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Article

Color Transitions in Tanjung-2 Chili Pepper at Green and Red Harvest Stages under Varying Growing Structures and Fertigation Levels

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Abstract. Fruit color is a primary determinant of market acceptance for chili peppers (*Capsicum annuum* L.). This study quantified the green-to-red color transition at harvest using the CIELAB system. The experiment had a split-plot RCBD. Four growing structures as main plots: greenhouse, screen house, rain shelter, and open field. Four fertigation levels (25, 50, 75, and 100% ETc) as subplots. Color parameters L^*, a^*, b^*, chroma, hue, and ΔE^* were measured at both green and red harvest stages. Interactions between structure and fertigation level were significant for all color parameters. At the green stage, L^* and b^* values were highest in the screenhouse and greenhouse at 75–100% ETc. At the red stage, a^* and chroma increased markedly, while hue decreased rapidly. This indicated accelerated carotenoid accumulation. Maximum ΔE^* was observed in greenhouse and screenhouse with 100% ETc. Screenhouse with 75–100% ETc for the green harvest stage yields higher lightness (L^*) and b^* values. An open field combined with 50% ETc should be recommended for the red harvest phase to achieve higher a^*, chroma, and ΔE^* values, indicating improved red color intensity and visual quality. ΔE^* was observed with 100% ETc, indicating accelerated ripening and a shorter harvest period.

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1. Introduction

Red chili pepper (*Capsicum annuum* L.) is one of the most commonly cultivated horticultural commodities in tropical countries, including Indonesia, due to its high economic value and culinary diversity [1-2]. In addition to the pungency imparted by the bioactive compound capsaicin, fruit color influences consumer appeal [3]. According to BPS-Statistic Indonesia (2025), the production of chili peppers in 2024 reached 1.47 million tons, a decrease of 5.48% (85.17 thousand tons) from 2023. Domestic household consumption in 2024 amounted to 600.42 thousand tons, down 11.05% (74.60 thousand tons) from the previous year[4]. This contraction in both production and consumption highlights the increasing importance of improving fruit quality attributes, particularly color uniformity at harvest, to maintain market acceptance and economic value. Fruit color is a critical quality attribute that influences consumer preference and market value. The bright red color of chili peppers typically indicates high ripeness and excellent quality, whereas the green color usually indicates early development and special uses [5]. Some physiological and biochemical changes occur in the fruit, leading to green-to-red coloration. Unripe fruits have higher chlorophyll content than ripe fruits, resulting in a higher chlorophyll level, which covers other pigments for a green-colored fruit appearance [6].

During ripening, chlorophyll breaks down, and carotenoid pigments, particularly capsanthin and capsorubin, accumulate. This process produces the bright red color [7]. Pigmentation changes are controlled by plastid morphology, gene expression, and enzyme activities within the carotenoid biosynthesis pathway [6]. Measurement of color parameters such as L^*, a^*, b^*, chroma, and hue enables accurate evaluation of fruit ripening dynamics [8]. These two factors that impact fruit color can be directly related to the local environment and cultivation practices [9].

Greenhouses, screen houses, rain shelters, and other structures provide microclimates that influence light intensity, spectral quality, temperature, and humidity. These environmental changes affect photosynthesis and secondary metabolism [10]. Photooxidative stress can be attenuated, and chlorophyll degradation can be retarded in controlled-light environments. As light and heat increase, ripening and pigment concentration accelerate [11]. In tropical areas, they protect plants from extreme environmental influences that influence physiology and yield quality. In chili pepper production, crop development, yield, and fruit quality are influenced by fertilization and irrigation [12].

Optimizing water and nutrient supply through fertigation improves water use, nutrient uptake, and coordination of metabolic events, including pigment synthesis [13]. A water deficit or excessive irrigation disrupts fertigation management, which in turn disrupts assimilate balance and enzyme activity, and consequently carotenoid biosynthesis and pigment accumulation [14]. Environmental and genetic factors influence fruit color and quality in Solanaceae, as previous research has shown. At maturity, chili pepper fruit color intensity is influenced by environmental variables, including photoperiod and light quality, which in turn affect carotenoid and phenolic profiles [15] [16]. Abiotic stresses like salinity have been found to modify chlorophyll content, carotenoid concentrations, and other physicochemical fruit properties during stages of development [17]. Taken together, these results suggest that environmental cues and genetic regulation interact to direct pigment biosynthesis pathways [2].

We hypothesize that reduced fertigation levels will delay red color development (lower a and chroma values) by constraining carotenoid biosynthesis, and that this effect will differ among growing structures due to microclimatic modulation. Therefore, this study aims to quantify color transitions using the CIELAB system under the combined effects of growing structures and fertigation levels at

green and red harvest stages, providing science-based recommendations for optimizing chili fruit color quality in tropical environments.

2. Experimental Section

2.1. Materials

The experiment was done at Bale Tatanen Experimental Farm, Universitas Padjadjaran, Indonesia (6°56′S; 107°46′E; 750 m a.s.l.). Chili peppers (*Capsicum annuum* L.) are grown in diverse contexts using various structures: greenhouses, screen houses, rain shelters, and open fields. So, to put it simply, these are microclimatic environments with distinct zones, with protected and open cultivation systems. The selected cultivar adopted in the study is Tanjung-2, due to its commercial relevance and known sensitivity to environmental variation in fruit color development, making it suitable for evaluating color responses to microclimate and water management. We used uniform-sized transplanted seedlings in all plots, and they were managed according to standard horticultural practices.

2.2. Experimental Design and Treatments

The experiment was set up in a Split-Plot Randomized Complete Block Design that had three parts: growing Structure, fertigation level, and harvest stage. Growing structures formed four cultivation environments. Fertigation levels were set at 25, 50, 75, and 100% of crop evapotranspiration (ETc) using 4 irrigation volumes. For each treatment batch, this was done three times in blocks. Each plot contained three plants, for a total of 144. Fertigation was done using a dual drip irrigation system to obtain both water and nutrients. The irrigation volumes were determined based on evapotranspiration and modified according to the ETc level. Nutrient solutions were provided per the nutritional therapy for chili pepper as suggested. Fertilizers were applied regularly throughout the growing period to keep soils moist and maintain uniform soil moisture across treatments.

2.3. Fertigation and Microclimate Description

Fertigation is applied once a day in the morning using AB mix nutrient solution, consisting of N-148 mg/litre, P-68.5 mg/litre, K-184.5 mg/litre, Ca-180 mg/litre, Mg-58 mg/litre, S-87.2 mg/litre, Fe-2.6 mg/litre. The nutrients have been dissolved in 1000 litres of water. Nutrient solution was applied to the surface of the planting media with a volume dosage based on the evapotranspiration of plants, calculated after 2 weeks of planting, with the following formula:

$$ETc = P + I - R - D - (Wn\text{-}1 - Wn)$$

Description:
ETc: Evapotranspiration (mm)
P: Precipitation (mm)
I: Irrigation/Volume of water applied (mm)
R: Runoff (mm)
D: Drainage/Percolation (mm)
Wn-1: Weight of media on day n-1 (g) Wn: Weight of media on day n (g)

Buildings such as greenhouses, rain shelters, and screenhouses have different temperatures and humidity levels than open land. Temperature and humidity observations in these buildings are carried out automatically every day using a thermorecorder as follows (Table 1):

Table 1. Average Temperature and Humidity Across Growing Structures

Growing Structure	Temperature (°C)	Humidity (%)
Greenhouse	27.6	57.3
Rain Shelter	25.3	64.6
Screenhouse	27.3	62.8
Open field	26.6	64.6

2.4. Harvest Stages and Color Measurement

Fruit samples were obtained in two stages from the same plant. The green stage contained green fruit, which is physiologically immature but marketable. In the red stage, the fruit is fully ripe. To detect color, we used a portable colorimeter (Konica Minolta, Tokyo, Japan) and measured color on pure fruit using the CIELAB color space. The recorded parameters were lightness (L^*), greenness–redness (a^*), and blueness–yellowness (b^*). Both paired-comparison methods and repeated-measures analyses were performed at two harvest times. The color intensity (chroma) of the fruit and its hue angle were obtained via CIELAB color coordinates a^* and b^*. These are obtained through the measurement at the green and red harvest steps. Chroma (C^*) is saturation or brightness, and was determined to be as follows:

$$C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

Hue (the primary color tone people perceive) was determined as:

$$h^\circ = \tan^{-1}\left(\frac{b^*}{a^*}\right)$$

In order to detect any color change during fruit ripening, delta values were obtained for each fruit. The difference between the red and green harvest stages was calculated using the following equations:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

These values indicated the extent of color change from Green to Red.

2.5. Data Analysis

ANOVA-mixed examined color parameters. Fixed effects growing Structure and fertigation level. The harvest stage was a repeated measure, and blocks and plants were random effects. Tukey's HSD was used for mean separation at the 5% significance level when effects were significant. All statistical analyses were performed using SmartStat XL.

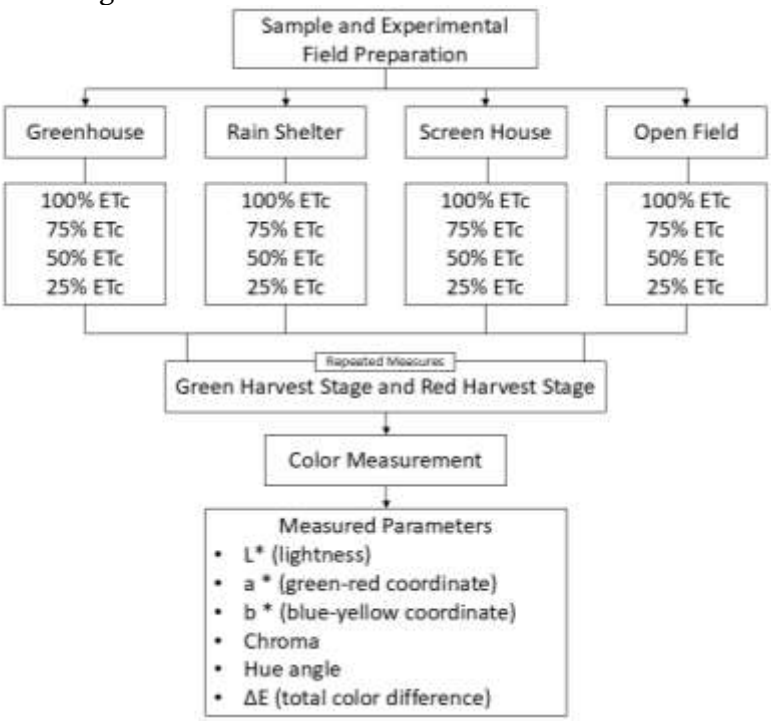

Figure 1. Schematic/Flowchart of research

3. Results and Discussion

3.1. Color: L* value

Color L* of chili fruit in this study was influenced by the interaction between context factor and growing Structure, fertigation level, and harvest stage; simple-effect Tukey test proved the effect. This suggests that the individual factors do not determine the color of chili fruit at all, but are instead controlled by definite relationships between the growing background and the physiological age.

At the green harvest stage, L* differences between green and red harvests were detected only under the screen house structure at 100% ETc. In this condition, the L* value at the green harvest was significantly lower than the red harvest value. Unlike in previous stages, there was no difference in the harvest phase among other structures at the same fertigation level. The selective response demonstrates that screening houses under different microclimate conditions led to fruit sensitivity to the physiological ripening transition, whereas increased brightness was observed across all treatments.

Table 2. Growing Structure and fertigation level interaction effect on L* value at green and red harvest stages

Structure, S	Volume, V	Harvest time, H	
		Green	Red
Greenhouse	100% ETC	33.98 a A (ab)	34.79 a A (a)
	75% ETC	32.12 a A (ab)	34.24 a A (a)
	50% ETC	32.74 a A (ab)	34.64 a A (a)
	25% ETC	34.83 a A (ab)	34.36 a A (ab)
Rain Shelter	100% ETC	37.44 a B (b)	33.93 a A (a)
	75% ETC	36.26 a B (b)	33.39 a A (a)
	50% ETC	36.54 a B (b)	33.72 a A (a)
	25% ETC	38.33 a B (b)	34.72 a A (b)
Screen house	100% ETC	38.25 b B (b)	33.98 a A (a)
	75% ETC	31.09 a A (a)	33.58 a A (a)
	50% ETC	31.15 a A (a)	34.13 a B (a)
	25% ETC	30.97 a A (a)	34.22 a B (ab)
Open Field	100% ETC	32.58 a A (a)	34.13 a A (a)
	75% ETC	33.90 a A (ab)	32.56 a A (a)
	50% ETC	33.96 a A (ab)	34.81 a A (a)
	25% ETC	34.19 a B (ab)	30.37 a A (a)

Note: The mean values followed by the same letter are not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Fertigation levels on the same Structure X Harvest stages. Capital letters (read horizontally), comparing Harvest stages on the same Structure X Fertigation level. The letters in parentheses (read vertically), comparing Structure on the same Fertigation level X Harvest stages.

The greatest L^* value was obtained with green collection (Table 2), which often occurs under screenhouse at higher fertigation stages, 100% ETc level. These forms suggest that moderating high solar irradiance under appropriate ventilation conditions can alleviate heat stress and favour epidermal growth. These environmental conditions support increased surface reflectance and a long delay in chlorophyll decay in unripe fruit, thereby increasing the perceived visibility (L^*). The same response can even be seen in chili plants grown under shaded or semi-protected conditions, where controlling light intensity can enhance fruit visual quality [18].

The lowest L^* value was obtained when green harvesting was concomitantly linked with an open field treatment and a low fertigation volume (25–50% ETc). This set of treatments may have produced water and heat stress concomitantly, which, in turn, accelerated the aging process and retarded the extracellular reproduction of epidermal cells. Water deficit affects fruit surface smoothness and pigment stability, thereby affecting light reflectance and the L^* indices [19]. The negative values are consistent with stress response rather than developmental fluctuation in the open field (low water) conditions [20].

L^* value of the red harvest value shows a narrower range and higher statistical homogeneity across the entire growing Structure and fertigation volume. The limited differences among fertigation treatments within the same structures suggest that fruit color development during ripening is less variable. Under ripening conditions, chlorophyll depletes, and carotenoids accumulate in a regulated, stable manner, promoting uniform darkening of the fruit surface despite environmental variation [21]. Therefore, environmental variation on L^* is less pronounced after the fruit ripens into red.

While the 100% ETc treatment at the green harvest stage showed the most dramatic contrast at harvest, it was not necessarily the best treatment for brightness. Instead, it is the most sensitive combination for the harvest-step transition, as treatment "performance" needs to be construed relative to the developmental stage and the parameter under investigation [22]. The results show that the growing structure and harvest stage are the main determinants of chili fruit lightness. In contrast, fertigation volume in the 25–100% ETc range has a secondary, structure-dependent influence.

3.2. Color: a^* value

The a^* value, that is, the red–green color of chili fruit, was highly sensitive to comparing the relationship between growth structure and fertigation level at different harvest stages (Table 3). Its interaction implies that the impact of fertigation levels on fruit coloring cannot be generalized across various structures, but rather is specific to individual growing systems. This affirms that pigment gene expression, especially during fruit maturation, is decisively affected by microclimatic modification induced by growing structures.

During the green harvest stage, the a^* value of the test was generally negative across all treatments, indicating green coloration and the predominance of chlorophyll pigments. At varying fertigation concentrations, however, there were vast differences between structures. The open field (75% ETc treatment) had the most extreme a^* value for green color: the lowest a^* (greenest green) was observed there. Higher water input intensity and greater daily temperature changes are consistent with delayed chlorophyll degradation under conditions of increased water availability [23], where more illumination can increase chlorophyll retention under open-field conditions [24]. The rain shelter with 25% ETc had the highest a^* value at the green stage, indicating less green coloration. This tendency is most likely the result of mild water stress exacerbating chlorophyll degradation under partially protected conditions, as reported elsewhere in Capsicum under deficit irrigation [25].

At the red harvest stage, the a^* value increased substantially and transformed to a positive value, indicating there was a move from chlorophyll dominance to carotenoid accumulation. In the open field, the highest a^* value was observed at 50% ETc, indicating better red color development than in other treatments. These results indicate that moderate water restriction in an open field, as observed here, could induce carotenoid biosynthesis, particularly capsanthin and capsorubin, which are responsible for the red coloration of chili peppers [26]. The lowest a^* value at the red stage, on the

other hand, was recorded in rain shelters with 25% ETc, indicating less intense red coloration. In a semi-protected environment under high water restriction, assimilate concentrations and the activity of enzymes required for carotenoid synthesis are likely to be low, limiting color formation [27].

Table 3. Growing Structure and fertigation level interaction effect on a* value at green and red harvest stages

Structure, S	Volume, V	Harvest time, H	
		Green	Red
Greenhouse	100% ETC	-8.37 a	36.26 b
		A (a)	B (c)
	75% ETC	-8.18 a	34.71 a
		A (a)	B (b)
	50% ETC	-8.56 a	35.28 ab
		A (a)	B (b)
	25% ETC	-9.06 a	34.80 a
		A (a)	B (b)
Rain Shelter	100% ETC	-7.68 a	31.62 a
		A (a)	B (a)
	75% ETC	-8.27 a	34.20 b
		A (a)	B (b)
	50% ETC	-7.07 a	32.82 ab
		A (a)	B (a)
	25% ETC	-7.08 a	31.69 a
		A (b)	B (a)
Screen house	100% ETC	-8.06 a	35.40 ab
		A (a)	B (bc)
	75% ETC	-7.48 a	34.40 a
		A (a)	B (b)
	50% ETC	-7.96 a	36.06 b
		A (a)	B (bc)
	25% ETC	-7.96 a	35.14 ab
		A (ab)	B (b)
Open Field	100% ETC	-8.06 a	34.07 b
		A (a)	B (b)
	75% ETC	-6.66 b	31.69 a
		A (a)	B (a)
	50% ETC	-7.19 ab	37.07 c
		A (a)	B (c)
	25% ETC	-8.54 a	36.04 c
		A (ab)	B (b)

Note: The mean value followed by the same letter is not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Fertigation levels on the same Structure X Harvest stages. Capital letters (read horizontally), comparing Harvest stages on the same Structure X Fertigation level. The letters in parentheses (read vertically), comparing Structure on the same Fertigation level X Harvest stages.

Screen house treatments were typically associated with intermediate a* values across growing structures at harvest. In the screen house, extreme microclimatic conditions can be mitigated by stable temperatures and reduced radiation levels, which moderate pigment changes and prevent excessive color variation [28]. The greenhouse treatments yielded somewhat similar a* values across fertigation types, suggesting that the effect of irrigation variability on fruit color may be minimized in tightly controlled environments [29]. Taken together, these results show that the best red color development

was achieved at moderate fertigation (mostly in open-field conditions) but not under full irrigation (100% ETc).

The highest green coloration was associated with a particular configuration and fertigation combination at the green harvest. This shows that high a^* or low a^* values have biological significance (due to distinct physiological processes: chlorophyll retention and carotenoid buildup) [30]. It was also found that fertigation volume should be adjusted according to the growing Structure to improve chilli fruit color at different harvest stages [31].

3.3. Color: b^* value

This is known as the b^* value, which describes the yellow-blue color axis within chili peppers and was determined by the interaction of growing Structure and fertigation at different harvest stages (Table 4). The existence of an interaction effect suggests that the responsiveness of yellow pigments to fertigation volume differs by planting structure and harvest stage, as the microclimate within the Structure modulates pigment dynamics during fruit development and ripening.

During the green harvest stage, b^* values showed significant differences across Structure–fertigation combinations. This was the most pronounced b^* value for the screen house at 100% ETc, suggesting a yellow element that was significantly stronger than that of other treatments. This response might be related to the moderate light and temperature in the screen house, indicating that it may favour carotenoid precursor accumulation and restrain an excessive chlorophyll dominance [32]. In the greenhouse, relatively large b^* values were observed at 25% ETc and at 75% ETc in the rain shelter, suggesting that moderate water restraint in semi-protected areas might promote yellow pigment expression by inducing metabolic changes under stress [33].

At the green stage, low to moderate fertigation in less protected structure conditions was found to produce the lowest b^* values (75% ETc open field and 50% ETc rain shelter). Reduction of yellow at treatments revealed that chlorophyll masking was stronger or carotenoid synthesis was minimal in more variable temperature and light conditions, as seen in open or semi-open systems [34] [35]. These results suggest that early pigment balance is primarily a function of both structural protection and fertigation, not fertigation independently [36]. At red harvesting, b^* values were more consistent among Structure, but significant differences did arise according to fertigation level.

The maximum b^* value was found in open fields at 50% ETc, suggesting that yellow-red fruit color intensity increased during ripening. This confirms that sufficient water availability in open field conditions can promote the accumulation of carotenoids, especially xanthophylls, that may enhance b^* levels in fruit ripening [37] [38]. By contrast, both rain shelters with 25% ETc and the greenhouse with 75% ETc showed smaller b^* values, indicating that either a restricted or insufficient quantity of water under protected systems can retard pigment synthesis during ripening.

For both harvest stages, the screen house had higher or more stable b^* values than the other Structure, suggesting a buffering effect of the microclimate that allows for consistent pigment development [39]. In contrast, open-field treatments showed greater variation, suggesting that carotenoid accumulation in response to fertigation level was more strongly influenced by environmental factors [40]. The only exception is the tendency for response values to be biased towards moderate, rather than maximal, fertigation, with the highest b^* values, suggesting that excessive water supply does not favor more intense yellow pigments [41].

Our findings show that b^* value is governed by heterogeneous effects of growing Structure with fertigation level and harvest stage [42] [43]. The highest yellow intensity was achieved with a specific combination of Structure and fertigation, rather than with high water input in general. The lowest b^* value indicated conditions in which pigment expression was inhibited [44]. Simultaneously, the lowest b^* value was indicative of pigment expression-impaired circumstances. Fertigation strategies for specific growing structures were optimized to improve fruit color properties across different developmental phases, as indicated by these findings [45].

Table 4. Growing structure and fertigation level interaction effect on b^* value at green and red harvest stages

Structure, S	Volume, V	Harvest time, H	
		Green	Red
Greenhouse	100% ETC	14.59 a A (a)	19.36 a B (a)
	75% ETC	16.40 a A (a)	17.99 a A (a)
	50% ETC	17.51 ab A (a)	18.62 a A (a)
	25% ETC	21.00 b B (b)	16.61 a A (a)
Rain Shelter	100% ETC	18.12 ab A (ab)	16.23 a A (a)
	75% ETC	19.18 b A (a)	17.77 a A (a)
	50% ETC	14.50 a A (a)	17.81 a B (a)
	25% ETC	15.62 ab A (a)	15.52 a A (a)
Screen house	100% ETC	22.43 b B (b)	18.40 a A (a)
	75% ETC	16.59 a A (a)	18.72 a A (a)
	50% ETC	18.07 a A (a)	18.50 a A (a)
	25% ETC	17.63 a A (ab)	18.82 a A (a)
Open Field	100% ETC	19.08 a A (ab)	18.43 a A (a)
	75% ETC	16.37 a A (a)	16.79 a A (a)
	50% ETC	16.91 a A (a)	20.41 a B (a)
	25% ETC	18.56 a A (ab)	17.16 a A (a)

Note: The mean values followed by the same letter are not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Fertigation levels on the same Structure X Harvest stages. Capital letters (read horizontally), comparing Harvest stages on the same Structure X Fertigation level. The letters in parentheses (read vertically), comparing Structure on the same Fertigation level X Harvest stages.

3.4. Color: Chroma

Chroma was significantly affected by the interaction among growing Structure, fertigation level, and harvest stage (Table 5). Different combinations of Structure–fertigation for lowercase and uppercase letters suggest that the chroma response varied across cultivation environments and fruit development, indicating that color vividness is modulated by microclimatic regulation rather than by unguided fertigation volume independently.

At the green harvest stage, the highest chroma value was observed in the screen house under 100% ETc, suggesting that the green fruit showed a much more saturated color than in the majority of the other treatments at the same level [43]. The results indicate that temperate conditions for

pigmentation accumulation in the early stages of fruit growth support balanced pigmentation accumulation in greenhouse conditions, which are defined by controlled radiation and attenuated environmental stress [46]. Even greenhouses with 25% ETc exhibited high chroma, indicating that mild water limitation under fully protected conditions can increase pigment concentration, thereby limiting excess vegetative growth and allocating assimilates to the fruit tissue [47]. These findings are consistent with reports that a combination of moderate environmental control and non-excessive water input appears to increase color saturation by boosting carotenoid and flavonoid production [48].

Table 5. Growing Structure and fertigation level interaction effect on Chroma value at green and red harvest stages

Structure, S	Volume, V	Harvest time, H	
		Green	Red
Greenhouse	100% ETC	16.68 a A (a)	41.10 a B (b)
	75% ETC	18.15 a A (a)	39.10 a B (a)
	50% ETC	19.49 ab A (a)	39.89 a B (ab)
	25% ETC	22.90 b A (b)	37.63 a B (a)
Rain Shelter	100% ETC	19.68 ab A (ab)	35.54 a B (a)
	75% ETC	20.89 b A (a)	38.54 a B (a)
	50% ETC	16.14 a A (a)	35.54 a B (a)
	25% ETC	17.16 ab A (a)	35.29 a B (a)
Screen house	100% ETC	23.93 b A (b)	39.90 a B (ab)
	75% ETC	18.35 a A (a)	39.17 a B (a)
	50% ETC	19.78 ab A (a)	40.54 a B (b)
	25% ETC	19.47 a A (ab)	39.87 a B (a)
Open Field	100% ETC	21.03 a A (ab)	38.74 ab B (ab)
	75% ETC	17.58 a A (a)	35.87 a B (a)
	50% ETC	18.38 a A (a)	42.32 b B (b)
	25% ETC	20.44 a A (ab)	39.92 ab B (a)

Note: The mean values followed by the same letter are not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Fertigation levels on the same Structure X Harvest stages. Capital letters (read horizontally), comparing Harvest stages on the same Structure X Fertigation level. The letters in parentheses (read vertically), comparing Structure on the same Fertigation level X Harvest stages.

The lowest chroma values observed at the green stage were generally correlated with the treatments under the rain shelter at 50% ETc and the greenhouse at 100% ETc. These differences were not always statistically different from intermediate treatments. Diminished chroma under such

conditions might have indicated low pigment synthesis due to suboptimal water consumption and/or diluted results caused by fast fruit growth from a high water input [49]. This supports the concept that excessive fertilization does not continually improve color quality and may even reduce pigment density in the early stages of development [50].

At the red harvest stage, chroma increased significantly across all treatments, indicating that fruit maturity has the greatest impact on color saturation. The maximum chroma value was observed in the open field at 50% ETc, compared with other structure–volume combinations. Indicating that moderate water supply in open-field may facilitate carotenoid deposition during ripening, with capsanthin and capsorubin contributing particularly to the color vividness of red chili fruits. Such more intense, diurnal variations in light in open-field systems may have boosted pigment production during ripening [51].

In contrast, lower chroma values at the red stage were observed in rain-shelter treatments and in the greenhouse under reduced fertigation levels, indicating that overly buffered environments may limit the full expression of color saturation during ripening [52]. This may be due to a lack of light or low temperature variation, which impairs the carotenoid biosynthesis pathway, even though it is no longer red and mature [6]. These results indicate that protecting the Structure can be beneficial during the initial growth period, and a less restrictive condition would likely be best for achieving maximum color intensity and reaching full maturity [53].

It is suggested that chroma is tightly controlled by interactions between the growth structure and fertigation levels and that harvest is a significant parameter of the treatment effect. The maximum chroma value was obtained with moderate fertigation, whereas the minimum was observed with the lowest level (limited pigment expression). In fact, this highlights that improving chili pepper color saturation depends on fertigation strategies tailored to the plant's Structure and developmental stage, and will not be appropriate for all environments when using the same irrigation strategy [13] [54].

3.5. Color: Hue

The hue angle for the dominant fruit color change (from green to red) was also strongly affected by the interaction among growing Structure, fertigation level, and harvest stage (Table 6). The interaction pattern showed that fertigation levels differed by Structure, and harvest stage exerted a significant modulating effect on hue expression within each Structure.

During the green harvest stage, the highest color intensity at 100% ETc was observed in the screen house, resulting in fruit that were greener than in other treatments. The strong color angle values at this time point are attributed to the dominance of chlorophyll and delayed carotenoid masking [55]. It showed that the controlled microclimate in the screen house, with low radiation and low thermal stress, can promote chlorophyll retention at the early fruit stage [56]. As similar but slightly lower hue values were obtained in the open field at 75% ETc and in the rain-shelter treatment, this implied that sufficient water and light availability can maintain green color until ripening [57]. These findings are consistent with a previous study, which found that a protected or semi-protected growing system may delay chlorophyll degradation by reducing photooxidative stress [58].

The green stages showed the lowest hue values in the greenhouse treatment, especially at low fertigation rates. Lower hue values indicate an earlier shift to yellow tones. This indicates either increased chlorophyll degradation or earlier carotenoid production [58]. In the greenhouse environment, where internal temperatures are higher and radiation capture increases, the pigment transition accelerates even at the threshold of ripening. These conditions are reported to induce chlorophyll catabolism and plastid conversion in suboptimal microclimate conditions [59].

The color angle values converged in most Structure–fertigation combinations at the red harvest stage, indicating that fruit ripening was the primary factor controlling color tone. The open field had the highest maximum hue value at 50% ETc, which was significantly higher than that of several other treatments. It is a slightly less intense red, with a lower hue value, indicating that a moderate water

supply in open-field conditions may retard the final carotenoid dominance stage, perhaps due to residual chlorophyll or changes in carotenoid composition under partial water stress.

The red stage, which emitted the lowest hue value (25% ETc), was observed in the open field and appeared deeper red. Another response has been described, in which moderate levels of water stress stimulate the carotenoid biosynthesis pathway, thereby increasing red pigment formation [60]. The color angle remained remarkably sensitive to the interplay between the growing Structure and fertigation level, with the harvest stage as the primary step in the pigment transition [61]. The high value of the green stage—the "green stage"—indicates that green plants are delayed in their color shift under controlled microclimate conditions (Liu et al., 2013). In contrast, the low color angles of the red stage indicate that those conditions favor intense red color. The highest and lowest hue values in this study indicate that optimal color development in chili fruits results from environment-based water management rather than the regular fertigation practices implemented across all buildings [63].

Table 6. Growing Structure and fertigation level interaction effect on Hue value at green and red harvest stages

Structure, S	Volume, V	Harvest time, H	
		Green	Red
Greenhouse	100% ETC	72.35 a B (a)	28.10 a A (a)
	75% ETC	76.32 b B (a)	27.40 a A (a)
	50% ETC	76.40 b B (a)	27.82 a A (a)
	25% ETC	78.79 b B (a)	26.15 a A (a)
Rain Shelter	100% ETC	79.79 a B (b)	27.17 a A (a)
	75% ETC	79.14 a B (ab)	27.46 a A (a)
	50% ETC	76.56 a B (a)	27.85 a A (a)
	25% ETC	78.07 a B (a)	26.08 a A (a)
Screen house	100% ETC	82.05 b B (b)	27.46 a A (a)
	75% ETC	77.49 a B (ab)	28.54 a A (a)
	50% ETC	78.53 a B (a)	27.15 a A (a)
	25% ETC	77.85 a B (a)	28.17 a A (a)
Open Field	100% ETC	79.50 a B (b)	26.18 ab A (a)
	75% ETC	80.87 a B (b)	27.91 ab A (a)
	50% ETC	79.77 a B (a)	28.84 b A (a)
	25% ETC	77.91 a B (a)	25.46 a A (a)

Note: The mean values followed by the same letter are not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Fertigation levels on the same Structure X Harvest stages. Capital letters (read horizontally), comparing Harvest stages on the same Structure X Fertigation level. The letters in parentheses (read vertically), comparing Structure on the same Fertigation level X Harvest stages.

3.6. Color: ΔE^*

The color difference ΔE^* (Table 7) represents the overall perceptible change and magnitude observed in fruit color as a function of the sum of L^*, a^*, and b^*. The interaction of growing Structure and fertigation volume influences it. These effects can be more easily visualized in the simple visual of actions shown in Figure 2, which clearly shows how the different response forms, ΔE^*, differ across fertigation levels for the growing structures. These findings show that growth color change in chili fruit is influenced by multiple factors, including microclimatic conditions and water availability, rather than one-factor effects.

In the greenhouse, the most significant color change was recorded with the increase to 100% ETc in a controlled environment. This treatment consistently yields a higher ΔE^* value than lower fertigation rates used for the same Structure, as illustrated in Figure 2. The greenhouse microclimate is generally characterized by high temperatures, low wind speeds, and high radiation retention, which increase metabolic activity associated with pigment degradation and synthesis [64] [40]. Given an adequate water supply, these conditions result in accelerated chlorophyll degradation and increased carotenoid accumulation, leading to greater color contrast and, consequently, higher ΔE^* values [65].

The least value of ΔE^* occurred when growing in the open field (25% ETc). This trend is clearly shown in Figure 2 by the significant decrease in ΔE^* at the lowest fertigation level, with limited water in open-field conditions limiting color development of chili fruits. Under open-field conditions, a lack of water may reduce photosynthetic capacity and limit the allocation of assimilates to secondary metabolite production, such as carotenoids, thereby inhibiting overall color development and eliminating visual evidence of coloration [15].

In the rain shelter and screen house structures, the ΔE^* responses are intermediate and exhibit a more moderate fluctuation across fertigation levels. In the rain shelter, the ΔE^* value remained stable, indicating that the rain-shelter support reduced over-stress and inhibited extreme pigmentation acceleration [66][67]. However, the screen house achieved comparatively high ΔE^* at both moderate and total fertigation levels, which is in line with the best light modification in terms of water availability balance. Studying the literature, we know that the conditions in the screen house, which attenuate radiation stress and provide a light atmosphere for carotenoid biosynthesis, are favourable for stable development [68].

Table 7. Growing Structure and fertigation level interaction effect on ΔE^* value

Structure, S	Volume, V			
	100% ETC	75% ETC	50% ETC	25% ETC
Greenhouse	45.42 c C	42.78 b A	44.04 b B	44.36 c BC
Rain Shelter	39.55 a A	42.77 b B	40.07 a A	39.25 b A
Screen house	44.23 bc C	41.85 b A	44.52 b C	43.04 c B
Open Field	41.94 ab C	38.54 a B	44.52 b D	27.77 a A

Note: The mean values followed by the same letter are not significantly different according to the Tukey (HSD) Test at the 0,05 significance level. Lowercase (read vertically), comparing Structure levels on the same Fertigation levels. Capital letters (read horizontally), comparing Fertigation levels on the same Structure.

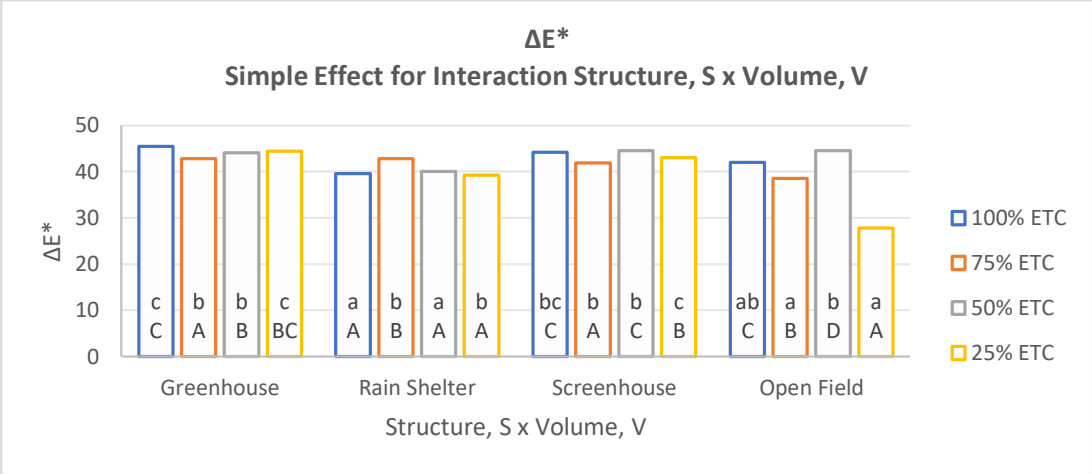

Figure 2. Growing Structure and fertigation level effect on ΔE^* value

A combined analysis of Table 6 and Figure 2 showed that ΔE^* is an integrative indicator of crop structure and is sensitive to control of fruit response to fertigation management. Appropriate water supply and favorable microclimate conditions in treatments may improve pigment changes and visual color differences. The combination of water and environmental conditions can limit pigment changes due to water deficiency and environmental stress. These results highlight the need for structure-oriented irrigation approaches to improve color output in chili pepper production systems [69].

Chroma and hue angle collectively demonstrated that optimal color saturation and a rapid green-to-red transition were achieved under greenhouse and screen-house systems with moderate to full fertigation. The highest ΔE* values under the rain shelter with 100% ETc indicate accelerated ripening and visually perceptible color change, confirming that balanced water supply combined with buffered microclimates enhances pigment transformation efficiency. Significantly, excessive fertigation did not universally improve color attributes, emphasizing the need for structure-specific fertigation strategies rather than uniform irrigation practices.

4. Conclusion

This research presents a holistic study on the impacts of growing structures, fertigation levels, and harvest stages on the color development of chili peppers (*Capsicum annuum* L.). The significant impact was influenced by the interaction of the growing Structure, fertigation level, and harvest stage on fruit color attributes. Brightness (L^*) is affected primarily by the growing Structure at the green harvest stage. Fruits cultivated in screenhouse and greenhouses are brighter than fruits cultivated in open fields. At the red harvest stage, light intensity (L^*) decreased. This demonstrates that the physiological ripening process comes to dominate the microclimate effect as the fruit ripens. Coordinating colors a^* and b^* represents the transition of green into red to signal chlorophyll breakdown and carotenoid accumulation in ripening. Non-protected cultivation systems generally demonstrate enhanced red color production.

Chroma and hue angle values support this trend, which indicates a progressive increase in color saturation and a continuously increasing shift towards red during fruit ripening. The difference in color (ΔE^*) from the measures of L^*, a^*, and b^* is a telltale signal of the visual color shifts between harvest activities. Variation in ΔE^* across growing structures alters the microclimate and pigment dynamics. Chili pepper cultivation under a greenhouse and screenhouse with 75–100% ETc for the green harvest stage yields higher lightness (L^*) and b^* values, showing brighter and more uniform green fruit appearance. An open field combined with 50% ETc should be recommended for the red harvest phase to achieve higher a^*, chroma, and ΔE^* values, indicating improved red color intensity and visual

quality. Based on physiological color transition dynamics, the fastest and most pronounced CIELAB color change (ΔE^*) was observed with 100% ETc applied under greenhouse and screenhouse indicating accelerated ripening and a shorter harvest period.

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