—A Review. *Plants*, **7**, Article 3. https://doi.org/10.3390/plants7010003

[54] Pathare, P.B., Opara, U.L. and Al-Said, F.A. (2012) Colour Measurement and Analysis in Fresh and Processed Foods: A Review. *Food and Bioprocess Technology*, **6**, 36-60. https://doi.org/10.1007/s11947-012-0867-9

[55] Elbagoury, M.M., Turoop, L., Runo, S., Sila, D.N. and Madivoli, E.S. (2022) Postharvest Treatments of Banana (*Musa acuminata* cv. 'Grand Nain', AAA) during Cold and Ripening Temperatures with Chitosan and Chitosan Nanoparticles to Alleviate Chilling Injury and Maintain Antioxidant Activity. *Horticulture, Environment, and Biotechnology*, **63**, 677-699. https://doi.org/10.1007/s13580-022-00436-4

[56] Aruwajoye, N.N., Sanusi, I.A., Aruwajoye, G.S., Mditshwa, A. and Tesfay, S.Z. (2025) Enhancing Postharvest Quality of Bananas: Comparative Study on the Use ZnO and Ag_2O Nanoparticles and ZnO/Ag_2O Composites. *Frontiers in Sustainable Food Systems*, **8**, Article 1480193. https://doi.org/10.3389/fsufs.2024.1480193

[57] Liu, B., Zhang, Y., Ke, Z., Sun, J. and Zhou, X. (2021) Effects of LED Light on the Ripening Regulation of Green Mature Banana during Storage and Transportation. *Transactions of the Chinese Society of Agricultural Engineering*, **37**, 295-302.

[58] Lado, J., Alós, E., Manzi, M., Cronje, P.J.R., Gómez-Cadenas, A., Rodrigo, M.J., *et al*. (2019) Light Regulation of Carotenoid Biosynthesis in the Peel of Mandarin and Sweet Orange Fruits. *Frontiers in Plant Science*, **10**, Article 1288. https://doi.org/10.3389/fpls.2019.01288