

Skin colour and softening synchronization during ripening of three avocado cultivars

Ledwaba, K. F.¹, Shikwambana, K.², Mafeo, T. P.¹, Satekge, T. K.¹ & Mathaba, N.¹

¹*School of Agricultural and Environmental Sciences, Faculty of Science and Agriculture, Department of Plant Production, Soil Science and Agricultural Engineering, University of Limpopo, P/Bag X1106, Sovenga, 0727*

²*Agricultural Research Council-Vegetable, Industrial and Medicinal Plants, Roodeplaat, Pretoria, South Africa*
Author for correspondence: nhlanhla.mathaba@ul.ac.za

Summary: Skin colour-softening de-synchronization during the early season remains a major quality concern in ‘Hass’ avocado, leading to consumer dissatisfaction and market losses. This study evaluated whether Hass-type cultivars ‘Carmen’ and ‘Maluma’ exhibit de-synchronization between skin colour and mesocarp softening as compared to ‘Hass’ avocado. The study was conducted using fruit harvested from a ZZ2 Moeketsi commercial farm in Tzaneen, Limpopo, South Africa. The ‘Carmen’ and ‘Maluma’ cultivars were harvested in April 2024, while the ‘Hass’ cultivar was harvested in May 2024. The harvested fruits were stored at 5.5 °C for 28 days. After cold storage, fruit were held at ambient temperature to induce ripening. Firmness declined significantly in all cultivars ($p < 0.001$), with ‘Carmen’ softening earlier and ‘Maluma’ showing a gradual softening pattern. Skin colour changed from green to purple and black; however, colour development was more pronounced and closely aligned with softening in ‘Carmen’ and ‘Maluma’. Chlorophyll and carotenoids decreased, whereas anthocyanin increased during ripening, with a stronger correlation between colour, firmness, and pigment changes in ‘Carmen’ and ‘Maluma’. These results indicate better skin colour-softening synchronisation in ‘Carmen’ and ‘Maluma’, supporting their suitability for early season export programs.

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Key words: avocado ripening, colour, fruit softening, chlorophyll degradation, total anthocyanin

Introduction

Avocado (*Persea americana* Mill.) Hass is the dominant cultivar in the global avocado production and marketing due to its high yield, resistance to postharvest handling, extended shelf-life and desirable fruit characteristics (size, high pulp content, thick dark skin when ripe, buttery taste and creamy texture) (Arpaia & Smith, 2010; Lahack et al., 2024; Ramos-Aguilar et al., 2025). The increasing global demand for ‘Hass’ cultivar has led to its overexploitation, extensive production expansion and heavy reliance on this cultivar, contributing to an array of environmental, social, economic challenges. These include excessive vegetative growth, high irrigation, input requirements, slow fruit development, and high susceptibility to pests and diseases (Mpai & Sivarkumar et al., 2020; Arpaia, 2020). In addition to production-related constraints, several studies have reported a decline in both internal and external fruit quality including reduced fruit size and uniformity, lower oil content, mineral content, poor skin colour development, diminished sensory and increased incidence of physiological disorders (Hofman et al., 2002; Mathaba et al., 2015; Sellamuthu et al., 2013; Salvo et al., 2016). These quality challenges have been linked to the expansion of ‘Hass’ avocado production into new regions, driven by the cultivar’s broad climate adaptability and further exacerbated by climate variability in major avocado production areas. To reduce dependence on ‘Hass’ and diversify avocado production systems, several Hass-type avocado cultivars including ‘Carmen’ and ‘Maluma’ have been developed in Mexico and

South Africa (Micheletti et al., 2025). These Hass-type cultivars have distinct agronomical advantages. ‘Carmen’, a somatic mutation of ‘Hass’, is early maturing, exhibits off-bloom flowering, good cold tolerance and generally produce smaller fruit size compared to ‘Hass’ (Kamper et al., 2021; Crane et al., 2025). ‘Maluma’, a naturally occurring clonal selection, is also early maturing and features an upright growth habit, produce pyriform fruit in shape with a shiny skin that turns purple-black upon ripening alongside improved cold tolerance, shelf life and enhanced resistance to oxidation (Ernst, 2007; Ernst et al., 2015).

The commercial success of ‘Hass’ and Hass-type avocado relies heavily on visual ripeness indicators, particularly the synchronization between skin colour development and mesocarp softening (Arancibia-Guerra et al., 2022). However, in the early season fruit, this synchronization is frequently inconsistent, with skin colour development lagging behind mesocarp softening (Mathaba et al., 2015; 2017). This colour-softening desynchronization reduces consumers’ confidence, increase fruit rejection and negatively affect market acceptance and profitability. In ‘Hass’ avocado fruit, skin colour change during ripening is driven by pigment change, specifically, the breakdown of chlorophyll and anthocyanin pigment synthesis and accumulation, especially, cyanidin-3-*O*-glucoside (Cox et al., 2004; Ashton et al., 2006). While the physiological and biochemical basis of skin colour development and softening has been extensively studied in ‘Hass’, it remains unclear

whether newer Hass-types cultivars ‘Carmen’ and ‘Maluma’ exhibit similar ripening behaviour, particularly with respect to the synchronization between colour change and softening during early season. Notably, ‘Carmen’ and ‘Maluma’ reach maturity earlier than ‘Hass’ and therefore enter market channels during a period when colour-softening desynchronization is most pronounced in ‘Hass’ fruit.

Despite their increasing commercial adoption and reported agronomic advantages, limited information is available on the ripening physiology of these cultivars, specifically regarding the degree of synchronization between skin colour development and fruit softening and the associated pigment change that underpin skin colour development. Therefore, this study aimed to investigate the synchronization between skin colour and fruit softening in ‘Carmen’ and ‘Maluma’ in comparison with ‘Hass’ and to evaluate associated pigment changes in chlorophyll, carotenoid and anthocyanin pigments, in order to assess whether these Hass-type cultivars exhibit more consistent ripening behaviour and improved suitability for early-season export markets.

Materials and methods

Experimental material

Three ‘Hass-type’ avocado fruit cultivars (‘Carmen’, ‘Maluma’ and ‘Hass’) were harvested at intervals from a ZZ2 Moeketsi commercial farm in Tzaneen, Limpopo, South Africa (23°34’46.2850’’S 3°8’36.6148’’E). The ‘Carmen’ and ‘Maluma’ cultivars were harvested in April 2024, while the traditional ‘Hass’ cultivar was harvested in May 2024. All orchards have followed consistent management practices over the years. After harvest, fruit were transported to the University of Limpopo laboratory (23.886°S, 29.718°E), whereby, fruit were sorted and stored at 5.5 °C for 28 days. After withdrawal from cold storage, fruit were then allowed to ripen at room temperatures (20±1 – 25±1°C). Each cultivar included 61 fruit, with 21 fruit evaluated and 3 randomly sampled at 2-day interval per evaluation day during ripening.

Firmness measurement

Fruit firmness was measured using a penetrometer. A section of the skin was removed using a fruit peeler to expose the flesh, allowing for direct contact with the plunger of the penetrometer. A penetrometer plunger was pressed into the flesh until penetration. The readings were performed in kilograms (kg/cm²). Firmness ranged from 100 (hard) to 0 (soft).

Colour measurements

Skin colour change was first assessed using a visual rating scale: 1 = emerald green, 2 = forest green, 3 = olive green, 4 = violet, 5 = purple, and 6 = black (Shikwambana et al., 2021). The same fruit were objectively evaluated using a chromometer (CR-400, Minolta, Sensing Incorporation, Japan). Colour measurements were recorded in L*, C*, and h° units. L* indicates lightness (0 = black, 100 = white), C* represents colour saturation (chroma), and h° (hue angle) indicates the dominant colour, with 0° = red, 90° = yellow, 180° = bluish-green, and 270° = blue. The hue angle and chroma were calculated using the equations described by McGuire (1992):

$$\text{hue angle } (h^\circ) = 180^\circ + \left[\tan\left(\frac{a^*}{b^*}\right) \right]$$

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

After the subjective and objective colour evaluations, the avocado skin was peeled and stored at -80 °C for later analysis. The frozen skins were then freeze dried overnight using a freeze dryer (Alpha 1-2 LSbasic, Germany). Once dried, the skins were ground into a powder using a mortar and pestle. Pigment analysis was performed according to the methods described by Cox et al. (2004) and Shikwambana et al. (2021).

Pigment measurements

Chlorophylls and carotenoids extraction and quantification were performed according to Cox et al. (2004) as follows: dry powdered avocado peel (0.5 g) was mixed with 10 mL 80% v/v acetone and kept on ice in the dark for 30 min. The mixture was then centrifuged at 6 000 × g for 5 min (Z206A, Hermle Labortechnik GmbH, Germany) to separate the liquid phase. The absorbance of the supernatants was measured at 663, 646, and 470 nm using a spectrophotometer (UV-1800, Shimadzu, Corp. Japan) for Chla, Chlb and carotenoids, respectively. Thereafter, the pigments were quantified using equation:

$$\text{Chlorophyll-a (Chl-a)} = 12.25 \times A_{663} - 2.79 \times A_{646}$$

$$\text{Chlorophyll-b (Chl-b)} = 21.5 \times A_{646} - 5.10 \times A_{663}$$

$$\text{Total Chlorophyll (TCC)} = 20.2 \times A_{646} + 8.02 \times A_{663}$$

$$\text{Total carotenoids} = 4.37 \times A_{470} + 2.11 \times A_{663} - 9.10 \times A_{646}$$

Total anthocyanin content was determined using the pH differential method described by Lee et al. (2005). Dry powdered avocado peel (0.5 g) was mixed with 5 mL of 105 acetic acid/methanol solution (v/v) at room temperature. The mixture was centrifuged at 3 000 × g for 10 min (Z206A, Hermle Labortechnik GmbH, Germany) to separate the supernatant. The supernatant was then mixed with a methanol:water:acetic acid solution in a 50:50:10 ratio. The anthocyanin content was assessed using the pH differential method described by Giusti & Wrolstad (2001). A 1:1 volume of the supernatant mixture was filtered through a funnel and a filter paper into a clean test tube. It was then mixed with 1 µL of potassium chloride buffer (pH_{1.0}) and sodium acetate buffer (pH_{4.5}). The mixture was incubated in the dark for 10 min before spectrophotometric (UV-1800, Shimadzu, Corp. Japan) analysis at 530 nm and 700 nm. The total anthocyanin content was calculated using the following formula:

$$A = (A_{530} - A_{700})_{\text{pH } 1.0} - (A_{530} - A_{700})_{\text{pH } 4.5}$$

$$\text{Total anthocyanin} = A \times \text{MW} \times \text{Df} / (e \times L)$$

Where: A = Absorbance. MW = Anthocyanin 164 Molecular Weight, Df = Dilution factor, e = Cyanidin-3-glucoside molar absorbance (26900). L = cell path length (1 cm)

Data analysis

All statistical analyses were performed using GenStat 18th (VSN International, Hemel, Hempsted, UK). Data were analyzed using analysis of variance (ANOVA) and means were separated using Duncan’s Multiple Range Test (DMRT) at a 5% level of significance. Pearson’s correlation coefficients were calculated to assess the relationship between skin colour, softening, colour parameters and pigment content.

Results

Firmness changes

The interaction between cultivar and ripening days was significant ($p < 0.001$) on firmness. During ripening, firmness differed significantly ($p < 0.001$) in all avocado cultivars (**Figure 1**). ‘Carmen’ avocado fruit softened more rapidly up to day 8 when compared with ‘Hass’ and ‘Maluma’. In contrast, ‘Hass’ remained relatively firm between days 0 and 4 but showed a sharp decline in firmness between days 8 and 10. ‘Maluma’ softened more slowly throughout the ripening period. By days 10–12, ‘Hass’ avocado fruit were softer than both ‘Carmen’ and ‘Maluma’.

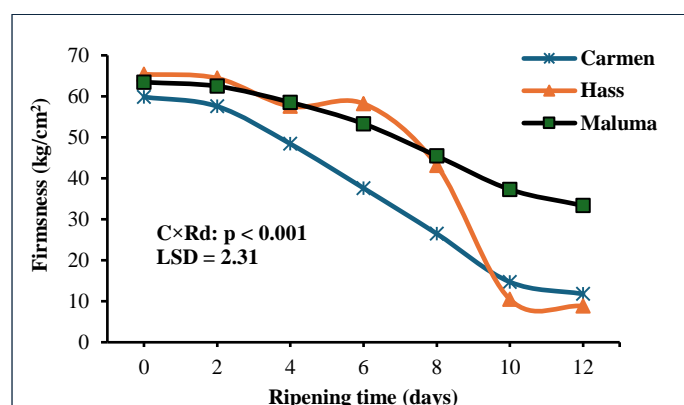


Figure 1. Firmness changes in the three (‘Carmen’, ‘Hass’ and ‘Maluma’) avocado cultivars during the 12 days of ripening at room temperature. Fruit had been stored at 5.5 °C for 28 days prior to ripening. Vertical bars represent the standard error ($n = 3$).

Colour change

The interaction between cultivar and ripening days was significant ($p < 0.001$) on skin colour. Changes in the skin colour differed significantly during ripening in all cultivars ($p < 0.001$) (**Figure 2**). At the start, all cultivars were emerald green, a colour that remained stable through day 4. Over 6–8 days, ‘Hass’ avocado fruit turned olive green, whereas ‘Carmen’ and ‘Maluma’ maintained the forest green skin colour. By day 10, ‘Carmen’ had turned fully purple colour, whereas ‘Hass’ and ‘Maluma’ appeared violet (**Figure 2**, **Figure 3**). After 12 days, both ‘Carmen’ and ‘Maluma’ were fully purple, whereas ‘Hass’ remained violet (**Figure 3**).

Skin colour variables (L^* , C^* , and h^o) differed significantly in the three cultivars during 12-day ripening period at ambient temperature (Table 1). ‘Carmen’ showed the lowest values of skin colour (L^* , C^* and h^o) as compared to ‘Hass’ and ‘Maluma’. The interaction between cultivar and ripening days was significant ($p < 0.05$) for C^* and h^o values but not for L^* ($p > 0.05$). All these three parameters declined during ripening. Over the 12-day period, the L^* values decreased for ‘Carmen’ (from 43.26 to 31.72), ‘Hass’ (from 43.71 to 32.21), and ‘Maluma’ (from 40.22 to 31.11) avocado fruits (Table 1). Similarly, C^* values also declined, reflecting reduced colour intensity. The ‘Hass’ avocado fruit showed the highest C^* value (11.42), indicating the most vivid starting colour but by day 12, all cultivars had lower C^* values. Likewise, h^o values dropped steadily, showing a shift towards a darker colour. By day 12, ‘Carmen’ avocado fruit had the lowest h^o values (near 100), whereas ‘Hass’ and ‘Maluma’ maintained slightly higher values.

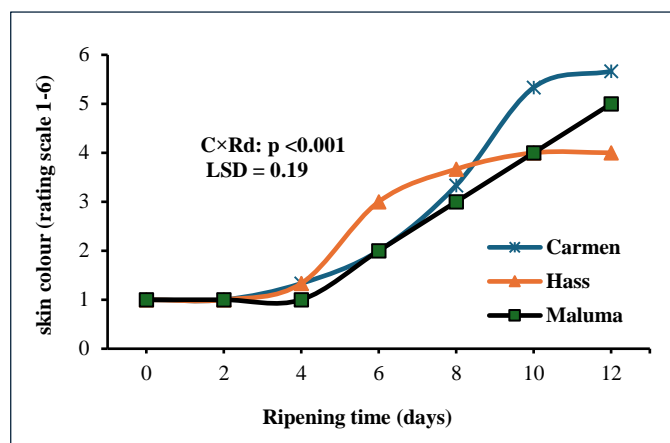


Figure 2. Skin colour changes in the three (‘Carmen’, ‘Hass’ and ‘Maluma’) avocado cultivars during the 12 days of ripening at room temperature. Fruit had been stored at 5.5 °C for 28 days prior to ripening. Vertical bars represent the standard error ($n = 3$).

Pigments change

Chlorophyll-a (Chl-a), chlorophyll-b (Chl-b), total chlorophyll (TCC) and total carotenoids (TCar)

The interaction between cultivar and ripening days significantly affected chl-a ($p < 0.05$), chl-b ($p < 0.05$), TCC ($p < 0.001$), and TCar ($p < 0.05$) avocado pigment concentrations (**Figure 4a-d**). ‘Maluma’ showed the highest Chl-a content between day 2 to 6 (27 – 22.65 mg⁻¹ DW) followed by ‘Hass’ (26.8–22.75 mg⁻¹ DW) and ‘Carmen’ (19.78–16.83 mg⁻¹ DW) (**Figure 4a**). A sharper decline in Chl-a was observed from days 8 to 12 and this decrease differed among all cultivars. While ‘Hass’ and ‘Maluma’ followed a similar trend in Chl-a content, ‘Carmen’ started with a lower Chl-a content and showed a more gradual, consistent decline from day 6 onwards. Chl-b also declined in all cultivars during ripening. ‘Hass’ showed a steady decrease, whereas ‘Maluma’ had a more irregular pattern (**Figure 4b**). ‘Carmen’ showed the slowest decline in Chl-b between days 2 and 10. TCC followed a similar pattern across cultivars, with ‘Hass’ and ‘Maluma’ having higher initial content than ‘Carmen’ (**Figure 4c**). From day 0 and 8, ‘Hass’ and ‘Maluma’ maintained higher TCC, but by day 12, ‘Carmen’ had slightly surpassed both other cultivars. For TCar, ‘Hass’ began with the highest content on day 0 (7.25 mg⁻¹ DW), followed by ‘Carmen’ (5.87 mg⁻¹ DW) and ‘Maluma’ (5.64 mg⁻¹ DW) (**Figure 4d**). All cultivars showed a decline between days 2 and 4. ‘Maluma’ peaked at day 6 (5.96 mg⁻¹ DW) before dropping sharply. By day 12, ‘Maluma’ had the lower TCar, while ‘Hass’ and ‘Carmen’ had highest content.

Total anthocyanin content (TAC)

The interaction between cultivar and ripening days had a highly significant effect ($p < 0.001$) on TAC during ripening (**Figure 5**). In all cultivars, TAC increased but the rate and pattern varied over the ripening period. On day 2, ‘Carmen’ had significantly lower TAC than ‘Hass’ and ‘Maluma’. However, ‘Carmen’ consistently showed higher TAC than both ‘Hass’ and ‘Maluma’ from days 4 onwards. By day 12, ‘Hass’ had the lowest TAC (3.68 mg⁻¹ DW) while ‘Carmen’ and ‘Maluma’ recorded higher values (7.23 and 6.22 mg⁻¹ DW, respectively).

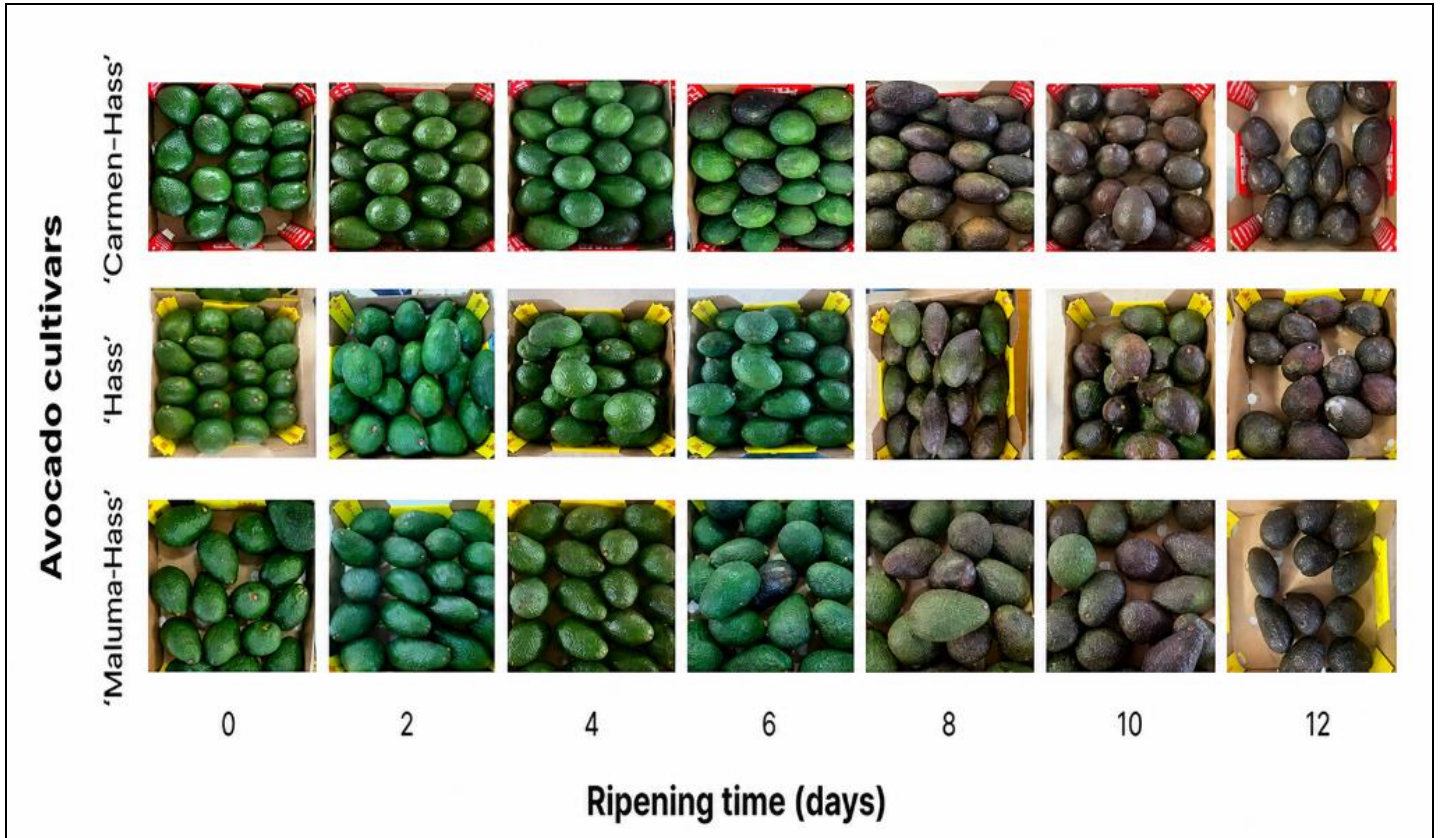


Figure 3. Virtual representation of the skin colour of the three avocado cultivars: 'Carmen', 'Hass' and 'Maluma', over a 12-day ripening period.

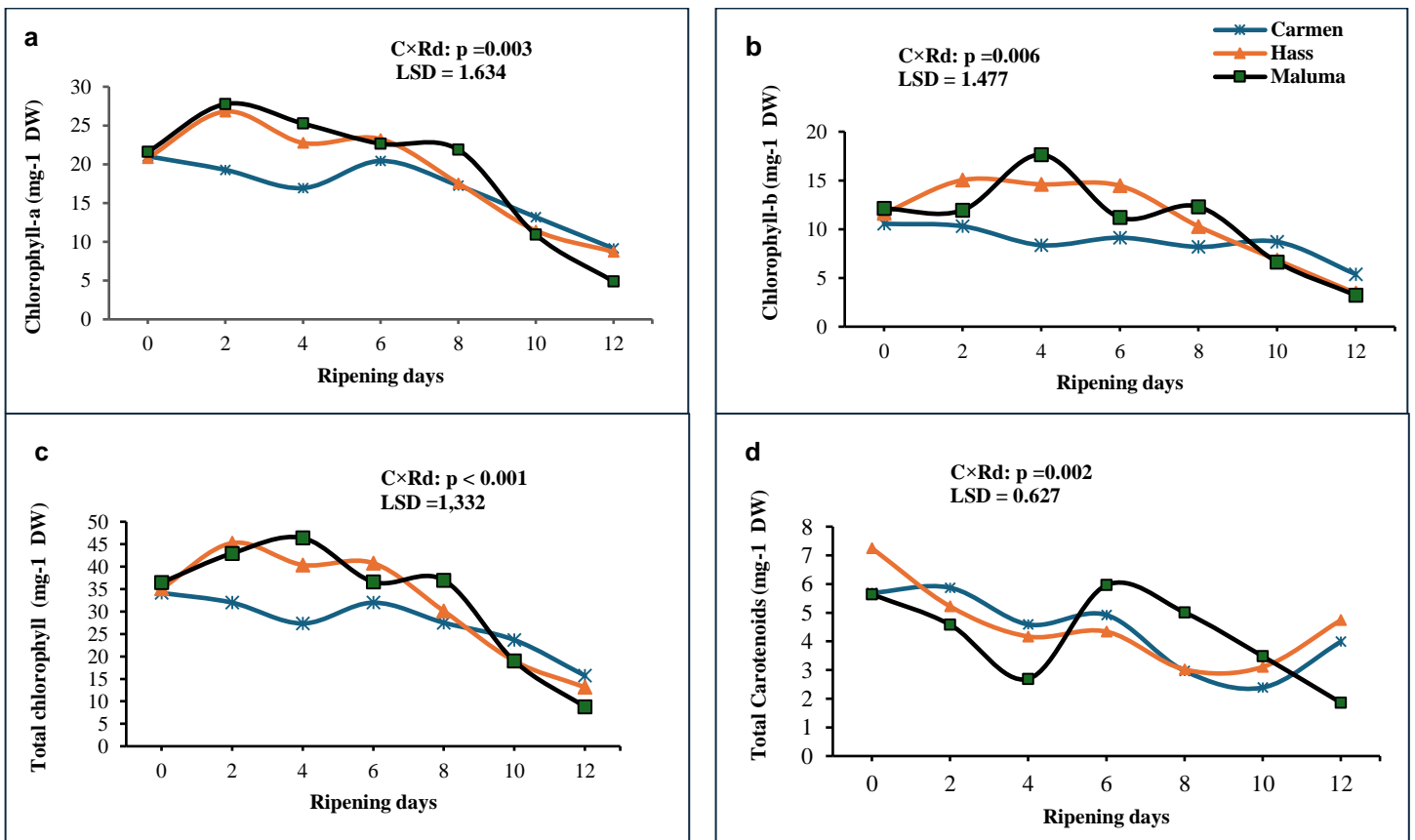


Figure 4. Changes in skin chlorophyll-a (a), chlorophyll-b (b), total chlorophyll (c), and total carotenoids (d) values in the three ('Carmen', 'Hass', and 'Maluma') avocado cultivars during the 12 days of ripening at room temperature. Fruit had been stored at 5.5 °C for 28 days prior to ripening. Vertical bars represent the standard error (n = 3).

Table 1. Objective colour parameters (L^* , C^* h°) of the three ('Carmen', 'Hass' and 'Maluma') avocado cultivars during the 12 days of ripening at room temperature. Fruit had been stored at 5.5 °C for 28 days prior to ripening.

Cultivars	Ripening day	Lightness (L^*)	Chroma (C^*)	Hue-angle (h°)
'Carmen'	0	43.26±0.729 ^{hi}	5.56±0.73 ^{de}	180.9±33.45 ^{cde}
	2	40.16±0.51 ^{fi}	2±1.05 ^a	143.9±29.28 ^{a-e}
	4	38.29±0.33 ^{efg}	8.5±0.82 ^e	136.6±2.059 ^{a-d}
	6	36.73±0.53 ^{def}	5.23±0.73 ^{de}	125.5±2.06 ^{abc}
	8	36.27±3.03 ^{e-f}	2.16 ±0.13 ^a	132.5±4.24 ^{a-d}
	10	31.72±1.1 ^{abc}	5.15±0.25 ^{bde}	139.3±6.95 ^{a-d}
'Hass'	0	43.71±0.42 ⁱ	11.42±1.04 ^h	135.8±2.71 ^{a-d}
	2	41.78±1.49 ^{ghi}	9.71±0.42 ^{gh}	137.4±2.63 ^{a-d}
	4	38.85±0.98 ^{e-h}	9.48±0.27 ^{gh}	134.2±1.04 ^{a-d}
	6	35.23±1.00 ^{b-e}	6.05±1.82 ^{ef}	189.8±9.04 ^{de}
	8	34.58±0.81 ^{b-e}	2.51±0.66 ^{abc}	199.4±46.95 ^e
	10	33.72±0.22 ^{bcd}	2.92±1.08 ^{a-d}	116.5±5.33 ^{ab}
'Maluma'	0	40.22±0.61 ^{fi}	3.54±1.03 ^{a-e}	190.3±26.9 ^{de}
	2	40.22±0.61 ^{fi}	3.84±0.68 ^{a-e}	169.8±9.31 ^{b-e}
	4	38.46±0.55 ^{efg}	5.33±0.74 ^{de}	181.3±41.33 ^{cde}
	6	33.23±0.53 ^{bcd}	8.49±0.83 ^{fg}	136.6±2.05 ^{a-d}
	8	31.74±0.42 ^{a-d}	1.93±0.9 ^a	124.3±1.71 ^{abc}
	10	31.74±3.22 ^{abc}	1.52±0.31 ^a	157.8±12.13 ^{a-e}
	12	31.11±3.19 ^{ab}	1.14±0.81 ^a	151.6±3.23 ^{a-e}
C × Rd, p value		ns	< 0.001	0.006
LSD_{0.05}		1.49	0.89	18.52

*Different letters indicate statistically significant differences among cultivars during ripening ($p \leq 0.05$). Each experiment was performed in triplicate ($n = 3$). C, cultivars; Rd, ripening days. Ns, not significant according to ANOVA

Table 2. Pearson correlation coefficient (r) and significance of the relationship (P) between subjective colour and objective colour parameters (L^* , C^* and h°), chlorophyll-a, chlorophyll-b, total chlorophyll (TCC), total carotenoid (TCar) and total anthocyanin (TAC) content for avocado cultivars ('Carmen', 'Hass' and 'Maluma') during ripening.

Cultivars	Firmness vs Colour	Colour vs L^* value	Colour vs C^* values	Colour vs h° values	Colour vs Chl-a	Colour vs Chl-b	Colour vs TCC	Colour vs TCar	Colour vs TAC	TCC vs TAC
'Carmen'	$r = -0.942$ $P < 0.001$	$P > 0.05$ (ns)	$P > 0.05$ (ns)	$P > 0.05$ (ns)	$P > 0.05$ (ns)	$P > 0.05$ (ns)	$r = -0.692$ $P < 0.001$	$r = -0.634$ $P < 0.001$	$r = 0.839$ $P < 0.001$	$r = -0.636$ $P < 0.001$
'Hass'	$r = -0.832$ $P < 0.001$	$P > 0.05$ (ns)	$r = -0.890$ $P < 0.001$	$P > 0.05$ (ns)	$r = 0.605$ $P < 0.05$	$r = -0.605$ $P < 0.05$	$r = -0.684$ $P < 0.05$	$r = -0.574$ $P < 0.05$	$P > 0.05$ (ns)	$P > 0.05$ (ns)
'Maluma'	$r = -0.942$ $P < 0.001$	$P > 0.05$ (ns)	$r = -0.555$ $P < 0.05$	$P > 0.05$ (ns)	$r = -0.904$ $P < 0.001$	$r = -0.856$ $P < 0.001$	$r = -0.922$ $P < 0.001$	$r = -0.505$ $P < 0.05$	$r = 0.810$ $P < 0.001$	$r = -0.622$ $P < 0.05$

Correlation between skin colour and objective colour parameters (L^* , C^* and h°), Ca, Cb, TCC and TCar and TAC

Fruit firmness showed a significant correlation with skin colour across all cultivars during ripening, with the stronger correlation observed in 'Carmen' and 'Maluma' than in 'Hass' (Table 2). In all cultivars, skin colour did not show a significant correlation with L^* and h° values but showed a significant correlation with C^* values in 'Hass' and 'Maluma'. Skin colour was also significantly correlated with Chl-a and Chl-b content these two cultivars (Table 2). Changes in visual colour ratings corresponded with a decrease in TCC and TCar content, regardless of cultivar. In 'Carmen' and 'Maluma', increases in skin colour were associated with increase in TAC content. In both cultivars, TAC increased as TCC decreased (Table 2).

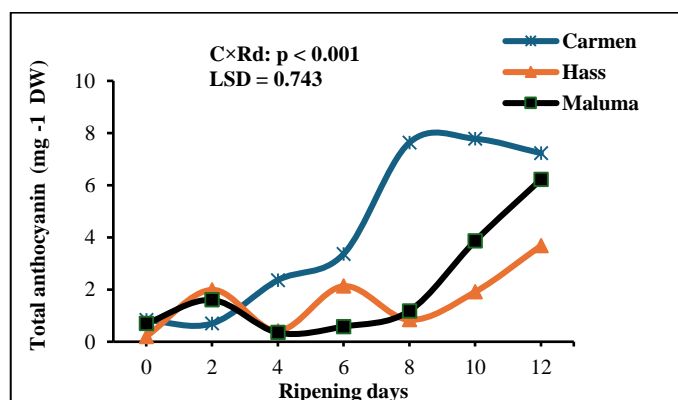


Figure 5. Changes in skin total anthocyanin values in the three ('Carmen', 'Hass', and 'Maluma') avocado cultivars during the 12 days of ripening at room temperature. Fruit had been stored at 5.5 °C for 28 days prior to ripening. Vertical bars represent the standard error ($n = 3$).

Discussion

This study investigated the synchronization of skin colour development and softening in ‘Hass-type’ avocado cultivars (‘Carmen’ and ‘Maluma’) when compared with the ‘Hass’ cultivar. Early-season desynchronization has been previously reported during ripening (Mathaba et al., 2015; Mathaba et al., 2017). Numerous studies have assessed avocado skin colour desynchronization with firmness in the ‘Hass’ cultivar fruit (Shikwambana et al., 2021; Arancibia-Guerra et al., 2022; Nunez-Lillo et al., 2023; Olivares et al., 2024). This study, therefore, further explores whether similar patterns occur in other Hass-type or hybrid cultivars. The results showed that fruit firmness decreased consistently over the ripening period across all cultivars (*Figure 1*), whereas skin colour rating increased (*Figure 2*), supporting trends reported in previous studies (Cox et al., 2004; Shikwambana et al., 2021; 2022; Setagane et al., 2021; Sibeko et al., 2024). Notably, the correlation between skin colour and softening (firmness) was stronger for ‘Carmen’ and ‘Maluma’ when compared with ‘Hass’ cultivar (*Table 2*), suggesting a better synchronization between skin colour development and softening in these hybrid cultivars. At ready to eat (Day 12), ‘Carmen’ and ‘Maluma’ consistently showed improved colour development, reaching an average skin colour ratings of 5.66 and 5 (deep purple), which was higher compared to ‘Hass’ (4-violet), and indicating better synchronisation (*Figure 2*).

Objective colour values (L^* , C^* and h^o) showed a decreasing tendency across all cultivars during ripening, consistent with previous findings (Cox et al., 2004; Setagane et al., 2021; Sibeko et al., 2024). While C^* values decrease with the increase in colour development for ‘Hass’ and ‘Maluma’ cultivars, no consistent correlation was observed between objective parameter and colour, indicating that objective colour parameters alone may not sufficiently capture colour development and ripening pigmentation changes. During ripening, avocado ‘Hass’ skin colour development is strongly associated to pigment dynamics, particularly the degradation of chlorophyll and carotenoids as well as the accumulation of anthocyanins (Ashton et al., 2006; Kayesh et al., 2013; Ranganath, 2022; Sibeko et al., 2024). A pattern we also observed in the current study (*Figure 4*) showed a significant decline in chlorophylls during ripening for all cultivars, consistent with previous studies (Cox et al., 2004; Ashton et al., 2006). Our results showed a strong correlation between skin colour and TCC was observed across all cultivars, supporting the findings described by Sebeko et al. (2024). This further indicates that chlorophyll degradation was associated with colour darkening.

Among evaluated cultivars, ‘Maluma’ demonstrated the strongest correlation between colour development and TCC, which may account for its comparatively lower chlorophyll content at day 12 relative to ‘Carmen’ and ‘Hass’ cultivar fruit (*Figure 4c*). Carotenoids, which contribute to the yellow-green pigmentation of avocado flesh and skin, decreased progressively during ripening across all cultivars. This observation is consistent with the findings of Ashton et al. (2006), who reported a decrease in carotenoids content during avocado ripening. The decrease in carotenoids is likely associated with ripening related processes including enzymatic activities and pigment change whereby chlorophyll degrade and anthocyanins accumulate (Wang et al., 2010; Villa-Rodriguez et al., 2020).

Anthocyanin, particularly cyanidin-3-*O*-glucoside in ‘Hass’ skin is the primary pigment responsible for purple to black colour change during ripening (Cox et al., 2004; Shikwambana et al., 2021). Although cyanidin-3-*O*-glucoside was not quantified in this study, total anthocyanin content increased significantly in all cultivars as ripening days increased with ‘Carmen’ and ‘Maluma’ having higher values as compared to ‘Hass’. This aligns with previous observation and support the hypothesis that TA accumulation is linked to skin colour change in ‘Hass’ (Ashton et al., 2006; Arancibia-Guerra et al., 2022) and ‘Carmen’ and ‘Maluma’ cultivar. Moreover, significant correlations were found between TAC and both skin colour and TCC in ‘Carmen’ and ‘Maluma’ (*Table 2*), further emphasizing the role of anthocyanin in colour development. At day 12, ‘Carmen’ exhibited the highest TAC, followed by ‘Maluma’, while ‘Hass’ had the lowest (*Figure 5*), suggesting cultivar-specific differences in anthocyanin biosynthesis. This difference may stem from differences in fruit size, and the expression levels of genes that regulate enzymes and hormones involved in anthocyanin biosynthesis pathways (Shikwambana et al., 2022; Sun et al., 2024; Zhang et al., 2024). In fact, Arancibia-Guerra et al. (2022) found that the black skin colour in ‘Hass’ avocado was strongly associated with total anthocyanin and abscisic acid (ABA) levels, as well as the expression of ACS, phenylalanine ammonia-lyase (PAL) and flavanone 3-hydroxylase.

Conclusions

In this study, ‘Carmen’ and ‘Maluma’ cultivars exhibited the highest synchronization between skin colour development and softening when compared with ‘Hass’, alongside superior pigment dynamics and overall fruit quality during ripening. These findings suggest that incorporating ‘Carmen’ and ‘Maluma’ into early season export programs could diversify market contribution, reduce dependency on a single cultivar and improve consistency in meeting ripeness and quality standards. Future research should focus on quantifying cyanidin-3-*O*-glucoside compound and exploring the molecular regulation of anthocyanin biosynthesis and firmness-related enzyme expression in these cultivars.

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References

- Arancibia-Guerra, C., Núñez-Lillo, G., Cáceres-Mella, A., Carrera, E., Meneses, C., Kuhn, N., Pedreschi, R. (2022): Color desynchronization with softening of ‘Hass’ avocado: Targeted pigment, hormone and gene expression analysis. *Postharvest Biology and Technology*. 194: 112067. <https://doi.org/10.1016/j.postharvbio.2022.112067>.
- Arpaia, M. L., Smith, H. (2004): Enhancement of Avocado Productivity. Plant improvement-selection and evaluation of improved varieties and rootstocks. In *Proceedings of the California avocado research symposium* (pp. 9-23). Riverside, California: University of California and California Avocado Commission.

- Ashton, O. B. O., Wong, M., McGhie, T. K., Vather, R., Wang, Y., Requejo-Jackman, C., Ramankutty, P., Woolf, A. B. (2006): Pigments in avocado tissue and oil. *Journal of Agricultural and Food Chemistry*. 54(26): 10151–10158. <https://doi.org/10.1021/jf061809j>
- Cox, K. A., McGhie, T. K., White, A., Woolf, A. B. (2004): Skin colour and pigment changes during ripening of ‘Hass’ avocado fruit. *Postharvest Biology and Technology*: 31(3): 287–294. <https://doi.org/10.1016/j.postharvbio.2003.09.008>
- Crane, J.H., Manosalva, P., Faber, B.A., Barrientos-Priego, A.F., Focht, E.D., Arpaia, M.L., Bender, G.S., Balerdi, C.F. (2025): Cultivars and rootstocks. In: Carrillo D, Schaffer B, Whiley AW, Wolstenholme BN (eds) *The avocado: botany, production and uses*, 3rd edn. CABI, Wallingford: 212–263
- Ernst, A. A., Ernst, Z. R., Ernst, E. D. (2015): ‘Maluma’: establishing a new generation avocado cultivar commercially. In VIII Congreso Mundial de la Palta: 1-8.
- Giusti, M. M., Wrolstad, R. E. (2001): Characterization and measurement of anthocyanins by UV-visible spectroscopy. *Current Protocols in Food Analytical Chemistry*. F1: 2.1-F1. 2.13.
- Hofman, P. J., Vuthapanich, S., Whiley, A. W., Klieber, A., Simons, D. H. (2002): Tree yield and fruit mineral concentrations influence ‘Hass’ avocado fruit quality. *Scientia Horticulturae*. 92(2): 113-123.
- Kämper, W., Ogbourne, S.M., Hawkes, D., Trueman, S.J. (2021): SNP markers reveal relationships between fruit paternity, fruit quality and distance from a cross-pollen source in avocado orchards. *Scientific Reports*. 11: 20043. <https://doi.org/10.1038/s41598-021-99394->
- Kayesh, E., Bilkish, N., Zhang, Y., Song, C., Han, J., Cheng, Z.-M., Fang, J., Shangguan, L., Sun, X., Korir, N. K. (2013): Fruit skin color and the role of anthocyanin. *Acta Physiologiae Plantarum*. 35(10): 2879–2890. <https://doi.org/10.1007/s11738-013-1332-8>
- Lahack, M., Noy, M., Szenes, N., Rubinovich, L. (2024): Vegetative growth, flowering, and physiological parameters of young avocado ‘Hass’ and ‘Hass’-like cultivars under extreme weather conditions. 19 December 2024, PREPRINT (Version 1) available at Research Square, <https://doi.org/10.21203/rs.3.rs-5675529/v1>
- Lee, J., Durst, R. W., Wrolstad, R. E. (2005): Determination of total monomeric anthocyanin pigment content of fruit juices, beverages, natural colorants, and wines by the pH differential method: Collaborative study. *Journal of AOAC International*. 88: 1269-1278.
- Mathaba, N., Mafeo, T. P., Kruger, F. J. (2015): The skin colouring problem of “Hass” avocado fruit during ripening. *South African Avocado Growers’ Association Yearbook*. 38: 51–51.
- Mathaba, N., Mathe, S., Mafeo, T. P., Tesfay, S. Z., Mlimi, J. (2017): Complexities of ‘Hass’ avocado skin colour change during ripening. *South African Avocado Growers’ Association Yearbook*. 40: 129–132.
- McGuire, R. G. (1992): Reporting of objective color measurements. *HortScience*. 27: 1254-1255. <https://doi.org/10.21273/hortsci.27.12.1254>
- Mpai, S., Sivakumar, D. (2020): Influence of growing seasons on metabolic composition, and fruit quality of avocado cultivars at ‘ready-to-eat stage’. *Scientia Horticulturae*. 265: 109159. <https://doi.org/10.1016/j.scienta.2019.109159>
- Núñez-Lillo, G., Ponce, E., Arancibia-Guerra, C., Carpentier, S., Carrasco-Pancorbo, A., Olmo-García, L., Chirinos, R., Campos, D., Campos-Vargas, R., Meneses, C., Pedreschi, R. (2023): A multiomics integrative analysis of color de-synchronization with softening of “Hass” avocado fruit: A first insight into a complex physiological disorder. *Food Chemistry*. 408(135215): 135215. <https://doi.org/10.1016/j.foodchem.2022.135215>
- Olivares, D., Ulloa, P. A., Vergara, C., Hernández, I., García-Rojas, M., Campos-Vargas, R., Pedreschi, R., Defilippi, B. (2024): Effects of delaying the storage of ‘Hass’ avocados under a controlled atmosphere on skin color, bioactive compounds and antioxidant capacity. *Plants*. 13: <https://doi.org/10.3390/plants13111455>
- Ramos-Aguilar, A. L., Ornelas-Paz, J., Tapia-Vargas, L. M., Gardea-Béjar, A. A., Yahia, E. M., de Jesús Ornelas-Paz, J., Ruiz-Cruz, S., Rios-Velasco, C., Ibarra-Junquera, V. (2021): Comparative study on the phytochemical and nutrient composition of ripe fruit of Hass and Hass type avocado cultivars. *Journal of Food Composition and Analysis*. 97: 103796. <https://doi.org/10.1016/j.jfca.2020.103796>
- Ranganath, K. G. (2022): Pigments that colour our fruits: An overview. *Erwerbs-Obstbau*. 64(4): 535–547. <https://doi.org/10.1007/s10341-022-00698-3>
- Salvo, J. E., Lovatt, C. J. (2016): Nitrogen fertilization strategies for the ‘Hass’ avocado that increase total yield without reducing fruit size. *HortTechnology*. 26(4): 426-435.
- Setagane, L., Mafeo, T. P., Mathaba, N., Shikwambana, K. (2021): Mitigation of chilling injury with hot water treatment to improve early-season ‘HASS’ avocado (*Persea americana*) fruit peel colour. *Research on Crops*. 22(1): 60–67. <https://doi.org/10.31830/2348-7542.2021.037>
- Shikwambana, K., Mafeo, T. P., Mathaba, N. (2021): Effect of postharvest glucose infusion on exocarp colour of ‘Hass’ avocado (*Persea americana* Mill) during ripening. *Journal of Horticulture and Postharvest Research*. 4(4): 439–452. <https://doi.org/10.22077/jhpr.2021.4254.1202>
- Shikwambana, K., Mafeo, T. P., Mathaba, N. (2022): The relationship between exocarp colour development and pigments of different size ‘Hass’ avocado fruit during ripening. *Acta Horticulturae*. 1340: 93–98. <https://doi.org/10.17660/actahortic.2022.1340.14>
- Sibeko, D. S., Shikwambana, K., Mathaba, N. (2023): Effect of ripening temperature on early-season “Hass” avocado fruit exocarp colour development and pigmentation during ripening. *Zahradnictvi (Prague, Czech Republic: 1992)*. 51(2): <https://doi.org/10.17221/72/2023-hortsci>
- Sun, Y., Zheng, Y., Wang, W., Yao, H., Ali, Z., Xiao, M., Ma, Z., Li, J., Zhou, W., Cui, J., Yu, K., Liu, Y. (2024): VvFHY3 links auxin and endoplasmic reticulum stress to regulate grape anthocyanin biosynthesis at high temperatures. *The Plant Cell*. 37(1): <https://doi.org/10.1093/plcell/koae303>

Villa-Rodriguez, J. A., Yahia, E. M., González-León, A., Ifie, I., Robles-Zepeda, R. E., Domínguez-Avila, J. A., González-Aguilar, G. A. (2020): Ripening of ‘Hass’ avocado mesocarp alters its phytochemical profile and the in vitro cytotoxic activity of its methanolic extracts. *South African Journal of Botany*. 128: 1–8. <https://doi.org/10.1016/j.sajb.2019.09.020>

Zhang, L., Song, B., Li, B., Zhang, S., Liu, Y., Chen, G., Zhang, J., Li, J., Wu, J. (2024): Genome-wide identification and expression analysis of fifteen gene families involved in anthocyanin synthesis in pear. *Horticulturae*. 10(4): 335. <https://doi.org/10.3390/horticulturae10040335>