Effect of Shading on Saffron (Crocus sativus L.) Performance under Intense Solar Radiation: Interactions with Planting Depth and Corm Weight

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Abstract

Background

Agronomic practices that mitigate temperature stress and optimize light conditions are vital for enhancing saffron (*Crocus sativus* L.) yield under intense solar radiation and minimal rainfall. This study evaluated the interactive effects of four shading levels (0%, 15%, 30%, 45%), three planting depths (10, 15, and 20 cm), and two corm weight classes (4–6 g and 9–11 g) in a splitfactorial design with three replications in an arid–semiarid context.

Results

Shading emerged as the dominant factor limiting yield, with high shade (45%) significantly decreasing pigment content, daughter corm weight, and stigma yield. Deeper planting under shaded conditions accelerated chlorophyll degradation—particularly in larger corms—while moderate shading (15–30%) promoted carotenoid accumulation. Heavier corms (9–11 g) partially mitigated the negative effects of shading and depth. Peroxidase activity increased over time across treatments and was consistently higher in larger corms. Optimal yield was achieved under moderate shading and shallow planting (10 cm) using heavier corms.

Conclusions

These findings highlight that moderate shading combined with shallow planting and heavier corms optimizes saffron performance in environments characterized by intense solar radiation, temperature fluctuations, and minimal precipitation. Tailored management of light exposure, planting depth, and corm size may significantly improve yield under such challenging environmental conditions.

Introduction

Saffron (*Crocus sativus* L.), is a perennial, herbaceous, sterile triploid geophyte of the Iridaceae family, prized for its red stigmas, which are widely used in culinary and medicinal applications. The spice is highly valued for its antioxidant, anti-inflammatory, and therapeutic properties, attributed to more than 100 bioactive compounds [1, 2]. Saffron is traditionally cultivated in arid and semi-arid regions with minimal rainfall and significant temperature fluctuations, such as southern Europe, North Africa, the Middle East, and Central Asia [3, 4].

Numerous studies have established corm size and planting depth as key factors influencing saffron growth and yield [5, 6, 7]. Selecting an appropriate planting depth can significantly enhance saffron production and quality [8]. Generally, saffron is planted at depths between 8 and 20 cm [9, 10]. The planting depth of saffron corms influences shoot emergence, leaf characteristics, number of flowers, corm diameter, and root production [5]. However, this depth varies depending on the cultivation purpose and methods [10]. Planting corms too shallowly exposes them to extreme summer heat and winter frosts, which can hinder growth and development [11], while excessive planting depth may limit daughter corm formation, reducing flower

production in the following year [12]. Corm size (corm weight) is a critical factor influencing saffron's growth traits, with larger corms being associated with higher flower yields, improved corm development, and greater concentrations of bioactive compounds [6, 7]. According to Behdani et al. [13], daughter corm weight increased significantly between the 150th and 200th days of plant growth, whereas mother corm weight declined considerably during the same period.

The saffron plants enter senescence approximately 170 days after first irrigation [14], with climatic factors significantly influencing yield. For instance, Hosseini et al. [15] noted that higher minimum temperatures in late March adversely affect saffron yield. Although solar radiation is crucial for photosynthesis and crop production, excessive radiation during the hot spring and summer months poses a major challenge, particularly in tropical and subtropical regions. Climate change further intensifies this challenge through a more rapid than anticipated increase in global air temperatures. The effects of shading on plant growth can vary depending on the crop species and shading intensity [16]. Controlled shading can be particularly beneficial for certain plants by effectively regulating temperature, reducing heat stress, and minimizing water loss through evaporation, which contributes to improved plant growth and yield [17].

Shade nets have been found effective in moderating intense sunshine and temperature, enabling vegetable production during hot periods. Notably, shade net technology has been successfully implemented in Florida, USA, to extend vegetable growing seasons and ensure consistent availability [18]. Shade nets can enhance crop yield and harvest quality by positively influencing the microclimate beneath them. Acting primarily as greenhouses and windbreaks, shade nets have been shown to improve the productivity, quality, and uniformity of plants and fruits, thereby creating an optimal microclimate for their growth [19].

While previous studies have examined reduced solar radiation effects on various crops, their specific impact on saffron yield remain poorly understood. Furthermore, understanding how planting depth and corm weight mediate saffron's response to shading is critical. Therefore, this study aims to fill that knowledge gap by evaluating the combined effects of shading, planting depth, and corm weight on growth parameters, pigment content and saffron yield.

Material and methods

Experimental Site

A two-year pot experiment was conducted at the experimental farm of Razi University, Kermanshah, Iran. The region has a semi-arid climate, with a long-term average temperature of 15.9°C, relative humidity of 41%, and annual precipitation of 525 mm. Daily weather data were collected from the Kermanshah weather station (47°15'E, 34°35'N, 1318.5 m above sea level), located approximately 3 km from the experimental site. Monthly rainfall and daily temperature patterns during the growing season are presented in Fig. 1. Soil physical and chemical characteristics of the site are summarized in Table 1.

Table 1
Soil Physical and Chemical Characteristics (0–30 cm)

soil texture	Sand (%(	Silt (%(	clay (%(	Available Phosphorus (ppm)	Available Potassium (ppm)	Organic carbon (%(	EC (dS/m)	pH
Silty-Clay-Loam	18.49	44.91	36.6	9.4	360	0.31	0.9	7.3

Experimental Design and Treatments

Saffron corms were obtained from a commercial supplier in the Khorasan Razavi region, Iran's main saffron-producing area. Prior to planting, the corms were disinfected with a benomyl-based fungicide solution (5 g per 1,000 m L). On October 7, 2019, one corm was planted per pot (10 cm diameter, 35 cm height), each containing 5.0 kg of field soil. The pots were arranged on the ground with 10 cm spacing and were irrigated every 18–21 days, as needed.

A split-factorial randomized complete block design with three replications was implemented. The main factor was shading (0%, 15%, 30%, and 45%), while subplots included two corm weight classes (4–6 g and 9–11 g) and three planting depths (10, 15, and 20 cm).

Shading treatments were applied from February 20 to April 20, 2020, using white shade cloth (Toorineh Baft, Iran) mounted on wooden frames. Shading intensity was adjusted by modifying the weave density of the material. Corms entered summer dormancy after leaf senescence around June 1, 2020. In the second year, flowering commenced on October 28, 2020, approximately 20 days after irrigation.

Measurements of Growth Parameters

Growth parameters, including the fresh weight of daughter corms, leaf dry weight, leaf chlorophyll and carotenoids content, measurement of the activity of the enzyme peroxidase, and stigma yield, were recorded throughout the crop cycle. After the shading treatment, three sampling phases were conducted at 20-day intervals from March 20, 2020, to April 20, 2020 (i.e., 166, 185, and 197 days after planting (DAP). In each sampling phase, three pots were randomly selected, and the saffron plants were removed for measuring the growth parameters.

Leaf dry weight was measured after drying at 75°C for 48 hours. Fresh weight of daughter corms was determined immediately after harvest. Leaf chlorophyll and carotenoid concentrations were analyzed following Lichtenthaler and Wellburn [20]. Fresh leaf tissue (0.5 g) was homogenized in liquid nitrogen and 96% ethanol, centrifuged, and absorbance was measured at 646, 663, and 470 nm. Chlorophyll a, chlorophyll b, and carotenoid concentrations (mg/g fresh weight) were calculated using the following formulas.

Chl *a* = 12.21 (A663) – 2.81 (A646)

Chl *b* = 20.13 (A646) – 5.1 (A663)

Carotenoid = (1000 A470–3.27 Chl a – 104 Chl b) / 227

The method developed by Chance and Maehly [21], with slight modifications, was employed to measure the activity of the peroxidase enzyme. The measurement was based on the extent of guaiacol oxidation catalyzed by the peroxidase enzyme.In this method, 50 microliters of extract obtained from saffron corm tissue were mixed with 2 milliliters of a peroxidase solution containing 13 mM guaiacol, 5 mM hydrogen peroxide, and 50 mM potassium phosphate buffer. The absorbance was measured for 2 minutes using a Bausch & Lomb 70 spectrophotometer at a wavelength of 470 nm.

EA = [ΔOD470 × (1000/A)× B] / EC × C

EA = Enzyme Activity

ΔOD470 = Absorption Value Read by Spectrophotometer

A = Amount of Extract Added to the Cuvette

B = Amount of Extraction Buffer Added

EC = Extinction Coefficient (EC = 26.6 Mm -1 cm-1)

C = Weight of Tissue Selected for Extract Preparation

In mid-October 2020, during the second-year flowering period, flowers were harvested daily from three pots within each plot. The stigmas were subsequently separated, spread on flat trays, and dried in the shade over several days. Finally, the dry weight of the stigmas was recorded.

Statistical Analyses

Data were analyzed using a general linear model (GLM) procedure in SAS. Sampling date was considered as a sub-subplot factor. Normality and outliers were assessed using the UNIVARIATE procedure. Mean comparisons were performed using the least significant difference (LSD) test at α = 0.05.

Results

Leaf Dry Weight

Leaf dry weight was significantly influenced by shading percentage (SH), planting depth (PD), corm weight (CW), sampling time (ST), and their interactions (SH × PD, SH × CW, PD × CW, and SH × CW × PD) (Table 2). An extension of sampling time from 166 to 185 days after planting (DAP) increased leaf dry weight by 5.7%, and from 166 to 197 DAP by 9.4%. Increasing shading from 0–45% decreased leaf dry weight progressively by 5.6%, 11.1%, and 16.7% (Fig. 2). Leaf dry weight decreased by 6.9% with planting depth increasing from 10 cm to 20 cm, but increased by 18.3% with corm weight increasing from 4–6 g to 9–11 g. The interaction between SH × PD × CW showed that under unshaded conditions, increasing PD from 10 to 20 cm reduced leaf dry weight by 6.3% and 11.4% for small and large corms, respectively (Table 3). Under shading conditions,

reductions were 8.7% and 3.75% for small and large corms, respectively. These results emphasize the stronger buffering role of larger corms under stress (Fig. 2) .At 166 DAP, leaf dry weight decreased by 5.9% and 14.3% as PD increased from 10 to 20 cm for CW of 4–6 g and 9–11 g under unshaded conditions, respectively. Under similar conditions and sampling time, the decreases were 11.5% and 6.9% for 4–6 g and 9–11 g corms under shading conditions, respectively. At 197 DAP, leaf dry weight decreased by 6.4% and 10.0% as PD increased from 10 to 20 cm for 4–6 g and 9–11 g corms under unshaded conditions, respectively. In contrast, the reductions under shading conditions were 7.5% and 2.3% for 4–6 g and 9–11 g corms, respectively (Table 3). These findings indicate that corm weight plays a more critical role in leaf growth when plants are subjected to shading and deeper planting.

Table 2. ANOVA significance levels for saffron traits affected by shading percentage, planting depth, corm weight, and sampling time.

Source of variation	Df	Fresh weight of daughter corm	Leaf dry weight	Chlorophyll *a*	Chlorophyll *b*	Carotenoids	peroxidase
Replication (Rep)	2	**	**	*	n.s	n.s	**
Shading percentage (SH)	3	***	***	n.s	n.s	*	**
Error (Whole-Plot)	6						
Planting depth (PD)	2	***	***	*	***	***	**
Corm weight (CW)	1	***	***	n.s	n.s	n.s	**
SH × PD	6	*	***	n.s	**	***	*
SH × CW	3	***	***	*	n.s	n.s	*
PD × CW	2	***	***	n.s	n.s	n.s	*
SH × PD × CW	6	***	***	*	n.s	n.s	**
Error (Subplot)	40						
Sampling time (ST)	2	***	***	***	***	***	**
ST × SH	6	n.s	***	n.s	n.s	***	n.s
ST × PD	4	n.s	***	***	**	***	n.s
ST × CW	2	n.s	***	n.s	**	**	n.s
ST × SH × PD	12	n.s	***	*	n.s	***	n.s
ST × SH × CW	6	n.s	***	n.s	n.s	n.s	n.s
ST × PD × CW	4	n.s	***	n.s	n.s	n.s	n.s
ST × SH × PD × CW	12	n.s	***	**	***	***	n.s
CV (%)		17.51	8.49	16.09	19.76	16.23	17.73

*****, **, * indicates significance at P levels of 0.001, 0.01 and 0.05, respectively and ns indicates no significance.**

Chlorophyll *a*

Leaf chlorophyll *a* was significantly influenced by ST, as well as the interaction of SH × PD, SH × CW and SH × PD × CW (Table 2). Leaf chlorophyll *a* was significantly influenced by ST, as well as the interaction of SH × PD, SH × CW and SH × PD × CW. Leaf chlorophyll a concentration declined significantly with increasing sampling time (Table 2). Compared to 166 DAP, it decreased by 17.34% at 185 DAP and 41.31% at 197 DAP (Fig. 3). The interaction of SH × PD × CW × SD indicated a 1.6% decrease in chlorophyll *a* for 4–6 g corms at the first sampling with increased PD from 10 to 20 cm under unshaded conditions (Table 4). Under shading, significant changes in leaf chlorophyll *a* due to increasing PD were observed only at the first sampling. For instance, chlorophyll *a* decreased by 2.25% for 4–6 g corms and 5.42% for 9–11 g corms as PD increased from 10 to 15 cm under 30 and 40% shading conditions at 166 DAP (Table 4). No significant changes in chlorophyll a in response to planting depth and corm weight were observed during subsequent growth stages. These findings suggest that the negative impact of increasing planting depth from 10 to 15 cm on leaf chlorophyll *a* content diminishes as planting depth increased from 15 to 20 cm and the saffron plants matured.

Chlorophyll b

Leaf chlorophyll b showed a consistent decrease with increased sampling time (22.6% at 185 DAP and 69.6% at 197 DAP compared to 166 DAP). Increased planting depth from 10 cm to 15 cm led to a 32.13% decline. Under moderate shading, chlorophyll b loss was more evident in plants with heavier corms (Figure 4). Leaf chlorophyll b content was influenced by PD, SD, and their interactions, including SH × PD, SD × PD, SD × CW, SH × PD × CW, and SD × SH × PD × CW (Table 2). Leaf chlorophyll b showed a consistent decrease with increased sampling time (22.6% at 185 DAP and 69.6% at 197 DAP compared to 166 DAP) (Figure 4). Increased planting depth from 10 cm to 15 cm led to a 32.13% decline. (Figure 4). However, under low to moderate shading conditions a significant decrease in chlorophyll b was observed with increasing planting depth from 10 cm to 15 cm in plants from high corm weights. Additionally, in plants from low corm weights, chlorophyll *b* decreased with increasing planting depth from 10 cm to 15 cm at the initial sampling (166 DAP) under 45% shading and at final sampling (197 DAP) under 30% shading (Table 4). These findings indicated that increasing planting depth may exacerbate chlorophyll b loss under low to moderate shading conditions.

Carotenoids

Leaf carotenoid levels were influenced by SH, PD and ST, as well as their interaction effects, including SH × PD, SH × CW, PD × CW, and SH × PD × CW (Table 2). It was also affected by the two-way, three-way and four-way interactions of sampling time with SH, PD, CW, SH × PD, and SH × PD × CW (Table 2). Leaf carotenoid content decreased by 24.6% and 37.6% as sampling time increased from 166 to 185 DAP and from 166 to 197 DAP, respectively (Fig. 5). It also significantly decreased by 18.0%, 19.7%, and 6.4% under shading percentages of 15%, 30%, and 45% compared to the no-shading condition, respectively. Increasing PD from 10 to 15 cm and 20 cm resulted in a 38.2% and 12.0% increase in carotenoid content, respectively (Fig. 5). The interaction of SH×PD×CW×SD revealed that carotenoid content showed no significant changes in response to PD and corm weight throughout the growing season under no shading conditions (Table 5). Under low and moderate shading levels, leaf carotenoids generally increased significantly with increasing PD from 10 to 20 cm, particularly at first and second sampling date and in high corm weight plants. At high shading level, leaf carotenoids in high corm weight generally showed a reduction in response to PD increase from 10 to 20 cm. Regardless of the corm weight, the mean carotenoid contents were 43.2 and 39.3% greater at deeper planting

depth compared to shallow planting (10 cm) under 30 and 40% shading levels, respectively. Furthermore, the lowest carotenoid contents were observed at CW of 20 cm under 45% shading level (Table 5).

Fresh Weight of Daughter Corm (FWDC)

FWDC was significantly influenced by SH, PD, CW, SD, and their interactions, including SH × PD, SH × CW, PD × CW, and SH × CW × PD (Table 2). As sampling time increased from 166 to 185 DAP and from 166 to 197 DAP, FWDC increased by 15.46% and 29.61%, respectively (Fig. 6). Increasing shading levels from 0–15%, 30%, and 45% led to reductions of 19.56%, 29.28%, and 42.21%, respectively (Fig. 6). Furthermore, increasing planting depth from 10 to 15 cm and 10 to 20 cm decreased FWDC by 12.2% and 12.60%, respectively. Conversely, increasing corm weight from 4–6 g to 9–11 g increased FWDC by 53.26% (Fig. 6). Under no-shading conditions, increasing planting depth from 10 to 15 cm and 10 to 20 cm decreased FWDC by 4.43% and 7.16% for 4–6 g corms and by 17.32% and 22.18% for 9–11 g corms, respectively (Table 3). Under medium shading (30%), the corresponding decreases were 6.76% and 12.82% for 4–6 g corms and 7.23% and 8.29% for 9–11 g corms (Table 3). Under high shading, the decreases were 12.11% and 30.03% for 4–6 g corms and 6.94% and 11.29% for 9–11 g corms (Table 3). These results indicate that both increased shading and planting depth negatively impact daughter corm weight. These results suggest that heavier corms are more resilient to the negative impacts of increased shading and planting depth.

Peroxidase enzyme

Peroxidase was significantly affected by shading percentage (SH), planting depth (PD), corm weight (CW), sampling time (ST), and their interactions (SH × PD, SH × CW, PD × CW, and SH × CW × PD) (Table 2). An extension of sampling time from 166 to 185 days after planting (DAP) increased peroxidase activity by 23.12%, and from 166 to 197 DAP by 41.1%. Increasing shading from 0–45% progressively increased peroxidase activity by 1.40%, 38.08%, and 72.08% (Fig. 7). Increasing the planting depth from 10 cm to 20 cm led to a 10.67% rise in peroxidase activity, while increasing corm weight from 4–6 g to 9–11 g resulted in a 114.03% increase.

The three-way interaction between SH × PD × CW revealed that under non-shaded conditions, increasing planting depth from 10 cm to 20 cm increased peroxidase activity by 54.22% and 28.05% in small and large corms, respectively (Table 5). Under shading conditions, the increases were 68.71%, 88.30%, and 16.03% for small corms, and 18.67%, 14.65%, and 0.78% for large corms, respectively.

These results from the triple interaction indicate that the incremental effects were more pronounced in smaller corms (Table 5). Overall, peroxidase activity increased over time in response to planting depth, corm size, and shading treatments. Moreover, peroxidase activity was higher in corms with greater weight.

Stigma Yield

Stigma yield was affected by Sh, PD and CW, as well as their interactions including SH × CW, PD × CW, and SH × PD × CW (Table 6). Stigma yield decreased by 26.68%, 37.05%, and 51.07% as shading level increased from 0–15%, 30%, and 45%, respectively. It also decreased by 16.88% and 18.06% when planting depth increased from 10 cm to 15 cm and from 10 cm to 20 cm, respectively. Stigma yield was 68.32% higher in larger corms compared to smaller corms (Fig. 8).

The SH × PD × CW interaction revealed that stigma yield decreased by 6.72% in smaller corms and 37.05% in larger corms as planting depth increased from 10 cm to 15 cm under no shading (Table 7). Under the similar conditions, stigma yield decreased by 26.89% in smaller corms and 27.71% in larger corms when planting depth increased from 10 cm to 20 cm (Table 7). Under low and moderate shading condition, the reduced stigma yield was observed in larger corms generally when planting depth increased from 10 to 20 cm (Table 7). However, stigma yield showed no significant response to increased planting depth, regardless of corm size at high shading levels.

Table 3
Daughter corm weight and leaf dry weight of saffron as affected by shading, planting depth, corm weight and sampling time.

Days after planting	Shading percentage (%)	planting depth (cm)	Fresh weight of daughter corm (g)			Leaf dry weight (g)		
			corm weight (g)		Mean	corm weight (g)		Mean
			(4–6)	(9–11)		(4–6)	(9–11)	
166 days	0	10	6.62d	9.89a	8.25A	0.17d	0.21a	0.19A
		15	6.48e	9.36b	7.92B	0.17d	0.19b	0.18B
		20	5.84f	8.77c	7.30C	0.16e	0.18c	0.17C
		Mean	6.31B	9.34A		0.17B	0.19A	
	15	10	5.17b	8.68a	6.92A	0.153c	0.183a	0.168A
		15	4.99b	8.02a	6.50A	0.150d	0.183a	0.166B
		20	4.58b	7.32ab	5.95A	0.147e	0.180b	0.163C
		Mean	4.91B	8.01A		0.150A	0.182A	
	30	10	4.50d	7.70a	6.10A	0.143d	0.177a	0.160A
		15	4.15e	7.15b	5.65B	0.137e	0.173b	0.155B
		20	3.76f	7.02c	5.39C	0.130f	0.170c	0.150C
		Mean	4.14B	7.29A		0.137B	0.173A	
	45	10	4.20d	5.64a	4.92A	0.14b	0.16a	0.150A
		15	3.71e	5.35b	4.53B	0.12c	0.154a	0.137B
		20	2.65f	5.28c	3.96C	0.11d	0.136b	0.123C
		Mean	3.52B	5.42A		0.123B	0.150A	
185 days	0	10	7.37d	13.49a	10.43A	0.175d	0.211a	0.193A
		15	7.05e	10.31b	8.68B	0.174e	0.197b	0.185B
		20	7.01f	10.22c	8.61C	0.172f	0.189c	0.180C
		Mean	7.14B	11.34A		0.174B	0.199A	
	15	10	5.83d	10.13a	7.98A	0.160d	0.187a	0.173A
		15	5.49e	8.90b	7.19B	0.157e	0.186b	0.171B
		20	5.27f	8.71c	6.99C	0.154f	0.185c	0.169C
		Mean	5.53B	9.25A		0.157B	0.186A	
	30	10	5.20d	8.07a	6.63A	0.151d	0.181a	0.166A

		15	4.82e	7.44b	6.13B	0.145e	0.178b	0.161B
		20	4.57f	7.39c	5.98C	0.139f	0.176c	0.157C
		Mean	4.86B	7.63A		0.145B	0.178A	
	45	10	5.02ab	6.50a	5.76A	0.151d	0.168a	0.159A
		15	4.93ab	5.95a	5.44A	0.134e	0.167b	0.150B
		20	3.55b	5.54ab	4.54A	0.127f	0.165c	0.146C
		Mean	4.50B	5.60A		0.137B	0.167A	
197 days	0	10	8.50dc	14.62a	11.56A	0.18d	0.21a	0.195A
		15	7.92d	11.25b	9.58B	0.17e	0.2b	0.185B
		20	8.09d	10.09bc	9.09B	0.16f	0.19c	0.175C
		Mean	8.17B	11.99A		0.17B	0.20A	
	15	10	6.50c	11.10a	8.80A	0.171d	0.193a	0.182A
		15	6.47c	9.22b	7.84B	0.168e	0.189b	0.178B
		20	6.29c	9.69b	7.99B	0.165f	0.187c	0.176C
		Mean	6.42B	10A		0.17B	0.19A	
	30	10	6.17d	9.05a	7.61A	0.163d	0.185a	0.174A
		15	5.85e	8.44b	7.14B	0.155e	0.181b	0.168B
		20	5.56f	8.36c	6.96C	0.153f	0.180c	0.166C
		Mean	5.86B	8.62A		0.157B	0.182A	
	45	10	5.90c	7.47a	6.68A	0.158d	0.175a	0.166A
		15	4.55d	6.93ab	5.74B	0.150e	0.172b	0.161B
		20	4.49d	6.52bc	5.50B	0.146f	0.171c	0.158C
		Mean	4.98B	6.97A		0.151B	0.173A	

Means followed by different letters are statistically different at P < 0.05 by LSD test. Small letters and capital letters signify differences among shading percentage and planting depth treatments, respectively.

Table 4
pigment content of saffron as affected by shading, planting depth, corm weight and sampling time.

Days after planting	Shading percentage (%)	planting depth (cm)	Chlorophyll a (mg/gram fresh leaf weight)			Chlorophyll b (mg/gram fresh leaf weight)		
			corm weight (g)		Mean	corm weight (g)		Mean
			(4–6)	(9–11)		(4–6)	(9–11)	
166 days	0	10	33.27a	33.10ab	33.18A	16.3a	16.14a	16.22A
		15	32.35abc	32.24bc	32.29B	12.82a	12.20a	12.51B
		20	31.74c	32.75ab	32.24B	15.56a	15.74a	15.65AB
		Mean	**32.45A**	**32.70A**		**14.89A**	**14.69A**	
	15	10	32.53a	32.68a	32.60A	17.96ab	24.47a	21.21A
		15	31.45ab	29.87b	30.66A	13.24b	11.45b	12.34B
		20	33.07a	32.32a	32.69A	14.54b	9.86b	12.2B
		Mean	**32.35A**	**31.62A**		**15.25A**	**15.26A**	
	30	10	32.97b	33.37a	33.17A	20.57a	17.66ab	19.11A
		15	32.58c	32.92b	32.75A	12.10c	12.45c	12.27B
		20	33.20ab	33.38a	33.29A	19.53a	15.97b	17.75A
		Mean	**32.92B**	**33.22A**		**17.40A**	**15.36B**	
	45	10	33.31a	31.96ab	32.63A	15.45ab	11.65b	13.55B
		15	32.63ab	31.23b	31.93A	12.68b	11.34b	12.01B
		20	32.03ab	33.14a	32.58A	15.81ab	19.78a	17.79A
		Mean	**32.66A**	**32.11A**		**14.65A**	**14.26A**	
185 days	0	10	27.19a	27.73a	27.46A	11.71a	12.65a	12.18A
		15	27.15a	25.64a	26.39A	10.06a	9.29a	9.67A
		20	26.76a	27.94a	27.35A	11.25a	12.1a	11.67A
		Mean	**27.03A**	**27.10A**		**11.01A**	**11.35A**	
	15	10	26.31a	26.75a	26.53A	14.51ab	16.08a	15.29A
		15	25.29a	25.92a	25.60A	8.76b	10.85ab	9.80B
		20	27.69a	25.74a	26.71A	12.45ab	9.27ab	10.86AB
		Mean	**26.43A**	**26.14A**		**11.91A**	**12.07A**	
	30	10	26.96a	28.45a	27.70B	12.66bc	16.31a	14.48A

		15	27.75a	27.87a	27.81AB	10.76c	10.95bc	10.85B
		20	28.17a	28.42a	28.29A	14.21ab	13.41abc	13.81A
		Mean	**27.63B**	**28.25A**		**12.54A**	**13.56A**	
	45	10	27.02a	24.48b	25.75A	10.48b	9.16b	9.82B
		15	26.78ab	26.63ab	26.70A	9.18b	8.85b	9.01B
		20	27.21a	27.19a	27.2A	11.99b	16.19a	14.09A
		Mean	**27A**	**26.1A**		**10.55A**	**11.40A**	
197 days	0	10	18.99a	20.25a	19.62A	7.60a	8.69a	8.14A
		15	19.83a	18.93a	19.38A	3.45a	3.47a	3.46A
		20	19.67a	21.02a	20.34A	4.95a	4.75a	4.85A
		Mean	**19.50A**	**20.07A**		**5.33A**	**5.64A**	
	15	10	19.05a	18.70a	18.87A	8.15a	7.34ab	7.74A
		15	17.93a	18.41a	18.17A	2.53b	4.78ab	3.65A
		20	20.20a	20.49a	20.34A	2.74b	4.06ab	3.40A
		Mean	**19.06A**	**19.2A**		**4.47A**	**5.39A**	
	30	10	19.86a	21.41a	20.63B	4.81b	10.35a	7.58A
		15	20.81a	21a	20.90A	3.48b	4.84b	4.16A
		20	21.02a	21.35a	21.18A	4.27b	6.24b	5.25A
		Mean	**20.56A**	**21.25A**		**4.19B**	**7.14A**	
	45	10	18.61a	18.49a	18.55A	2.61b	4.83ab	3.72AB
		15	18.81a	19.91a	19.36A	1.06b	1.74b	1.4B
		20	20.28a	19.02a	19.65A	3.56b	9.69a	6.62A
		Mean	**19.23A**	**19.14A**		**2.41A**	**5.42A**	

Means followed by different letters are statistically different at P < 0.05 by LSD test. Small letters and capital letters signify differences among shading percentage and planting depth treatments, respectively.

Table 5

pigment content of saffron as affected by shading, planting depth, corm weight and sampling time.

Days after planting	Shading percentage (%)	planting depth (cm)	Carotenoids (mg/gram fresh leaf weight)			Peroxidase enzyme (mg^{-1} protein)		
			corm weight (g)		Mean	corm weight (g)		Mean
			(4–6)	(9–11)		(4–6)	(9–11)	
166 days	0	10	9.56a	9.46a	9.51A	42.23abc	50.72ab	46.48A
		15	10.43a	10.67a	10.55A	24.86bc	44.44abc	34.65A
		20	9.45a	9.52a	9.48A	8.34c	61.75a	35.04A
		Mean	**9.81A**	**9.88A**		**27.97B**	**49.47A**	
	15	10	6.73b	3.24c	4.98B	41.37bc	43.04b	42.20A
		15	10.65a	11.19a	10.92A	25.19d	62.55a	43.87A
		20	8.92ab	10.66a	9.79A	21.78d	25.46cd	23.62B
		Mean	**8.77A**	**8.36A**		**30.67B**	**42.46A**	
	30	10	5.43bc	4.54c	4.98B	26.53b	55.34ab	40.93B
		15	11.39a	11.09a	11.24A	29.07b	64.56a	46.81AB
		20	3.78c	7.57b	5.67B	50.45ab	77.99a	64.22A
		Mean	**6.87A**	**7.73A**		**44.53A**	**56.78A**	
	45	10	9.95ab	11.19a	10.57A	43.57a	67.90a	55.73A
		15	11a	10.79a	10.89A	87.68a	90.45a	88.92A
		20	6.28bc	5.74c	6.01B	61.95a	101.25a	81.60A
		Mean	**9.08A**	**9.24A**		**73.33A**	**77.50A**	
185 days	0	10	6.82a	6.89a	6.85A	51.73c	64.09b	57.91A
		15	7.9a	7.6a	7.75A	30.67d	53.69c	42.18B
		20	6.85a	7.4a	7.12A	8.36e	77.44a	42.90B
		Mean	**7.19A**	**7.30A**		**34.38B**	**60.95A**	
	15	10	4.20c	2.79c	3.49B	47.05c	53.54b	50.29A
		15	7.07ab	6.68ab	6.87A	30.23de	73.18a	51.71A
		20	6.27b	9.10a	7.68A	27.49e	31.54d	29.51B
		Mean	**5.85A**	**6.19A**		**36.28B**	**51.40A**	
	30	10	2.26d	4.77c	3.51C	32.64e	70.47c	51.56C

		15	8.91a	8.87a	8.89A	35.32e	81.87b	58.60B
		20	4.22c	6.33b	5.27B	60.63d	91.36a	76.01A
		Mean	**5.13B**	**6.66A**		**53.11B**	**70.99A**	
	45	10	6.92ab	7.57a	7.24AB	52.78e	84.26c	68.52C
		15	8.13a	8.68a	8.40A	109.97b	116.90b	113.43A
		20	6.43ab	5.15b	5.79B	71.61d	130.66a	101.14B
		Mean	**7.16A**	**7.13A**		**90.92B**	**97.81A**	
197 days	0	10	6.89a	6.22a	6.55A	57.34b	61.22ab	59.28AB
		15	6.1a	6.62a	6.36A	42.57c	65.16ab	53.86B
		20	5.18a	6.40a	5.79A	57.74b	69.91a	63.82A
		Mean	**6.06A**	**6.41A**		**53.84B**	**64.14A**	
	15	10	2.83bc	4.78ab	3.80B	52.66b	54.73b	53.70B
		15	4.47abc	2.35c	3.41B	31.07c	46.31bc	38.69C
		20	6.48a	6.27a	6.37A	69.64ab	96.37a	96.50A
		Mean	**4.59A**	**4.47A**		**60.73A**	**65.21A**	
	30	10	5.19ab	3.96b	4.57A	91.16b	112.01ab	101.58A
		15	5.85ab	6.21a	6.03A	57.94c	61.75c	59.84B
		20	6.34a	5.62ab	5.98A	61.01c	127.58a	94.30A
		Mean	**5.79A**	**5.26A**		**70.04B**	**100.45A**	
	45	10	5.85a	4.17ab	5.01B	64.09d	81.33bc	72.71A
		15	6.66a	7.04a	6.85A	71.64cd	86.54ab	79.09A
		20	6.31a	2.98b	4.64B	59.41d	98.51a	78.96A
		Mean	**6.27A**	**4.73B**		**65.05B**	**88.79A**	

Means followed by different letters are statistically different at P < 0.05 by LSD test. Small letters and capital letters signify differences among shading percentage and planting depth treatments, respectively.

Table 7
ANOVA significance levels for saffron Stigma yield affected by shading percentage, planting depth and corm weight.

Source of variation	df	Stigma yield
Replication (Rep)	2	**
Shading percentage (SH)	3	**
Error (Whole-Plot)	6	n.s
Planting depth (PD)	2	**
Corm weight (CW)	1	**
SH × PD	6	n.s
SH × CW	3	**
PD × CW	2	*
SH × PD × CW	6	*
Coeff Var		12.82
***, **, * indicates significance at P levels of 0.001, 0.01 and 0.05, respectively and n.s indicates no significance.		

Table 7. Stigma yield of saffron as affected by shading, planting depth and corm weight.

Shading percentage (%)	Planting depth (cm)	Dry stigma yield (mg per pot)		
		Dry stigma yield (mg per pot)		
		Corm weight (g)		Mean
5	**10**			
0	10	42.66c	85.64a	64.15A
	15	39.79d	62.61b	51.2B
	20	37.54d	61.91b	49.72B
	Mean	**40B**	**70.05A**	
15	10	30.87cd	60.79a	45.83A
	15	28.79d	50.88ab	39.83B
	20	27.94d	42.79bc	35.36AB
	Mean	**29.20B**	**51.49A**	
30	10	27.38c	46.41a	36.89A
	15	25.81c	42.13b	33.97B
	20	24.54c	41.56b	33.05B
	Mean	**25.91B**	**43.37A**	
45	10	26.13ab	35.35a	30.74A
	15	19.84b	31.55ab	25.69A
	20	19.61b	29.05ab	24.33A
	Mean	**21.86B**	**31.98A**	

Means followed by different letters are statistically different at $P < 0.05$ by LSD test. Small letters and capital letters signify differences among shading percentage and planting depth treatments, respectively.

Discussion

Low saffron yield per hectare remains a persistent agronomic constraint, frequently attributed to premature leaf senescence during early spring and late-season growth decline [22]. In saffron, senescence precedes corm dormancy and initiates a cascade of physiological shifts mediated by genetic and environmental cues [14]. Among these, light intensity emerges as a pivotal determinant of nutrient allocation and metabolic activity within corm tissues. Zhou et al. [23] demonstrated that elevated light intensity compromises stigma yield and quality. Despite that, they noted a lack of clarity around how maternal corm reserves respond to light variations, especially regarding daughter corm development.

Building upon this context, our results reveal strong interactions among shading, planting depth, and corm weight across multiple developmental traits. Shallower planting (10 cm) and larger corms (9–11 g) typically yielded higher leaf biomass, pigment levels, daughter corm weight, and stigma yield, although these effects were modulated by shading intensity. These observations align with Mzabri et al. [24], who reported that moderate shading (30%) improves vegetative growth and yield in saffron.

Impact of Shading and Planting Depth on Photosynthetic Pigments

The contents of chlorophyll a, chlorophyll b, and carotenoids declined over time, consistent with the natural process of leaf senescence [25]. Deeper planting under shaded conditions further accelerated chlorophyll loss, particularly in plants grown from larger corms. Interestingly, carotenoid levels increased with planting depth under moderate shading (30–45%), but dropped under heavy shading, suggesting a critical threshold beyond which photoprotective functions are compromised. Shading disrupts the plant's carbon balance by raising carbohydrate demand while lowering carbon supply due to reduced photosynthesis [26]. This imbalance can weaken photoprotective mechanisms, impair chlorophyll fluorescence, reduce net photosynthetic capacity [27, 28], and ultimately promote leaf senescence [29]. These results highlight the need to optimize planting depth [30] and avoid excessive shading in order to sustain chlorophyll and carotenoid levels, which are essential for efficient photosynthesis and overall plant productivity [31].

Influence of Planting Depth and Shading on Vegetative Growth

Our results suggest that the negative effects of planting depth and shading on leaf weight and daughter corm weight diminish as plant growth progresses. Furthermore, the adverse impact of shading on leaf dry weight was less severe in heavier corms. Similarly, the negative effect of increased shading and planting depth on daughter corm weight was also less pronounced in heavier corms, indicating that corm size may buffer against environmental stressors. Previous studies have shown that shading significantly reduces specific leaf weight, stomatal density, leaf thickness, photosynthesis, chlorophyll fluorescence, total biomass, and yield-related traits [26]. Banhangi et al. [32] reported that corms planted at 10 cm had a higher leaf area index, leading to increased photosynthesis and consequently greater daughter corm weight. Likewise, Pavek and Thornton [33] observed that as planting depth decreased, soil growing degree days increased, leading to faster emergence and canopy establishment.

Interaction Between Planting Depth and Corm Size

The relationship between planting depth and corm size is critical, as larger corms generate more biomass but respond differently to depth [30]. Koocheki and Seyyedi [34] recommend a planting depth of 12–15 cm for corms weighing 8.1–12 g. Deeper planting (e.g., 20 cm) delays emergence and reduces yield, as seen in potatoes [35] and saffron. Kumar et al. [11] reported that shallower planting initially increased corm weight more than deeper planting. Additionally, deeper planting reduces reproductive capacity by altering soil moisture, temperature, and aeration, leading to smaller daughter corms [36] and inhibiting flowering [37, 38].

Impact on Peroxidase Enzyme

Numerous physiological functions, including H2O2 detoxification, cell elongation, cell wall construction and differentiation, plant responses to stress, salinity tolerance, aging, and defense against pathogens, have been attributed to various mechanisms [39]. Under stress conditions, oxidative processes occur due to the production of reactive oxygen species (ROS). Among the most important ROS-scavenging enzymes are superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase [40]. The study found that the levels of peroxidase enzyme increased with higher shading levels, planting times, and planting depths. It can be inferred that increased shading and aging act as stress factors for the plant, leading to elevated production of peroxidase enzymes, particularly in larger corms. Antioxidant enzymes, such as peroxidase, catalase, and ascorbate peroxidase, likely mitigate ROS accumulation, thereby delaying fruit ripening and senescence[41]). These findings support the notion that antioxidant enzyme activity serves as an adaptive mechanism to mitigate light-induced oxidative stress in saffron, consistent with the ROS-scavenging framework proposed by Valizadeh Kaji et al. [40].

Impact on Yield and Potential Mechanisms

Our results demonstrate that shading is the primary factor limiting saffron yield, outweighing the effects of planting depth or corm size. Although deeper planting and smaller corms consistently led to reduced yields compared to shallower planting and larger corms, the magnitude of their impact was influenced by shading intensity. Interestingly, our findings differ from those of Zhou et al. [23], who observed yield reductions under excessive light exposure. This discrepancy may be attributed to ecotype differences or environmental variations.

We hypothesize that diminished photosynthesis caused by pigment degradation and reduced leaf biomass restricted carbohydrate accumulation in daughter corms, ultimately impairing floral initiation and stigma development.

Conclusion

This study demonstrated that shading, planting depth, and corm weight interact to influence saffron yield and physiology. Shading was the most influential factor, with excessive shade (45%) significantly reducing growth, pigment content, and stigma yield. Optimal outcomes were achieved with shallow planting (10 cm), heavier corms (9–11 g), and moderate shading (15–30%). These insights offer valuable guidance for saffron cultivation in regions experiencing intense solar radiation and depth management.

Abbreviations

DAP
Days after planting
SH
Shading percentage
PD
Planting depth
CW
Corm weight

ST
Sampling time
FWDS
Fresh weight of daughter corm
cm
Centimeter (a metric unit of length)
g
Gram (unit of mass)
Kg
Kilogramme (unit of mass)
Mg
Miligram (unit of mass)
Mm
Millimolar (unit of concentration)
nm
Nanometer (a metric unit of length)
mm
Millimeter
°C
Degrees Celsius (temperature unit)
ppm
parts per million (unit of measurement)
dS/m
decisiemens per meter (a unit of electrical conductivity commonly used in soil testing)
SAS
Statistical data analysis
%
indicate a percentage of shading
LSD
Least Significant Difference
P
Probability
Rep
Replication
mg -1 protein
Mg per protein
Chl a
Chlorophyll a
Chl b
Chlorophyll b

Declarations

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

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Naser Karimi: Methodology, Formal analysis.

Mansour Ghorbanpour: Methodology, Resources.

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Figures

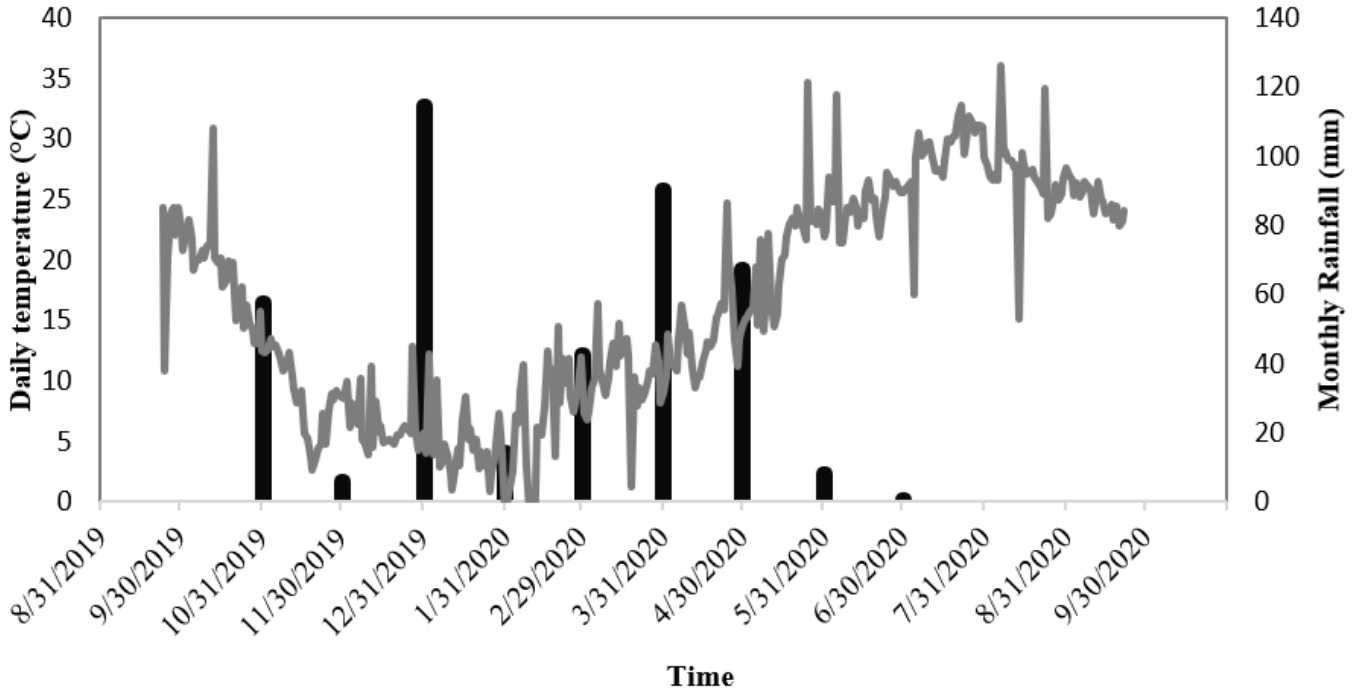

Figure 1

Daily maximum and minimum temperature, precipitation and solar radiation during the growing season in 2019 and 2020 for kermanshah, Iran.

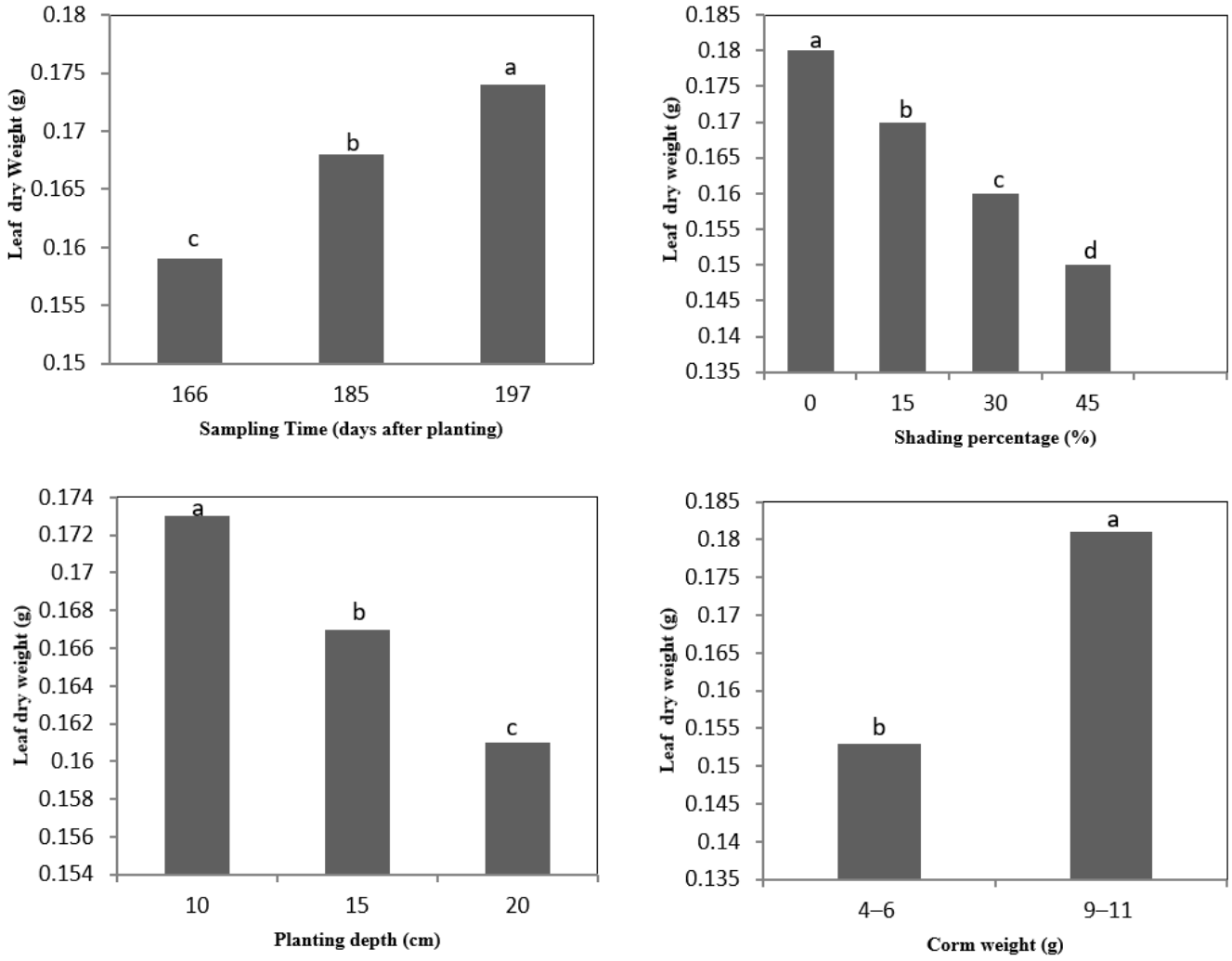

Figure 2

The effect of sampling time, shading percentage, planting depth and corm weight on leaf dry weight. Means with different letters indicate significant differences ($p \leq 0.05$).

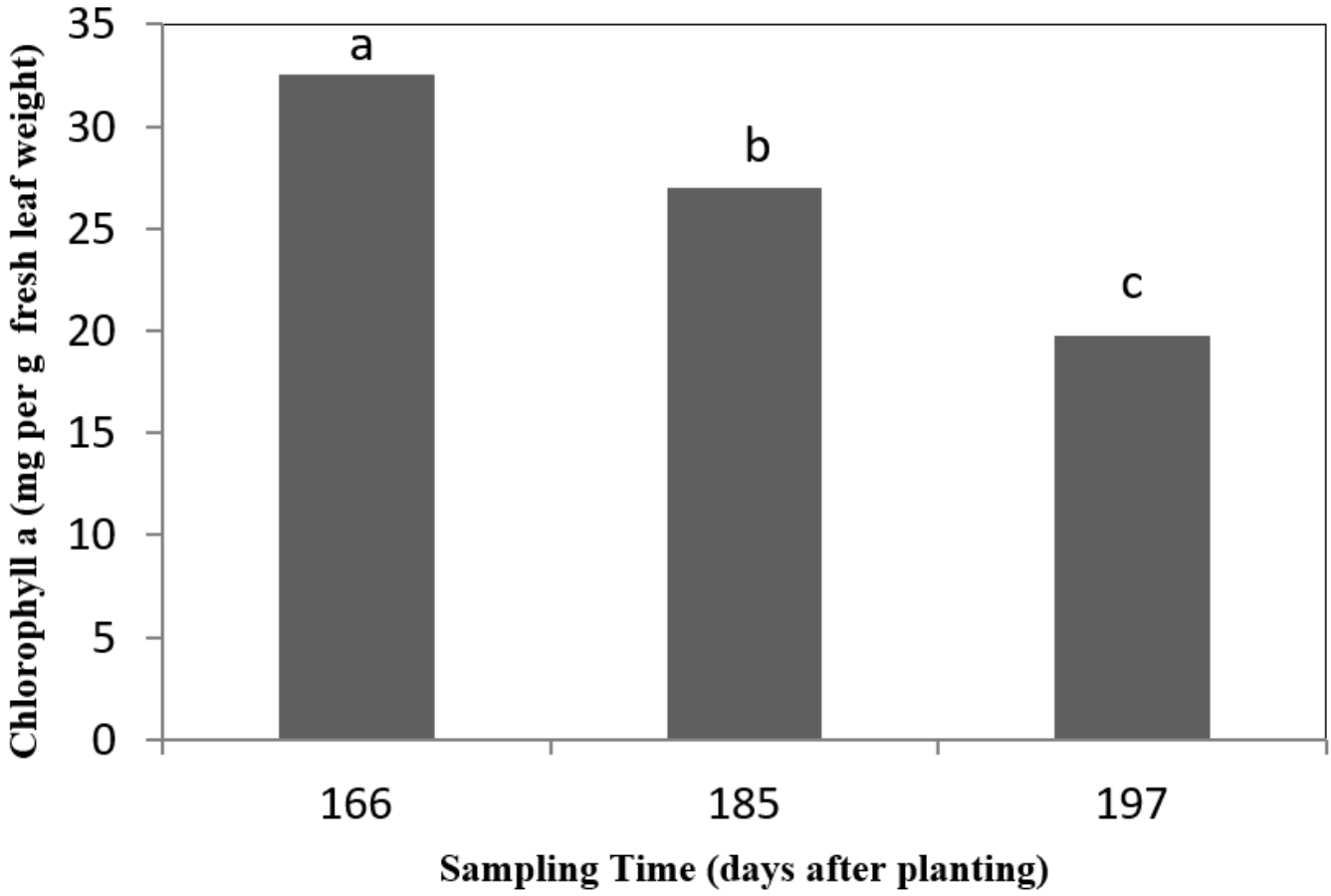

Figure 3

The effect of sampling time on chlorophyll *a*. Means with different letters indicate significant differences ($p \leq 0.05$).

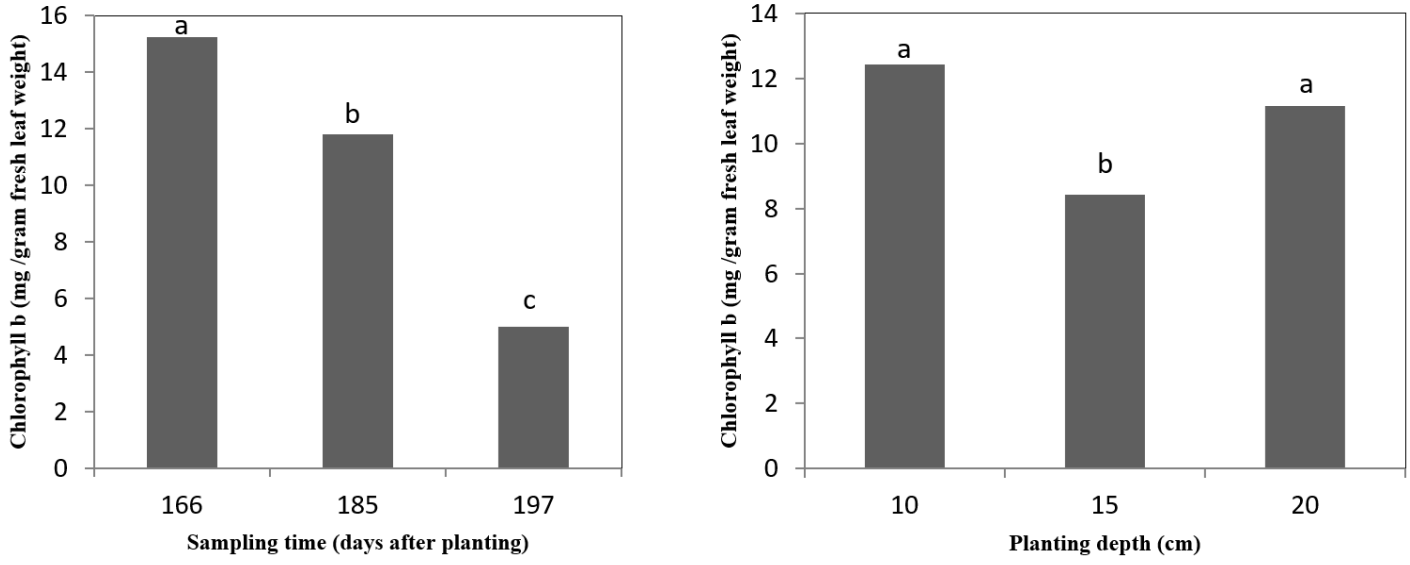

Figure 4

The effect of sampling time, and planting depth on chlorophyll *b*. Means with different letters indicate significant differences (p ≤ 0.05).

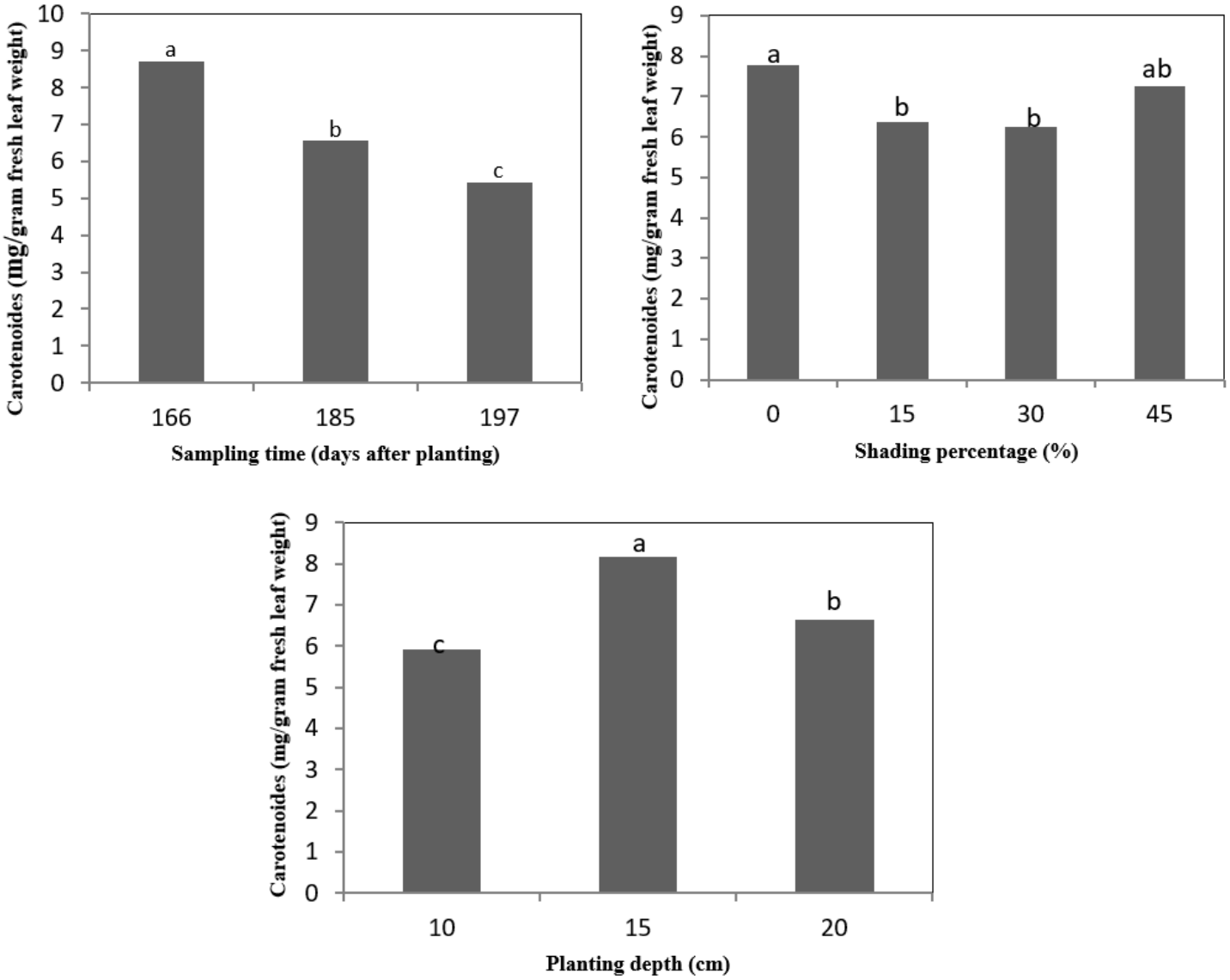

Figure 5

The effect of sampling time, shading percentage and planting depth on carotenoids. Means with different letters indicate significant differences (p ≤ 0.05).

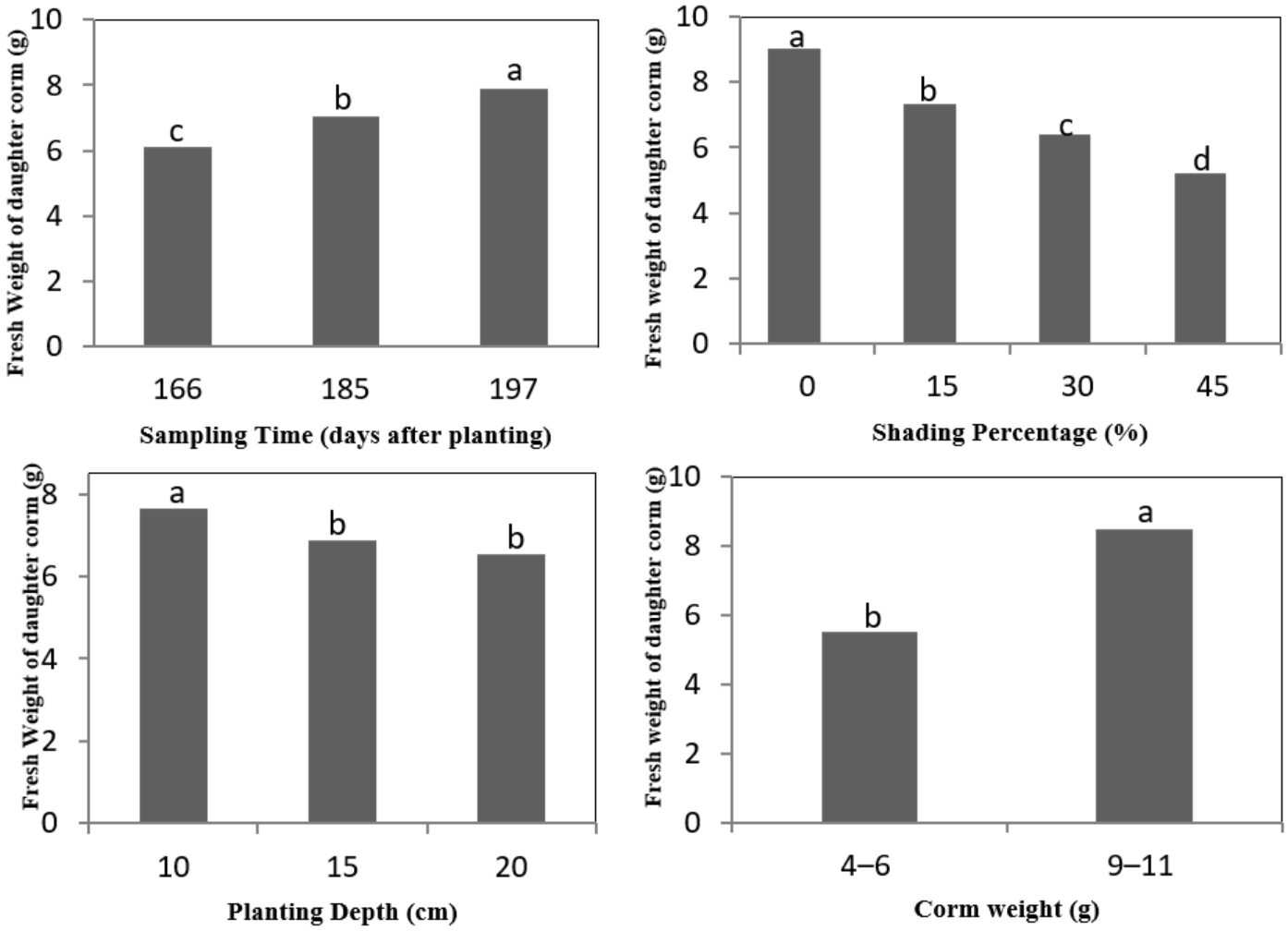

Figure 6

The effect of sampling time, shading percentage, planting depth and corm weight on fresh weight of daughter corm. Means with different letters indicate significant differences ($p \leq 0.05$).

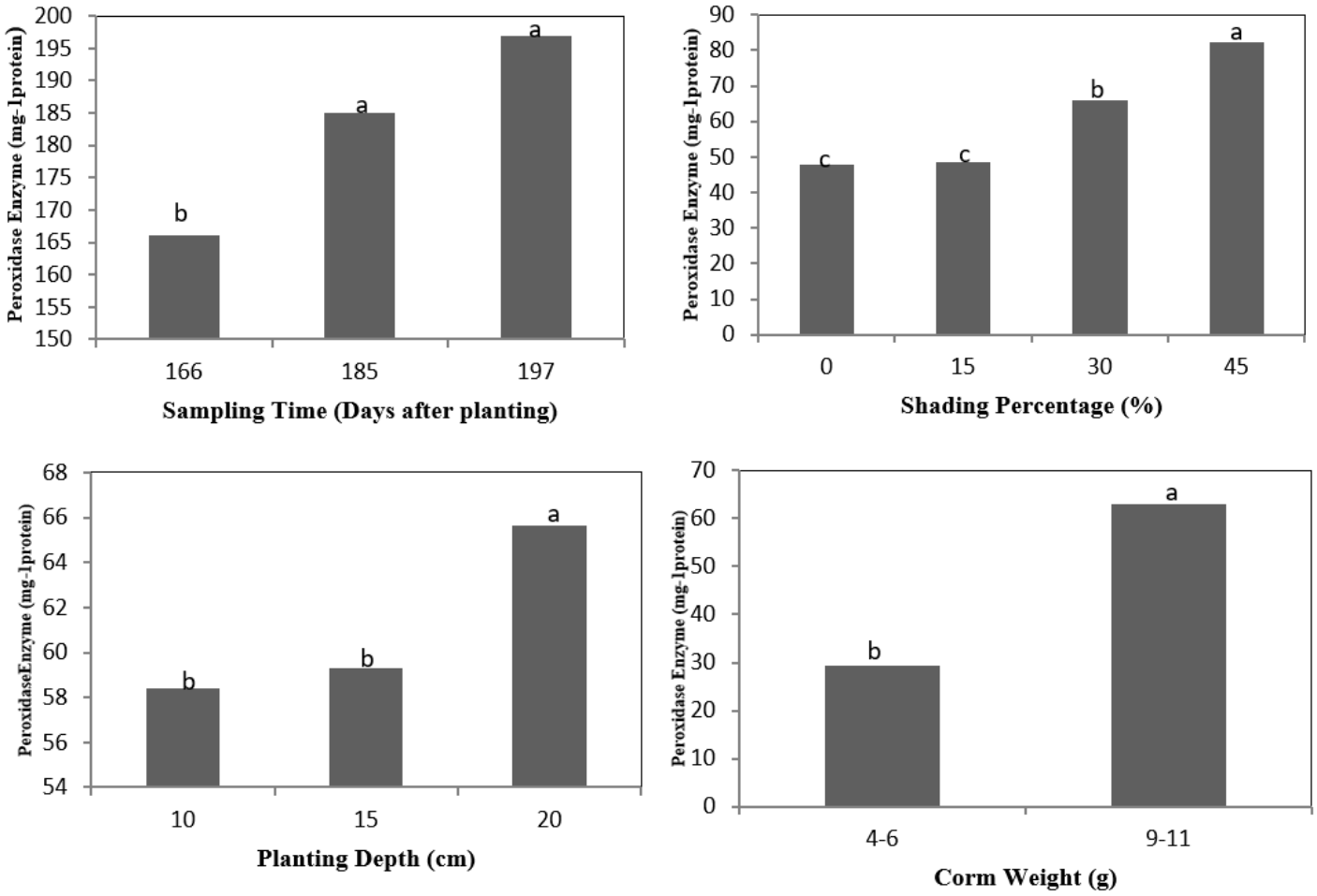

Figure 7

The effect of sampling time, shading percentage, planting depth and corm weight on peroxidase enzyme. Means with different letters indicate significant differences ($p \leq 0.05$).

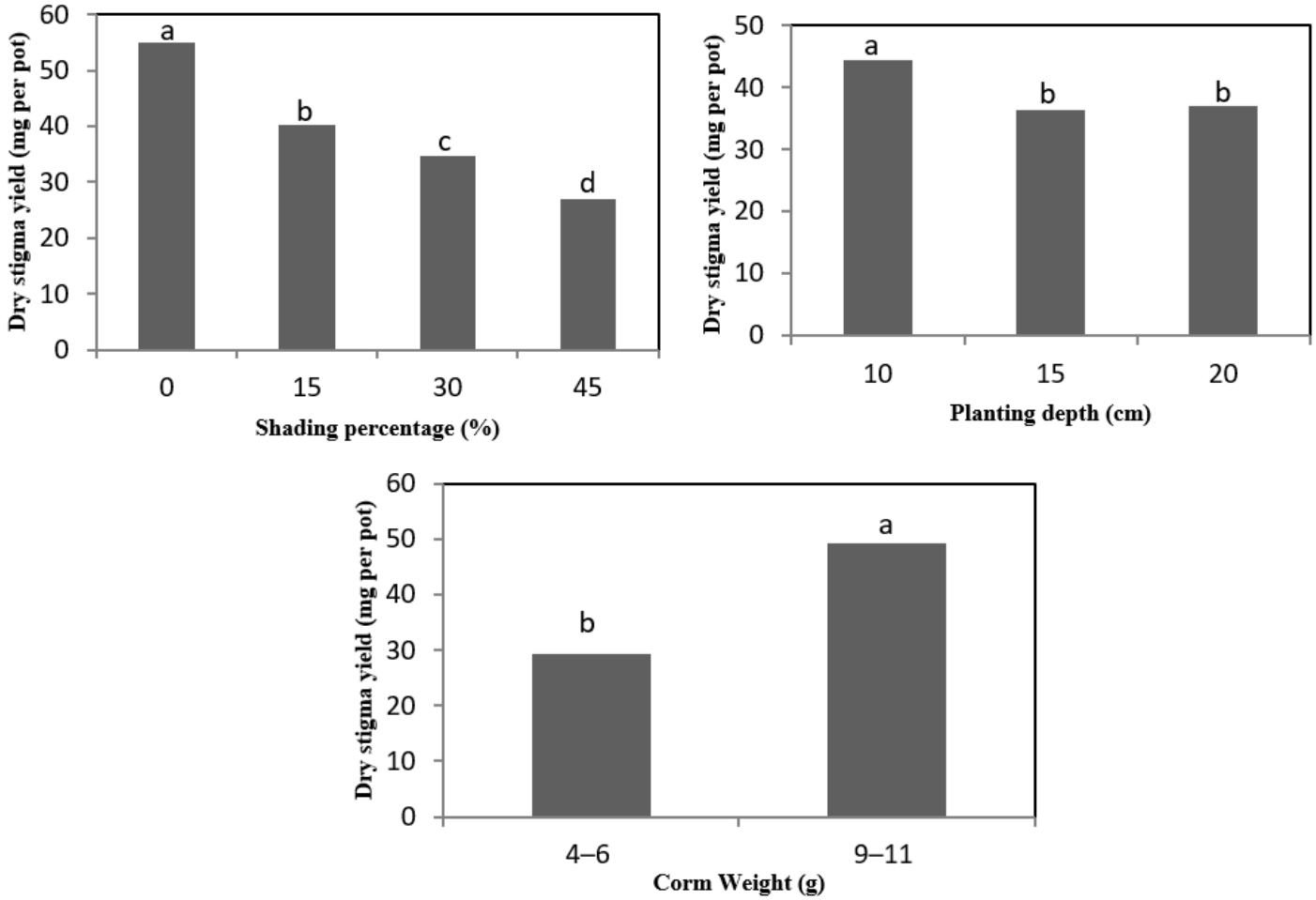

Figure 8

The effect of shading percentage, planting depth and corm weight on Dry stigma yield. Means with different letters indicate significant differences ($p \leq 0.05$).