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Light, Shade, and Temperature Effects on Date Palm Fruits Ripening, Pigments, and Phytohormones

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ABSTRACT

Optimizing light, shade, and temperature conditions can substantially enhance the growth, yield, and quality of date palm fruits. This study evaluated the effects of light intensity, shading (via bagging), and temperature on the physiological and biochemical characteristics of date palm fruits, with a focus on pigment biosynthesis and phytohormonal regulation during ripening. Four cultivars, 'Barhee', 'Braim', 'Khassab', and 'Hellawi', were examined under two light regimes (direct sunlight and paper-bag-induced shade) across four developmental stages from June to August. Chlorophyll levels declined progressively in all cultivars as ripening advanced, with more rapid degradation observed under shaded conditions. In contrast, anthocyanin and carotenoid contents generally increased under shade conditions, particularly in 'Braim' and 'Hellawi', contributing to enhanced fruit coloration. Shading also helped preserve phenolic compounds, while light-exposed fruits exhibited higher ascorbic acid levels, indicating a physiological trade-off between antioxidant accumulation and oxidative stress. Shade treatments promoted higher levels of growth-related hormones, indole-3-acetic acid (IAA), gibberellic acid (GA3), and cytokinins, during mid-season stages, and elevated abscisic acid (ABA) levels during late ripening, suggesting enhanced developmental regulation and stress adaptation. Bagging effectively moderated the fruit microclimate by reducing temperature and increasing relative humidity, thereby improving fruit quality and ripening dynamics. These findings support the use of controlled shading as a practical agronomic strategy to enhance date palm fruit quality under climate stress, while highlighting the importance of cultivar-specific responses in optimizing management practices.

Introduction

The date palm (*Phoenix dactylifera* L.) is among the most significant cultivated plants globally, serving both as a staple food and a symbol of well-being (Al-Karmadi and Okoh, 2024). As one of the earliest domesticated trees, its cultivation has been historically linked to the advancement of human civilization (Hammami et al., 2023). In recent years, scientific interest in the factors influencing the growth and development of date palm fruits has increased, particularly in light of global climate change, including rising temperatures and extreme drought conditions. Research is also expanding into identifying new regions suitable for date palm cultivation. This growing body of knowledge is vital not only for ensuring sustainable production but also for enhancing the economic value of this culturally and nutritionally important crop (Alotaibi et al., 2023).

Date palm cultivars exhibit considerable diversity in fruit morphology, including variations in size, shape, color, and biochemical composition. Both genetic and environmental factors influence these traits. Some cultivars are genetically predisposed to produce larger, sweeter fruits with higher levels of chlorophylls and carotenoids, thereby improving both nutritional quality and visual appeal (Alrashidi et al., 2023). However, environmental stresses, such as elevated temperatures, heat waves, water scarcity, and soil salinity, can significantly affect the accumulation of photosynthetic pigments in both leaves and fruits, ultimately impacting fruit quality. For example, cultivars adapted to arid or harsh environments may accumulate higher carotenoid levels to protect the photosynthetic machinery, resulting in fruit with distinctive coloration (Kordrostami et al., 2022). Environmental variables such as light intensity, shading, and temperature are especially critical for date palm fruit development. These factors directly influence the photosynthetic apparatus, which drives the physiological and biochemical processes underlying growth and ripening (Al-Alawi et al., 2017). Light availability and temperature fluctuations affect not only the rate of photosynthesis but also the biosynthesis and degradation of pigments such as chlorophylls and carotenoids, which in turn influence the ripening process and overall fruit quality (Shareef and Al-Khayri, 2020).

Light intensity, duration, and spectral composition play a pivotal role in modulating key physiological and metabolic processes in plants, including photosynthesis, chlorophyll synthesis, and broader metabolic activity (Paradiso and Proietti, 2022). In date palms, light availability influences canopy architecture by shaping the distribution of photosynthetically active radiation (PAR), which in turn affects fruit quality and yield (Tang et al., 2019). Alterations in spectral composition, due to neighbouring trees or artificial shading methods, create heterogeneous light environments that reduce photosynthetic efficiency and pigment synthesis (Ladux et al., 2021). These changes ultimately influence plant growth and the overall quality of date palm fruits (Shareef and Al-Khayri, 2020). Temperature is another crucial environmental factor that significantly affects plant physiology and metabolism. Although date palms are well-adapted to a broad range of temperatures (Kadri and Mimoun, 2020), diurnal and seasonal fluctuations can profoundly impact fruit development (Shareef, 2024). Temperature regulates enzymatic activity, membrane fluidity, and hormonal balance, all of which are integral to fruit growth, ripening, and pigment accumulation (Anwar et al., 2018). Therefore, the interplay between light, shade, and temperature is critical for optimizing the physiological and biochemical pathways that govern fruit development in date palms (Shareef, 2024). Understanding these interactions is essential for developing effective cultivation practices. Strategic use of shading and bagging techniques can help regulate microclimatic conditions, thus improving fruit yield and quality (Shareef and Al-Khayri, 2020). Bagging, in particular, has reportedly protected fruits from harsh environmental conditions, such as high temperatures and low relative humidity, which can negatively affect fruit maturation and overall quality (Omar, 2015). The microenvironment created by the bags maintains more stable conditions conducive to fruit development, reduces fruit drop, and improves physical and chemical quality traits (Kahramanoğlu and Usanmaz, 2019). In contrast, unbagged fruits are more vulnerable to environmental stressors. They typically exhibit reduced weight and volume, as well as inferior chemical characteristics such as lower sugar content (Jubeir et al., 2023). Moreover, the lack of protective barriers increases susceptibility to pests, diseases, and environmental damage, including sunburn, cracking, and desiccation, compromising both appearance and taste (Alebidi et al., 2024; Dawoud and El-Rauof, 2022). These findings highlighted the value of microclimate control through bagging as a practical strategy for enhancing both the agronomic performance and market quality of date palm fruits.

Plant hormonal and antioxidant responses play a crucial role in the ripening of date palm fruits by modulating metabolic processes, particularly under high light intensity. In contrast, shaded conditions, by limiting direct light exposure, slow down the oxidation of key metabolites and prolong the developmental stages of the fruit (Shareef and Al-Khayri, 2020). This study investigated the physiological and biochemical responses of multiple date palm cultivars to differing light and shade conditions. Specifically, it examined how variations in light intensity and temperature during the ripening period influence the accumulation of photosynthetic pigments, phenolic compounds, and phytohormones in the fruits. The overarching objective was to identify optimal cultivation strategies that improve fruit quality and enhance resilience to environmental stressors.

Materials and Methods

The experiment was conducted using a randomized complete block design (RCBD) with three factors: light intensity at two levels (direct and indirect sunlight, corresponding to unbagged and bagged treatments, respectively), four cultivars ('*Barhee*', '*Braim*', '*Khassab*', and '*Hellawi*'), and sampling time at four intervals after pollination (early June, late June, July, and August) (Fig. 1). Each treatment included five replications. The study was carried out during the 2023 growing season in a private orchard located in the Al-Hartha region of Basrah, Iraq (30°44'43.4"N, 47°39'40.9"E), using nine-year-old date palm trees. All trees were maintained under uniform horticultural practices, including standard pruning, irrigation, and fertilization. Forty trees were selected as experimental units, with five inflorescences retained on each tree. Artificial pollination was performed using male spathes from the ‘*Al-Ghannami Al-Akhdhar*’ cultivar. Two to three strands of male flowers were inserted into the female spathes. Immediately after pollination, fruit bunches were bagged using 50 × 70 cm brown paper bags to create shaded conditions (Fig. 2). Unbagged bunches on comparable trees were used to represent the direct sunlight treatment. The bags were applied immediately following pollination and remained on the bunches until the final sampling in August. For each cultivar, five trees were assigned to the bagged treatment and five to the unbagged control. Beginning two months after pollination, fruit samples (100 fruits per treatment) were collected monthly for analysis. Light intensity was measured daily at 11:00 AM using a photometer. At the same time, temperature and relative humidity were recorded both in the open field and under the bags using a hygro-thermometer. As shown in Table 1, environmental conditions fluctuated throughout the study period, and no precipitation was recorded. The light intensity under the brown paper bags was consistently measured at 0.00 cd, confirming the exclusion of direct light.

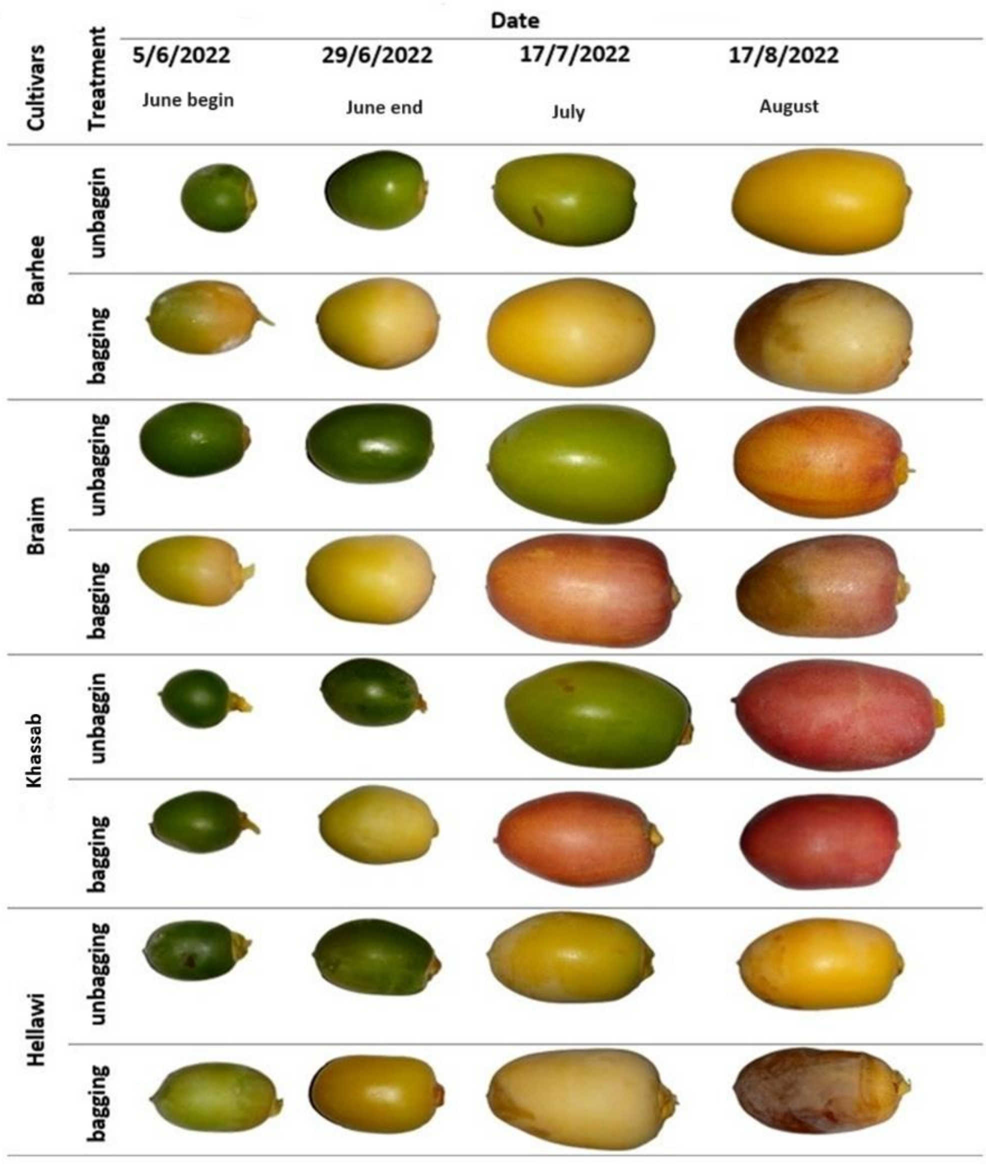

Fig. 1. Effects of direct sunlight (unbagged) and indirect sunlight (bagged) on fruit growth and photosynthetic pigments of four date palm cultivars: ‘Barhee’, ‘Braim’, ‘Khassab’, and ‘Hellawi’. Bagging generally accelerates the color change. For most cultivars, the fruit color transition follows a pattern from green to yellow and, in some cases, to red.

Fig. 2. Fruit bunches bagged using 50 × 70 cm brown paper bags. Unbagged bunches on similar trees represented the direct sunlight treatment.

Table 1. Daily light intensity and temperature during the 2023 growth season.

Month	Light intensity, (cd)	Air temperature, (°C)	Temperature under the bags, (°C)	Relative humidity (%)	Relative humidity under the bag (%)
June 5-6-2023	0.98	42	37	28.8	34.2
June 29-6-2023	1.00	44	38	32.6	38.5
July 17-7-2023	1.01	46	40	34.2	39.5
August 17-8-2023	1.19	47	42	32.3	37.6

Analysis of photosynthetic pigments

Pigment contents were extracted from fresh date palm fruits following the method of Lichtenthaler and Wellburn (1983). Briefly, 200 mg of fruit tissue was homogenized in 8 mL of 80% acetone and centrifuged at 3000 rpm for 3 min. The supernatant was collected, and absorbance was measured using a spectrophotometer at 645 nm for total chlorophyll, 663 nm for anthocyanins, and 470 nm for carotenoids.

Total phenolic content

Phenolic content was determined using the Folin–Ciocalteu method as described by Waterman and Mole (1993). In a 1.5 mL Eppendorf tube, 790 µL of distilled water, 10 µL of the sample extract, and 50 µL of Folin–Ciocalteu reagent were mixed and vortexed for 5 min. Then, 150 µL of 20% sodium carbonate (Na_2CO_3) was added, followed by another 5 min of vortexing. The mixture was incubated in the dark at room temperature for 2 h. Absorbance was measured at 750 nm using a spectrophotometer. Total phenolic content was quantified using a gallic acid standard curve and expressed as milligrams of gallic acid equivalents per 100 g of fresh tissue (mg GAE 100 g^{-1} fresh weight).

Ascorbic acid content

Ascorbic acid (AsA) content was determined following a method described by Luwe et al. (1993), with minor modifications. Briefly, 0.5 g of date fruit tissue was ground in liquid nitrogen and homogenized in 1% cold trichloroacetic acid (TCA). The homogenate was centrifuged at 12,000 × g for 20 min at 4 °C. A 50 µL aliquot of the resultant supernatant was mixed with 100 mM potassium phosphate buffer (pH 7.0), and absorbance was measured at 265 nm using a spectrophotometer to estimate the AsA concentration.

Analysis of hormones

To ensure data consistency, the same tissue extracts were used for the quantification of indoleacetic acid (IAA), abscisic acid (ABA), gibberellic acid (GA_3), and zeatin (ZT). Date fruits were collected, washed, surface-dried, and immediately flash-frozen in liquid nitrogen before storage at -20 °C. Fresh tissue samples (1 g) were ground in liquid nitrogen and extracted overnight with 30 mL of 80% cold methanol at 4 °C. The extract was then centrifuged at 2000 × for 15 min at 4 °C, and the supernatant was collected. Additional cold methanol was used to re-extract the residue, and the combined supernatants were dried and reconstituted in 10 mL of methanol. Quantification of IAA, ABA, GA_3, and ZT was performed using high-performance liquid chromatography (HPLC) on a C18 reverse-phase column (250 × 4.60 mm, 5 µm) under isocratic elution conditions. The mobile phase consisted of acetonitrile:water (26:74, v/v) containing 30 mM phosphoric acid, following the protocol of Tang et al. (2011).

Statistical analysis

The data were analyzed using SPSS version 21.0 (SPSS, Chicago, IL) and mean values were separated using Duncan's test ($P \leq 0.05$).

Results

Chlorophyll content

As shown in Figure 3, chlorophyll content in date palm fruits was significantly influenced by both light conditions and developmental stage. In all cultivars, chlorophyll levels were consistently higher under direct light compared to shaded (bagged) conditions. A progressive decline in chlorophyll concentration was observed from early June through August, reflecting a typical pattern of pigment degradation associated with fruit maturation. The decline was more pronounced under shaded conditions, where chlorophyll levels were substantially reduced and, in some cases, nearly undetectable by August. Among the cultivars, '*Barhee'* and '*Hellawi'* exhibited a more rapid reduction in chlorophyll content under both light regimes, whereas '*Braim'* and '*Khassab'* maintained relatively higher levels during the early stages of development.

Anthocyanin content

Anthocyanin accumulation in date palm fruits was significantly affected by cultivar, developmental stage, and light exposure (Fig. 4). Shaded conditions consistently resulted in higher anthocyanin content compared to direct light across all cultivars. Anthocyanin levels increased progressively from early June to August, reflecting the typical pattern of pigment accumulation during ripening. The shading effect was especially pronounced in the 'Braim' and 'Khassab' cultivars, which showed substantial increases in anthocyanin content under shade, particularly in July and August. In contrast, 'Barhee' and 'Hellawi' exhibited more moderate responses, with overall lower anthocyanin levels and less sensitivity to shading.

Carotenoid content

Carotene pigment levels in date palm fruits were influenced by light conditions, developmental stage, and cultivar-specific responses (Fig. 5). '*Barhee'* and '*Hellawi'* exhibited a steady increase in carotene content throughout the ripening period, with slightly higher concentrations under shaded conditions, particularly in the later stages. In contrast, '*Braim'* demonstrated an initial rise in carotene levels under both light regimes, followed by a marked decline under shade after July. '*Khassab'* maintained relatively stable carotene concentrations across both light and shade treatments, showing minimal variation throughout development.

Phenols content

According to Figure 6, phenolic content in date palm cultivars was significantly affected by light exposure, developmental stage, and genotype. In general, shaded conditions favored higher phenol retention compared to light-exposed conditions. Across most cultivars, phenolic levels declined progressively from June to August, with the reduction more pronounced under light exposure. However, shading appeared to mitigate this decline, particularly during the later stages of fruit development, as evident in the 'Barhee', 'Braim', and 'Hellawi' cultivars. Notably, 'Khassab' displayed a distinct trend and accumulated higher phenol levels under shade during early development, but exhibited minimal differences between light and shade treatments in the later stages.

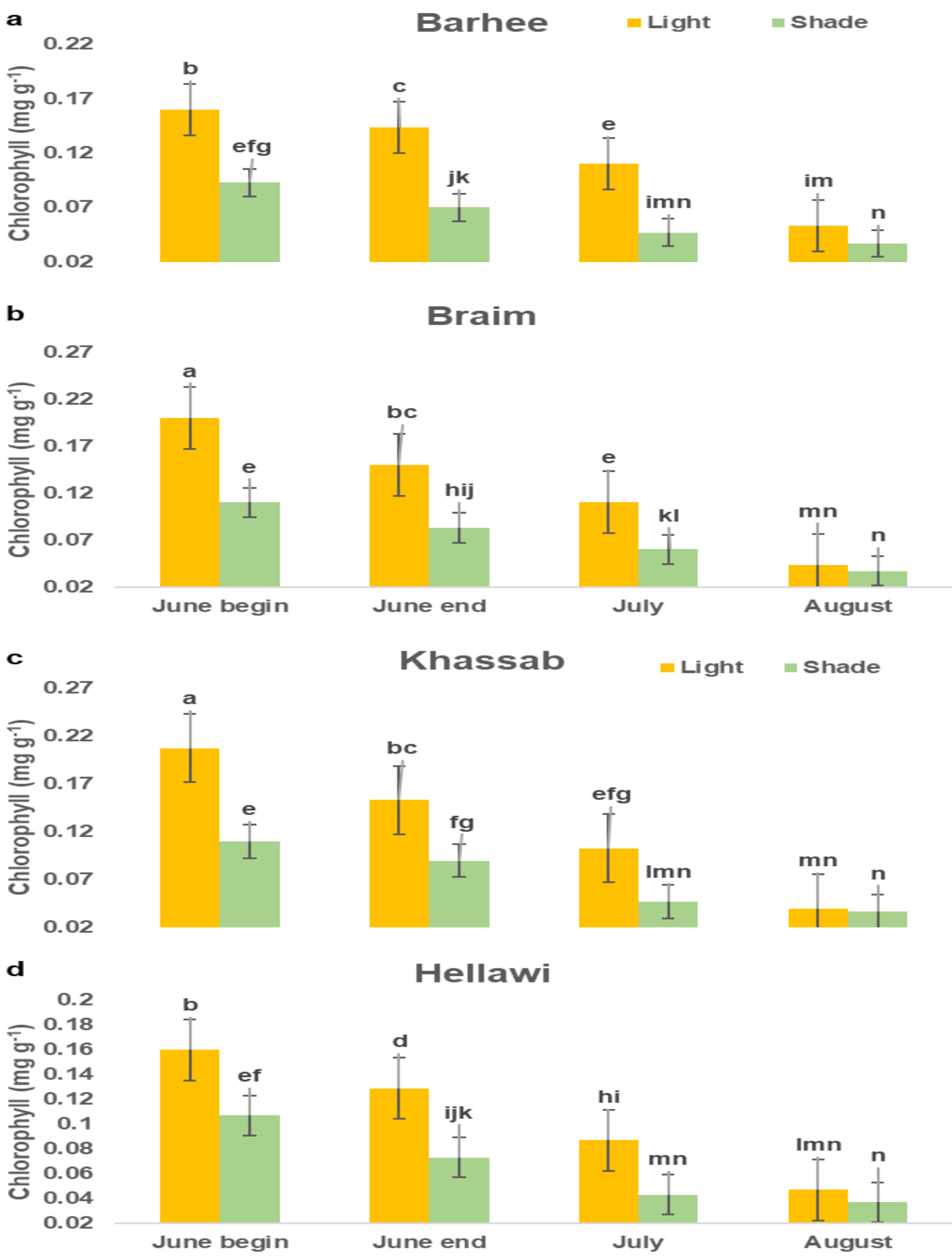

Fig. 3. Effects of light and shade on the chlorophyll content of four date palm cultivars: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Ascorbic acid content

Figure 7 showed that ascorbic acid content in date palm cultivars was influenced by light exposure, developmental stage, and varietal differences, with higher concentrations observed under light conditions compared to shade. In most cultivars, ascorbic acid levels declined gradually from early June to August. This decline was more pronounced under shaded conditions, particularly in 'Barhee', 'Braim', and 'Hellawi'. Meanwhile, 'Khassab' exhibited a relatively moderate reduction, maintaining closer values between light and shade throughout development.

Indole-3-acetic acid content

According to Figure 8, light and shade affected indole-3-acetic Acid (IAA) levels in various date palm cultivars over time. The results indicated that IAA accumulation is influenced by light exposure, with higher concentrations observed in shaded conditions during the early months. The

'Barhee' and 'Braim' cultivars exhibited peak IAA levels in July under both light and shade, though they experienced declines by August. Similarly, the 'Khassab' cultivar showed consistent trends, maintaining elevated IAA levels in shaded conditions. In contrast, the 'Hellawi' cultivar displayed a significant drop in IAA content by August, particularly in non-shade conditions.

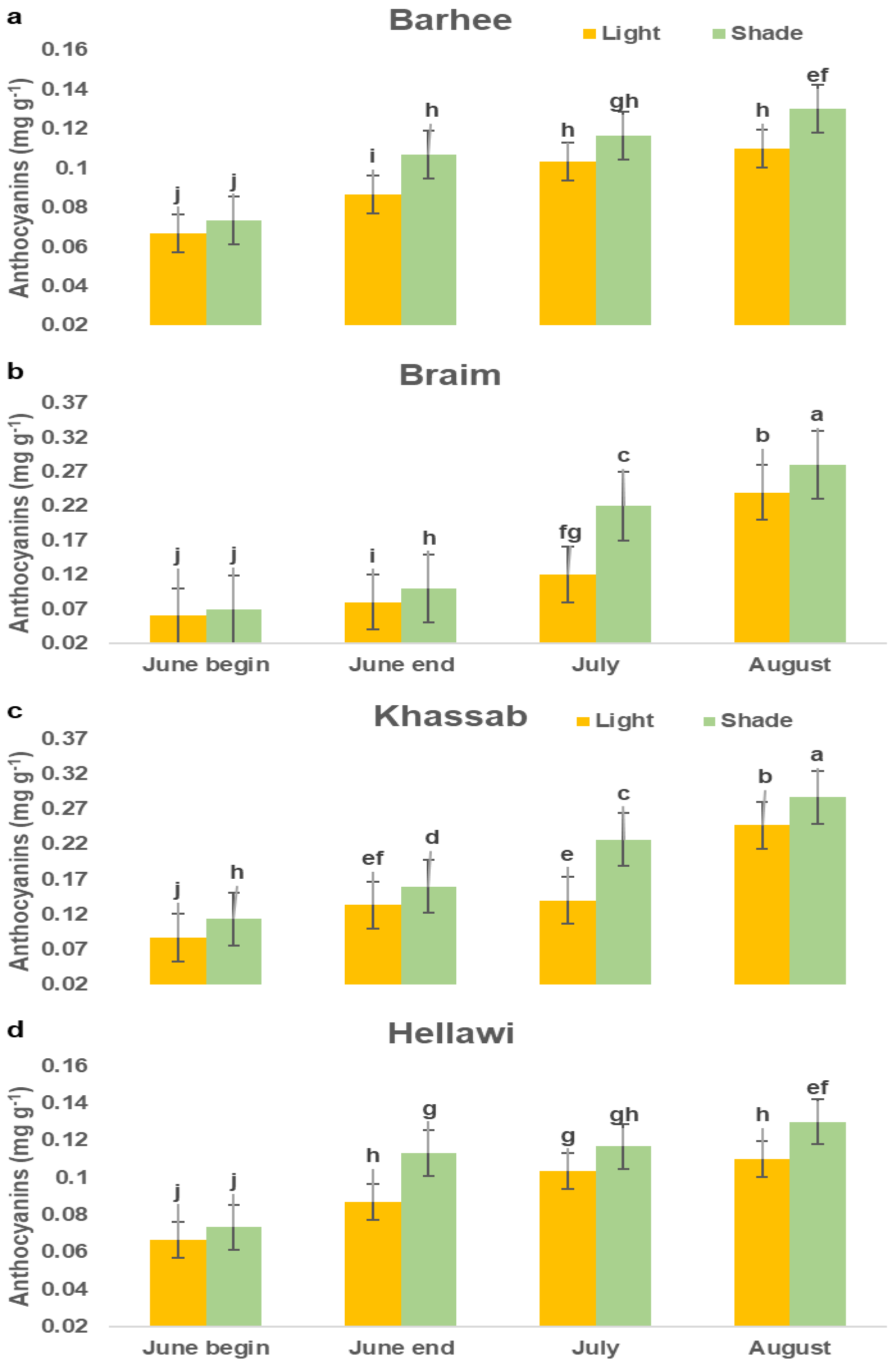

Fig. 4. Effects of light and shade on the content of anthocyanins in four date palm cultivars: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

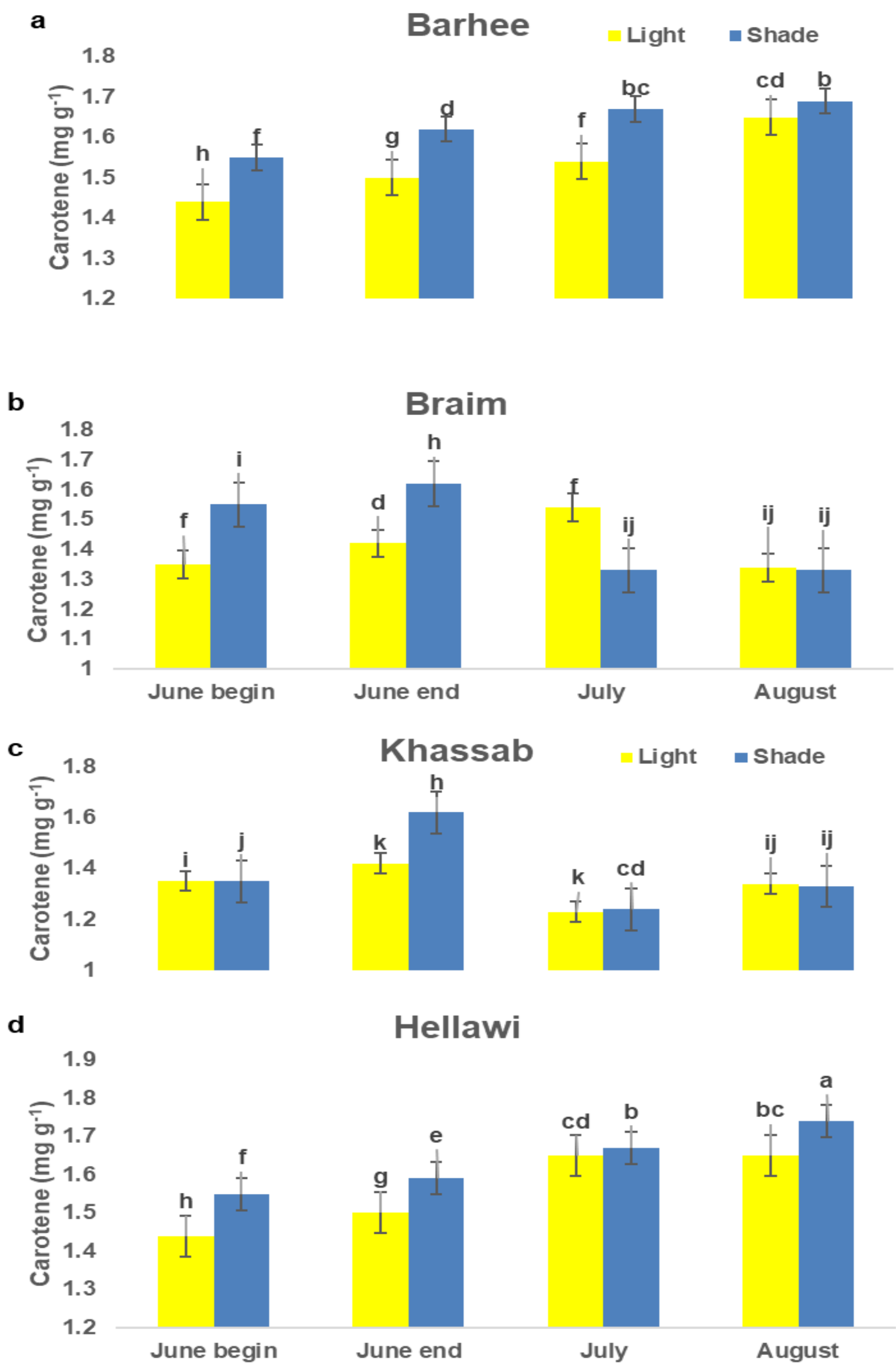

Fig. 5. Effects of light and shade on carotene content in date palm cultivars: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Gibberellic acid content

Figure 9 illustrates the influence of light and shade on gibberellic acid (GA_3) concentrations in various cultivars of date palm throughout the growing season. The results indicate that GA_3 levels were significantly higher under shaded conditions during the early months, with peak concentrations observed in July. Notably, the 'Barhee' and 'Braim' cultivars exhibited pronounced increases in GA_3 levels when grown in shade. In contrast, a general decline in GA_3 concentration was observed in light-exposed conditions by August across most cultivars. The 'Khassab' cultivar demonstrated relatively stable GA_3 levels under both light regimes, whereas the 'Hellawi' cultivar exhibited marked fluctuations, underscoring cultivar-specific variability in hormonal responses to light conditions.

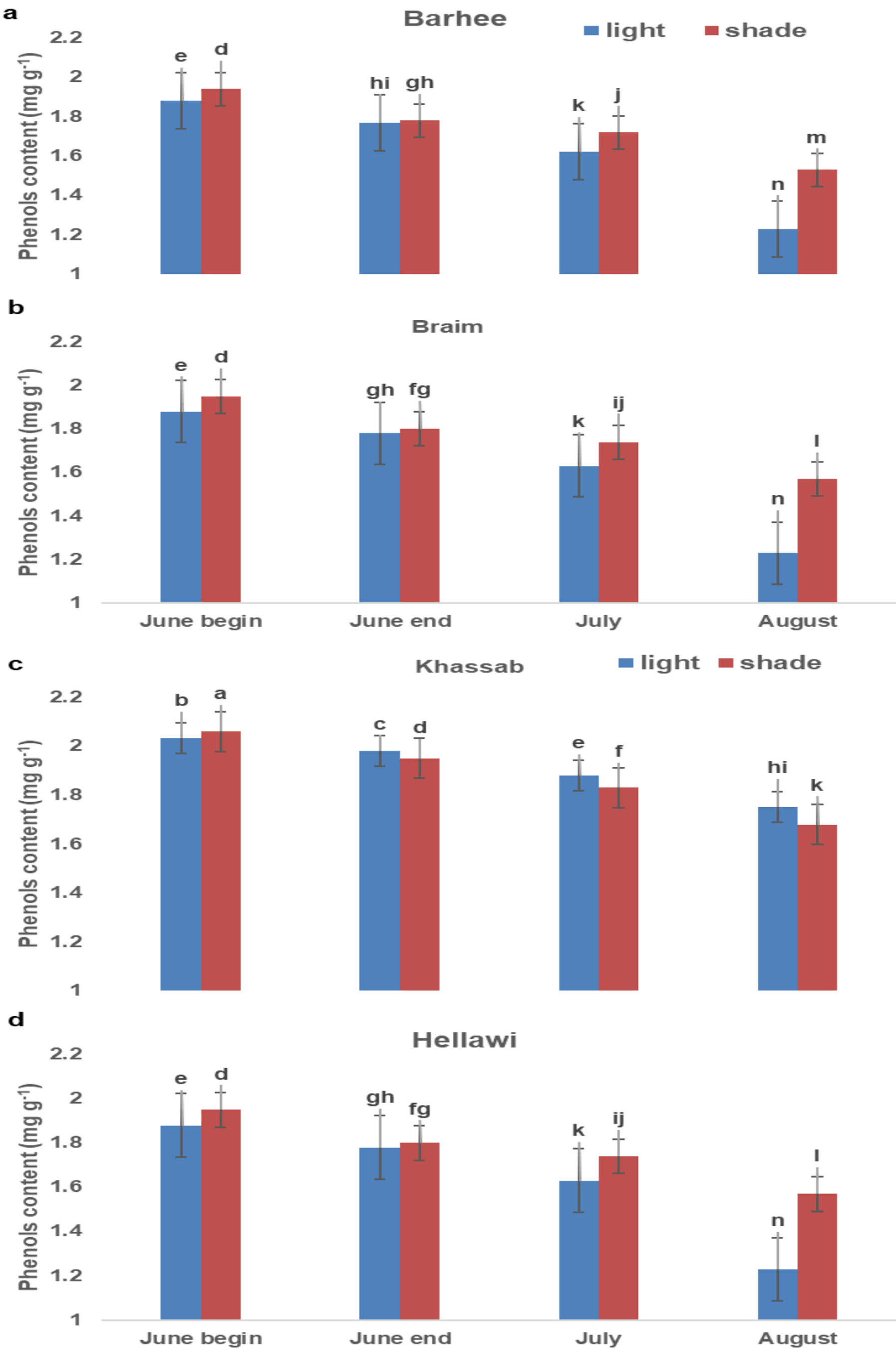

Fig. 6. Effects of light and shade on phenols content in the four date palm cultivars: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during summer months: June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Cytokinin (CK) content

The effects of light and shade on cytokinin (CK) content differed in various date palm cultivars throughout the growing season (Fig. 10). The data reveal that CK levels increased in shaded conditions, particularly during the mid to late season. The 'Barhee' and 'Braim' cultivars exhibited consistent increases in CK content in the shade, with notable peaks observed in August. In contrast, the 'Khassab' cultivar displayed lower CK levels compared to others, although it still showed a response to shade, particularly in June and July. The 'Hellawi' cultivar demonstrated a significant rise in CK content by August under light conditions.

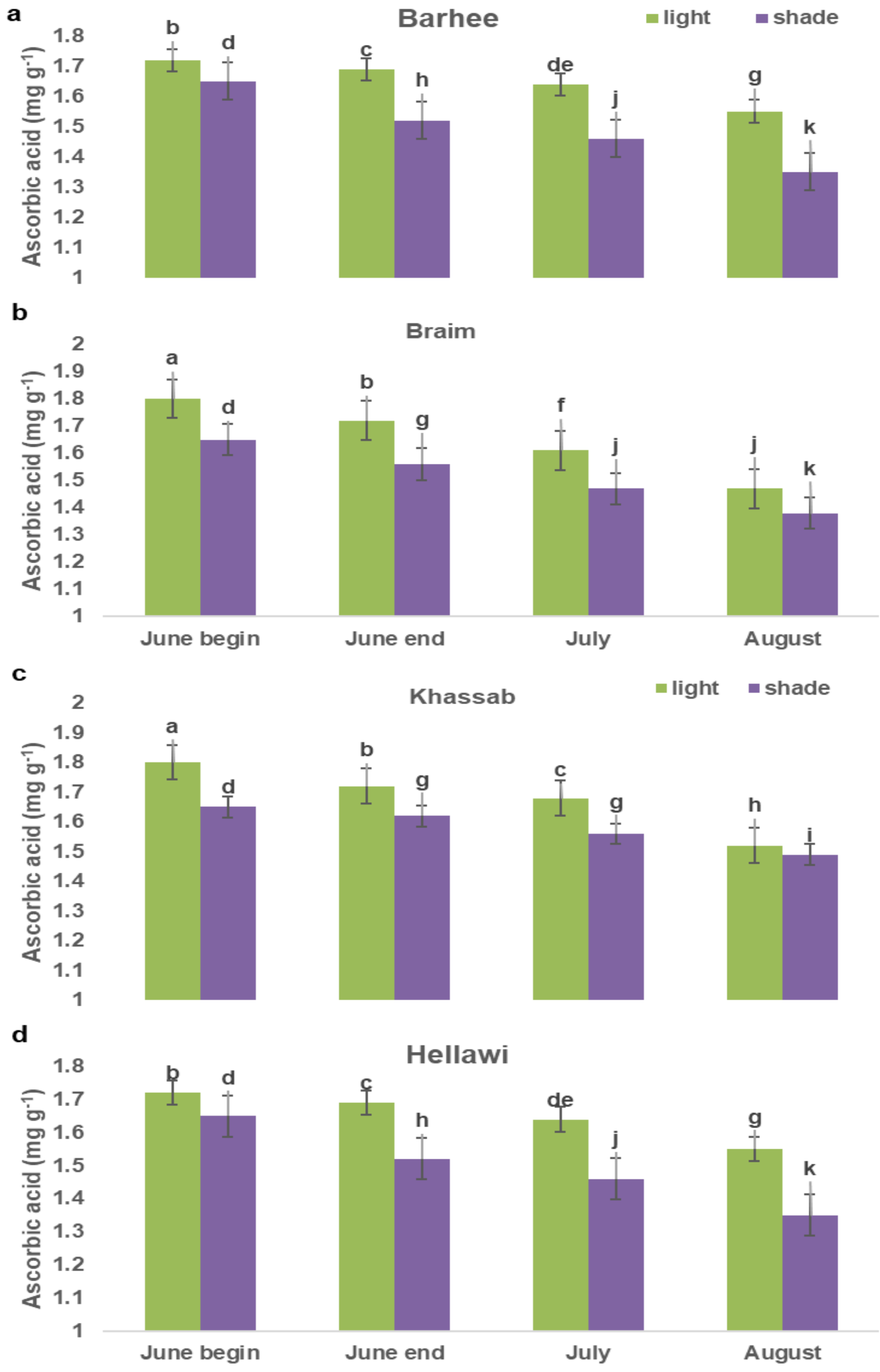

Fig. 7. Effects of light and shade on ascorbic acid content in the four date palm cultivars: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during summer months: June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

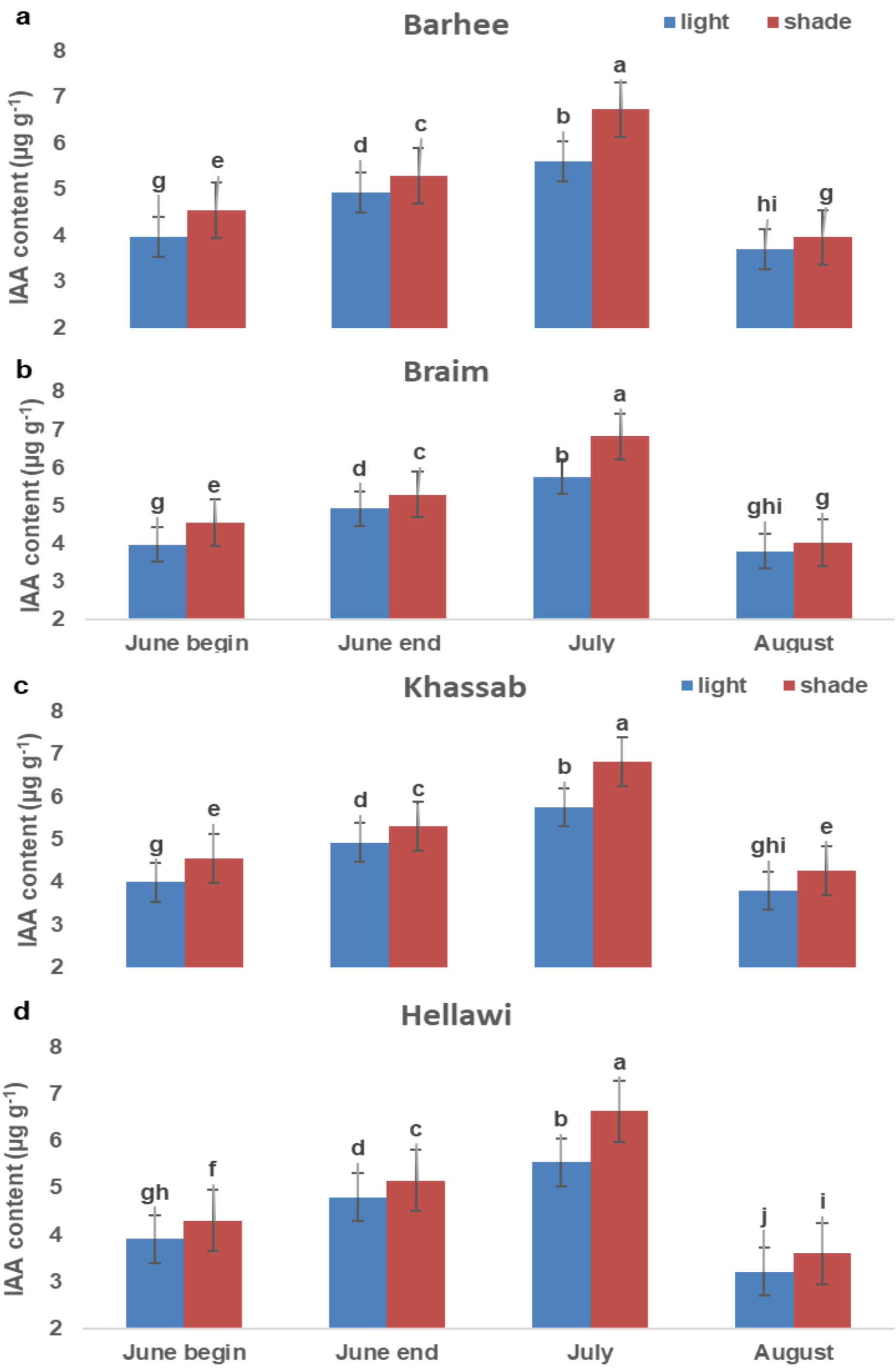

Fig. 8. Effects of light and shade on phytohormone content IAA in date palm: (**a**) 'Barhee'; (**b**) 'Braim'; (**c**) 'Khassab'; (**d**) 'Hellawi' during the summer months: June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Abscisic acid (ABA)

The effects of light and shade on abscisic acid (ABA) levels varied among the date palm cultivars throughout the growing season (Fig. 11). The results indicated that ABA concentrations increased under shaded conditions, particularly evident in the late summer months. Both the 'Barhee' and 'Braim' cultivars displayed consistent ABA levels in the light and shade, with slight increases noted in shaded environments. The 'Khassab' cultivar maintained stable ABA levels, while the 'Hellawi' cultivar exhibited notable fluctuations, especially a significant rise in light conditions during July.

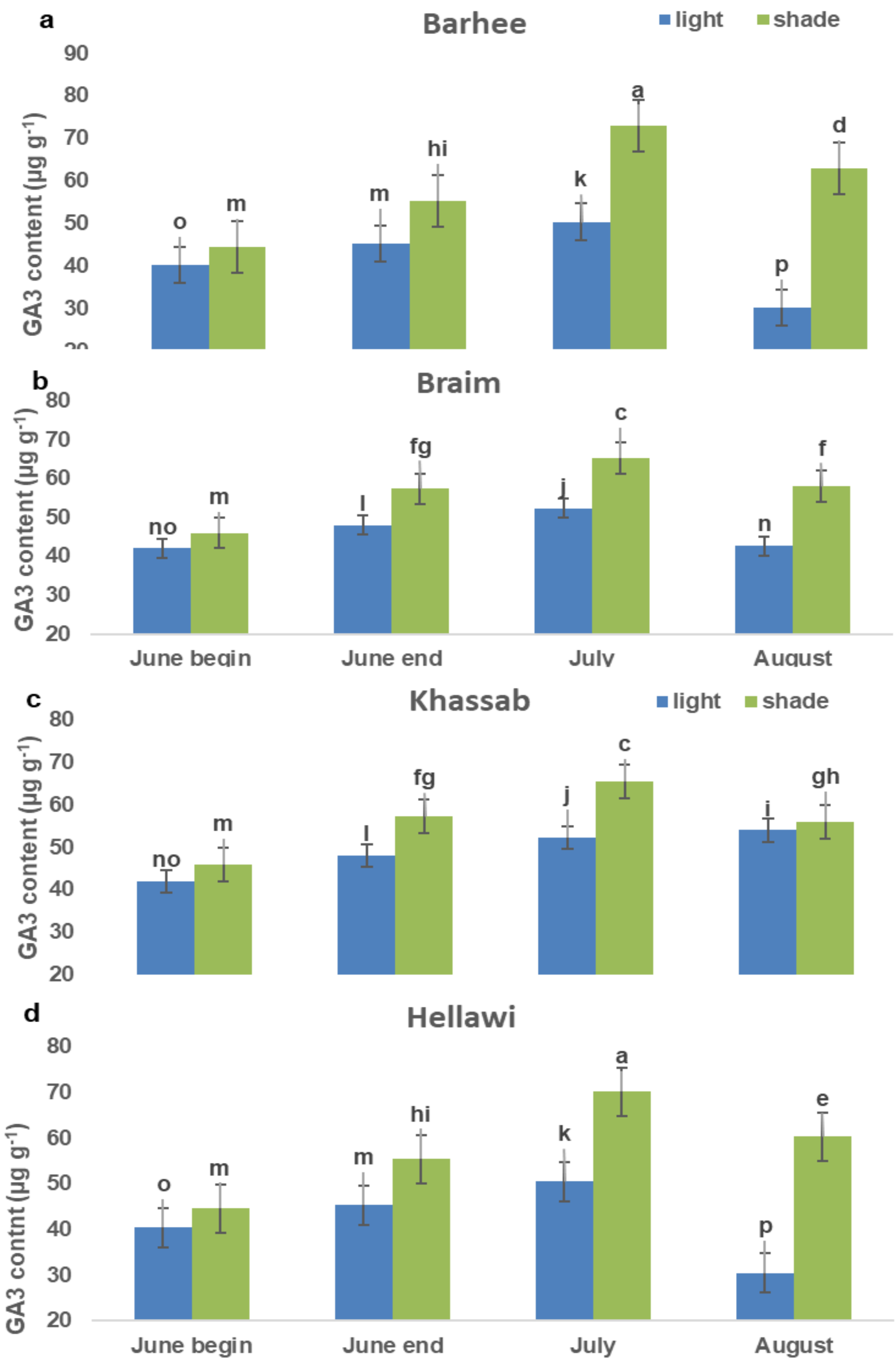

Fig. 9. Effects of light and shade on phytohormone content GA3 in date palm: (**a**) 'Barhee', (**b**) 'Braim', (**c**) 'Khassab', (**d**) 'Hellawi' during the summer months: June (beginning), June (end), July, and August). Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

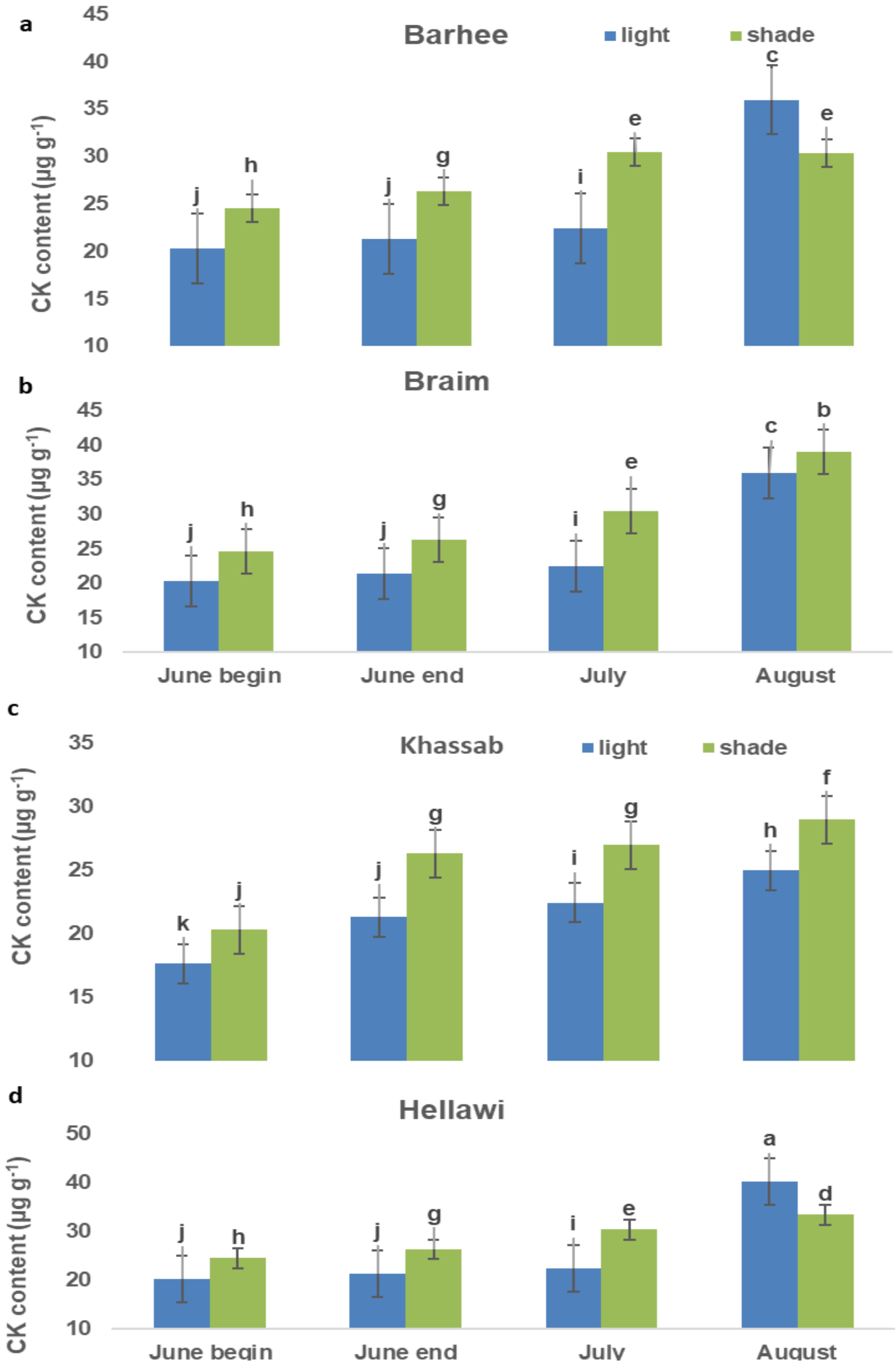

Fig. 10. Effects of light and shade on phytohormone content CK in date palm : (**a**) 'Barhee', (**b**) 'Braim', (**c**) 'Khassab', (**d**) 'Hellawi' during the summer months: June (beginning), June (end), July, and August. Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Discussion

This study presented a comprehensive analysis of how environmental variables, specifically light intensity, shading (via fruit bagging), and temperature, influenced the physiological and biochemical development of date palm (*Phoenix dactylifera* L.) fruits. The investigation encompassed four cultivars ('*Barhee'*, *'Braim'*, '*Khassab'*, and '*Hellawi'*), with a particular emphasis on pigment biosynthesis and hormonal regulation during the ripening process. The findings highlighted the crucial role of microclimate manipulation, such as fruit bagging, in improving fruit quality and yield under extreme environmental conditions, a factor of increasing relevance in the context of climate change. As shown in Table 1, bagging consistently moderated the microclimate surrounding the developing fruits. Ambient air temperatures ranged from 42 °C in early June to 47 °C by mid-August, whereas temperatures inside the bags remained approximately 4–5 °C lower. Relative humidity within the bags was also higher by up to 6%. These microenvironmental modifications were instrumental in regulating enzymatic activity and hormonal metabolism (Anwar et al., 2018), thereby creating favorable conditions for pigment stability and hormonal balance. These adjustments appeared to alleviate oxidative stress and supported a more controlled ripening trajectory, particularly in relation to temperature-sensitive processes such as chlorophyll degradation and anthocyanin accumulation. In this research, it was further confirmed that the lower internal temperatures resulting from bagging facilitated the enzymatic and hormonal processes necessary for accelerated and regulated fruit ripening under otherwise high-temperature stress conditions.

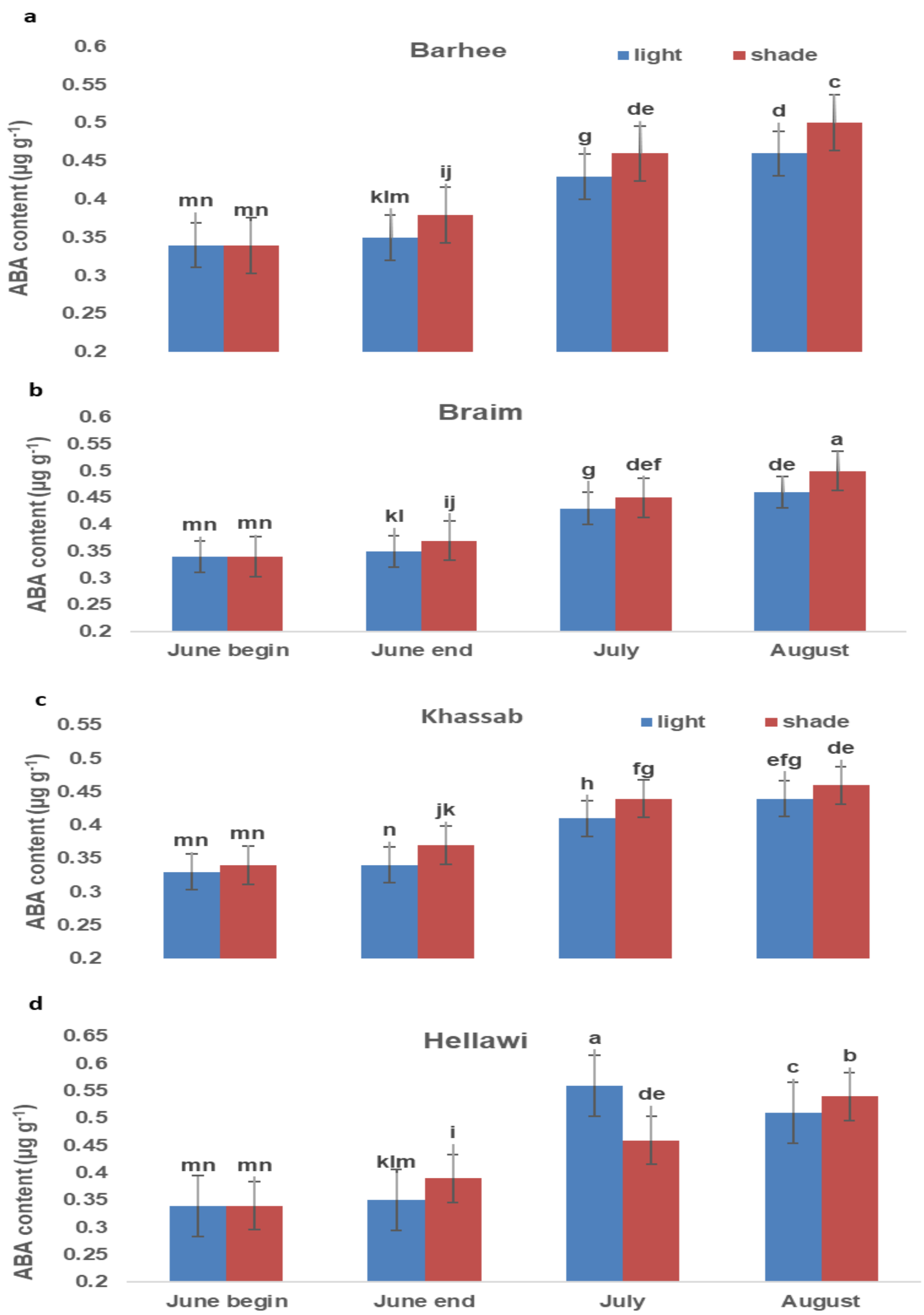

Fig. 11. Effects of light and shade on phytohormone content ABA in date palm cultivars: (**a**) ‘Barhee’, (**b**) ‘Braim’, (**c**) ‘Khassab’, (**d**) ‘Hellawi’ during the summer months: June (beginning), June (end), July, and August). Data are mean values of five samples (trees) ± SE. Means with the same letters are not significantly different ($P \leq 0.05$).

Chlorophyll levels declined steadily from early June to August across all cultivars, consistent with typical ripening progression. However, the rate of decline was significantly greater under shaded (bagged) conditions compared to direct sunlight. These results suggested that shading accelerated chlorophyll degradation, facilitating a faster transition from green to yellow coloration, a process regulated by both environmental stimuli and hormonal signaling. Anthocyanin concentrations increased markedly during the maturation period and remained consistently higher under shaded conditions, with this effect being particularly pronounced in the '*Braim'* and '*Khassab*' cultivars. The elevated anthocyanin levels under shade were likely due to the activation of low-light signaling pathways involving photoreceptors such as phytochromes and cryptochromes (Shi et al., 2023). Additionally, shaded environments have been associated with reduced levels of reactive oxygen species (ROS), thereby minimizing anthocyanin degradation (Lin et al., 2021). These findings indicated that indirect light conditions fostered a hormonal and metabolic environment conducive to anthocyanin accumulation, enhancing both fruit coloration and potential antioxidant capacity (Al-Farsi et al., 2005). Carotene accumulation patterns varied among cultivars. '*Barhee'* and '*Hellawi'* demonstrated consistent increases under both light conditions, with slightly elevated levels in shaded environments, particularly later in the season. In contrast, '*Braim'* exhibited a mid-season peak in carotene levels followed by a decline under shade, while '*Khassab'* showed minimal variation throughout the season. Carotenoids, such as β-carotene, function both as precursors to vitamin A and as protectants against photooxidative stress. Their biosynthesis is closely tied to environmental factors such as light intensity and temperature. The observed enhancement of carotenoid accumulation under shade in some genotypes aligned with previous findings that moderate light exposure promotes carotenoid stability, potentially by reducing photobleaching (Sawicki et al., 2015). Phenolic compound levels declined as fruits matured, with a more pronounced reduction observed under direct sunlight. In contrast, shading effectively slowed this decline, particularly in the '*Barhee*' and '*Braim*' cultivars. Phenolics play a key role in plant defense and the mitigation of oxidative stress. Their biosynthesis is typically stimulated by moderate environmental stress, but sustained oxidative conditions can lead to their degradation (Duarte et al., 2013). Thus, the buffered microenvironment created by fruit bagging appeared to preserve phenolic content, potentially enhancing both fruit quality and nutritional value.

Ascorbic acid (vitamin C) content was generally higher in fruits exposed to light, although it declined over time under both treatment conditions. Light is known to promote ascorbate biosynthesis, a critical antioxidant in plant tissues. However, this advantage may be counterbalanced by increased photooxidative stress, which accelerates ascorbate degradation (Yin et al., 2022). The '*Khassab'* cultivar maintained relatively stable ascorbic acid concentrations throughout the season, suggesting an inherent genetic resilience. These observations underscore the importance of optimizing light exposure to maximize antioxidant biosynthesis while minimizing stress-induced losses. Indole-3-acetic acid (IAA), the primary form of auxin, peaked in July, particularly in shaded fruits. Its subsequent decline by August corresponded with the onset of ripening, consistent with the known suppression of auxin during the transition to ethylene- and abscisic acid (ABA)-mediated ripening pathways (Park et al., 2017). Gibberellic acid (GA_3) followed a similar seasonal pattern, with shaded fruits maintaining elevated levels through mid-season. Gibberellins are central to fruit development, particularly in promoting cell elongation and fruit enlargement. Their biosynthesis is sensitive to both light intensity and temperature (Stavang et al., 2007). The prolonged GA_3 presence in shaded conditions likely contributed to enhanced fruit growth, aligning with previous research that associated fruit bagging with increased fruit size and weight (Kahramanoğlu and Usanmaz, 2019).

Cytokinin (CK) levels increased progressively over the growing season, peaking in August under shaded conditions, most notably in the '*Barhee'* and '*Braim'* cultivars. Cytokinins are known to regulate cell division and delay senescence, thereby prolonging the developmental phase. Abscisic acid (ABA) concentrations increased in all cultivars toward the end of the season, with consistently higher levels observed in shaded fruits. ABA plays a pivotal role in initiating ripening and mediating stress responses. Recent findings have confirmed its central function in regulating date palm fruit ripening (Elbar et al., 2023). The elevated ABA levels in shaded fruits suggested that bagging not only mitigated environmental stress but also enhanced the fruit's physiological preparedness for ripening onset. Collectively, the results demonstrated that microclimate modification through fruit bagging, by reducing ambient temperature and altering light intensity, significantly influenced the hormonal regulation and ripening dynamics of date palm cultivars. The observed temperature reduction inside the bags likely fostered an optimal biochemical environment conducive to pigment biosynthesis, hormone balance, and overall fruit quality enhancement.

Conclusion

This research demonstrated that modifying the microenvironment surrounding developing date palm fruits through shading (bagging) significantly influenced ripening dynamics, pigment biosynthesis, and phytohormonal regulation across cultivars. Shading consistently reduced ambient temperature and increased relative humidity, conditions that favored enhanced synthesis of anthocyanins and carotenoids, improved retention of phenolic compounds, and prolonged activity of growth-associated hormones such as indole-3-acetic acid (IAA), gibberellic acid (GA_3), and cytokinins. These effects collectively improved fruit coloration and quality. Although ascorbic acid concentrations were generally higher in light-exposed fruits, reflecting some nutritional advantages of sunlight exposure, the overall benefits of shading in mitigating thermal stress and enhancing fruit quality were more pronounced. Consequently, fruit bagging represents a practical, cost-effective agronomic intervention for improving fruit development and quality under high-temperature conditions, with cultivar-specific responses that warrant consideration in management strategies.

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Author contributions

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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