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Effect of planting dates and foliar application of mannitol on the growth and yield of flax (*Linum usitatissimum* L.)

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Abstract

Determining the appropriate planting date is a crucial strategy for ensuring the efficient and stable cultivation of a specific crop. Planting timing is a fundamental factor influencing the success and productivity of agricultural production, as it is directly linked to prevailing environmental conditions-such as temperature, rainfall, relative humidity and photoperiod. Selecting the right planting date creates favourable conditions for seed germination and plant growth and development, thereby positively impacting both the quantity and quality of the yield. Furthermore, the study addressed the use of natural nutrients; accordingly, a field experiment was conducted during the 2023–24 winter season in Saqlawiyah (Anbar Governorate) to evaluate the response of the flax crop to varying planting dates (October 20, November 10, November 30 and December 20) and foliar application of the sugar alcohol mannitol at concentrations of 0, 3, 6 and 9 g L^{-1}. The experiment was laid out in a randomised complete block design (RCBD) using a split-plot arrangement with 3 replicates. The results revealed significant variations based on planting dates, with the second date (November 10) showing significant superiority in plant height (145.20 cm), number of branches (3.83 branches $plant^{-1}$), 1000-seed weight (7.47 g) and seed yield (1.64 t ha^{-1}). Regarding mannitol, the highest concentration (9 g L^{-1}) yielded the highest values for the growth and yield parameters under study.

Keywords: crop productivity; flax; foliar application; *Linum usitatissimum*; planting dates; sugar alcohols

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Introduction

The widespread cultivation of industrial crops in various regions of the world has become essential due to their economic value and attractive market prices for agricultural investors. These crops are used in numerous industries, such as food processing and cosmetics, in addition to their significant role in the pharmaceutical industry and the production of medicines. One such crop is flax (*Linum usitatissimum* L.), a winter crop belonging to the family Linaceae (1). It is cultivated globally for its oil and fibre and its seeds contain a high percentage of oil, ranging from 20 % to 40 % (2). Its oil is widely used in food and medicine, as it is considered one of rich source of α-linolenic acid (Omega-3), linoleic acid (Omega-6) and oleic acid (Omega-9), which have anti-inflammatory properties and reduce the risk of diseases such as cardiovascular disease, diabetes and some types of cancer (3). The productivity of this crop in Iraq has deteriorated and the areas cultivated for it are now limited to scientific research and studies for many reasons, the most important of which is the focus on strategic winter crops and the lack of specialised factories for extracting oil from the crop. Given its industrial and medicinal importance, it is essential to focus on its cultivation and management by adopting modern scientific methods. This is particularly crucial considering global climate changes affecting the world in general and developing countries, which have had a clear impact on plant cultivation and productivity (4). The efffects of heat and other environmental changes contribute to the degradation of one-third of agricultural lands and pose a significant challenge to plant growth and development. Astronomical statistics predict further temperature changes, which have already become evident in arid and semi-arid regions, including Iraq. Therefore, these changes must be considered a warning sign, prompting the identification of factors that enhance plant adaptation to changing environmental conditions (5). Planting dates are among these key factors; their importance lies in determining the thermal requirements, photoperiod and radiation intensity that directly influence the plant's major developmental processes such as germination, the formation of vegetative and floral buds, fruit production

and seed development. The planting date dictates the time required for the plant to progress through its successive growth stages; optimal timing ensures robust vegetative growth capable of highly efficient solar radiation interception, thereby enabling greater synthesis and accumulation of nutrients (6, 7). Variations in temperature during the growth and development of flax fruit which differ according to planting dates affect oil content and the concentration of medically active compounds, ultimately leading to reduced productivity. Therefore, it is essential to determine the appropriate planting date for any crop based on the specific conditions of the local environment, rather than applying the same date to different ecological locations (8). Plant growth depends on more than just the right planting time; plants require growth stimulants during developmental stages susceptible to fluctuating environmental conditions. These stimulants work synergistically enhancing growth, yield and quality. Given the need to boost productivity while minimising environmental pollution caused by the excessive use of mineral fertilisers, it has become essential to seek alternatives. Natural biostimulants offer a solution, playing a positive role in achieving high yields and superior quality; their use represents a modern agricultural practice within the framework of sustainable agriculture (9, 10). Sugar alcohols including mannitol, are non-nitrogenous organic compounds that stimulate and support all plant biological processes. They play a fundamental role in increasing cell membrane permeability, stimulating enzymatic reactions, enhancing cell division and elongation and boosting the production of key plant enzymes within cells, all of which directly contribute to improved plant growth (11). In addition to promoting plant growth, these compounds enhance tolerance to biotic and abiotic stresses. Their low molecular weight facilitates movement across cell membranes. These compounds stimulate carbon assimilation within the vegetative parts of the plant (12). These compounds also serve as a primary source of carbon and an aid in the synthesis and production of carbohydrates (13). To facilitate the wider cultivation of the plant moving beyond mere research and studies and to circumvent competition from strategic crops, it became essential to seriously investigate cultivation techniques across diverse environmental conditions. Despite the growing agricultural and industrial significance of flax, the optimisation of planting schedules and targeted physiological interventions for arid environments remain insufficiently understood. It is hypothesised that adjusting planting dates to synchronise critical growth stages with favourable environmental conditions, combined with the foliar application of mannitol, significantly mitigates abiotic stress and enhances crop productivity. Therefore, this study was undertaken to evaluate the individual and interactive effects of varying planting dates and mannitol concentrations on the growth, yield and overall productivity of flax.

Materials and Methods

Experimental site

A field experiment was conducted during the 2023–24 winter season at Al-Anbar Governorate, Iraq. Field operations–including plowing, leveling and smoothing the soil–were carried out and the experimental site was divided into experimental units measuring 2 × 2 m (resulting in an area of 4 m² per unit). Seeds were then sown in rows spaced 25 cm apart, with each experimental unit containing 6 rows (14).

Experimental treatments

First factor

Four planting dates (October 20, November 10, November 30 and December 20).

Second factor

Sugar alcohols in the form of mannitol−a colorless, odorless hexahydric sugar. It is a pure organic compound that appears as white crystals and is water-soluble. It was applied at 4 concentrations: 0, 3, 6 and 9 g L^{-1}.

Experimental design and statistical analysis

A randomised complete block design (RCBD) was employed using a two-factor split-plot arrangement with 3 replicates. Planting dates were assigned to the main plots, while sugar alcohol concentrations were assigned to the sub-plots, resulting in a total of 48 experimental units.

After data collection and tabulation, analysis of variance (ANOVA) was performed using Genstat software. The least significant difference (LSD) test was used to compare means at a probability level of 0.05, based on the two-factor split-plot arrangement within a RCBD (15).

Traits studied

Plant height (cm)

Ten plants were randomly selected from the two central rows of each experimental unit during the capsule formation stage. Plant height was measured from the soil surface to the plant's highest point.

Number of branches per plant (branches $plant^{-1}$)

The average number of branches was calculated for the 10 plants.

Chlorophyll estimation (SPAD)

This was calculated as the mean reading of 20 leaves collected at the 100 % flowering stage, using a SPAD-502 Plus chlorophyll meter.

Dry weight (g $plant^{-1}$)

The 10 plants were placed in perforated paper bags and dried in an electric oven at 68 °C for two consecutive days until a constant weight was achieved; the average weight of the dried samples was then calculated.

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Number of capsules per plant (capsules plant^{-1})

This was calculated as the average for 10 plants randomly selected from the harvested plants.

Number of seeds per capsule (seeds capsule^{-1})

Calculated as the average of 10 capsules randomly selected from those mentioned in the previous section.

1000-seed weight (g)

1000 seeds were randomly selected from the seed yield of each experimental unit and weighed using a sensitive electronic balance.

Seed yield (t ha^{-1})

The calculation is done by harvesting the area of the experimental unit, weighing it and converting it to tonnes.

Results and Discussion

Plant height (cm)

The analysis results presented in Table 1 demonstrated a clear, significant response in flax plant height to the effects of planting dates, mannitol levels and the interaction between them. The planting date of November 10 achieved the highest mean plant height (145.20 cm), significantly outperforming the other dates, whereas delaying planting until December 20 resulted in a sharp decrease in height, bringing it down to 102.37 cm. This superior performance associated with the mild autumn planting date (mid-November) is attributed to favourable climatic conditions specifically temperature and solar radiation during the early stages of vegetative growth. These conditions enhanced photosynthetic efficiency and the rate of cell elongation, in contrast to later planting dates, where plants suffered from lower temperatures that slowed biological processes and inhibited vegetative growth, this result is consistent with the findings of previous researchers regarding the fenugreek plant (16). Furthermore, the results indicate a significant positive dose-dependent response between increasing mannitol concentration and plant height; the highest concentration (9 g L^{-1}) yielded the greatest mean height of 139.16 cm, compared to the control treatment (106.98 cm). This positive effect of mannitol, a sugar alcohol can be attributed to its dual role: acting as an osmolyte that protects plant cells and maintains the turgor pressure essential for cell division and elongation and also serving as an additional carbon source and biostimulant that enhances internal hormonal balance (such as increasing the synthesis of gibberellins and auxins). This result aligns with the previous findings, which indicated a significant effect of the plant height trait in grapevines (11). Regarding the interaction effect, the combination of the optimal timing and the highest mannitol concentration (10/11 × 9 g L^{-1}) yielded the greatest absolute plant height 161.89 cm. This underscores the synergistic effect between favorable climatic conditions and biochemical support, enabling the flax plant to fully express its genetic potential for vegetative growth.

Table 1. Effect of planting dates, mannitol and their interaction on plant height

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	116.53	128.20	135.66	151.36	132.94
10/11	125.65	140.93	152.31	161.89	145.20
30/11	95.50	100.40	111.74	126.43	108.52
20/12	90.23	94.77	107.55	116.94	102.37
Means	106.98	116.08	126.82	139.16	
LSD$_{0.05}$	P = 8.43		M = 5.76		**P × M = 11.26**

LSD: least significant difference.

Number of branches per plant (branch plant^{-1})

The statistical analysis results in Table 2 revealed a significant effect of both planting dates and mannitol concentrations as well as their interaction on the number of branches in flax plants. The planting date of November 10 recorded the highest mean number of branches (3.83 branches plant^{-1}); this is attributed to favorable thermal and light conditions during the early stages of vegetative growth, which enhanced photosynthetic efficiency and stimulated lateral bud activity. This result is consistent with the earlier findings on flax plant (17). Furthermore, foliar spraying with mannitol resulted in a significant, positive correlation between concentration and the number of branches; the 9 g L^{-1} concentration yielded the highest mean (3.35 branches plant^{-1}). This highlights mannitol's vital role as an osmolyte and antioxidant that enhances the plant's growth potential and carbon partitioning among lateral branches. Regarding the interaction effect, the combination of the early planting date (October 20) and the highest mannitol concentration (9 g L^{-1}) produced the greatest response (3.93 branches plant^{-1}), reflecting a positive synergy between early planting and exogenous osmotic support in improving the morphological structure of the flax crop's vegetative canopy.

Table 2. Effect of planting dates, mannitol and their interaction on the number of branches (branch plant^{-1})

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20 / 10	3.24	3.45	3.70	3.93	3.58
10 / 11	3.85	3.89	3.71	3.85	3.83
30 / 11	2.66	2.72	2.82	2.80	2.75
20 / 12	2.34	2.69	2.85	2.81	2.67
Means	3.02	3.19	3.27	3.35	
LSD $_{0.05}$		P = 0.18		M = 0.09	P × M = 0.38

LSD: least significant difference.

Dry weight (g)

Statistical analysis results presented in Table 3 revealed a significant effect of both planting dates and mannitol concentrations on the dry weight of flax plants, whereas the interaction between them did not reach statistical significance. The planting date of November 10

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significantly outperformed the others, recording the highest mean dry weight (31.50 g); this is attributed to the alignment of this date with optimal thermal and photoperiodic requirements, which enhanced photosynthetic efficiency and the crop's cumulative growth rate throughout the vegetative season compared to later planting dates. Furthermore, foliar spraying with mannitol resulted in a significant, positive correlation with dry weight; the 9 g L^{-1} concentration yielded the highest value (30.77 g). This positive response is attributed to mannitol's fundamental role as an osmolyte and physiological stimulant that improves cellular water status, enhances cell membrane stability and activates enzymatic systems thereby positively influencing dry matter synthesis and accumulation within plant tissues.

Table 3. Effect of planting dates, mannitol and their interaction on dry weight (g)

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20 / 10	27.47	28.13	28.33	31.27	28.80
10 / 11	29.51	31.22	31.45	33.81	31.50
30 / 11	21.67	22.83	27.27	29.73	25.38
20 / 12	19.47	22.47	25.47	28.27	23.92
Means	24.53	26.16	28.13	30.77	
LSD $_{0.05}$		P = 0.52	M = 1.44		P × M = N S

LSD: least significant difference; NS: not significant.

Chlorophyll (Soil plant analysis development unit)

Statistical analysis results presented in Table 4 revealed a significant effect of both planting dates and mannitol concentrations on the chlorophyll content of flax leaves, whereas the interaction between the two factors was not statistically significant. The November 10 planting date achieved the highest mean chlorophyll content, 46.35 Soil plant analysis development (SPAD) unit, significantly outperforming the later dates (November 30 and December 20). This result is attributed to the favourable temperatures and solar radiation levels associated with this planting date, which created an optimal environment for the synthesis of plant pigments and prevented their thermal degradation. Furthermore, foliar spraying with mannitol resulted in a significant, progressive increase in chlorophyll content; the 9 g L^{-1} concentration recorded the highest value (45.20 SPAD unit). This is attributed to mannitol's physiological role as an osmoprotectant, helping to maintain the integrity of the thylakoid membrane within chloroplasts and protecting chlorophyll molecules from environmental stress by scavenging free radicals and activating antioxidant effects that positively influenced the efficiency and functional readiness of the plant's photosynthetic apparatus.

Number of capsules per plant (capsules $plant^{-1}$)

The results presented in Table 5 demonstrate a significant effect of planting dates, mannitol concentrations and their interaction on the number of capsules per plant in the flax crop. The planting date of November 10 significantly outperformed the other dates, recording the highest mean of 32.69 capsules $plant^{-1}$; this is attributed to the favourable climatic conditions associated with this date, which aligned well with the critical stages of flowering and yield formation. Conversely, delaying planting until December 20 resulted in the lowest mean for this trait, at 21.39 capsules $plant^{-1}$. Regarding the mannitol treatment, increasing concentrations resulted in a significant, direct improvement in the number of capsules, peaking at a concentration of 9 g L^{-1} with an average of 28.74 capsules $plant^{-1}$. This reflects mannitol's vital role as an osmotic stabiliser and physiological stimulant that enhances photosynthetic efficiency and protects plant tissues. The optimal positive interaction was observed with the combination of the early planting date (October 20) and the 9 g L^{-1} concentration, which achieved the highest yield of 35.39 capsules $plant^{-1}$; this significantly outperformed the control treatment the late planting date without mannitol which yielded the lowest value of 17.14 capsules $plant^{-1}$. Thus, early planting supplemented with mannitol spraying constitutes the optimal strategy for maximising flax yield components under the study conditions.

Table 4. Effect of planting dates, mannitol and their interaction on chlorophyll content (SPAD unit)

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	44.51	42.98	45.79	46.98	45.06
10/11	45.46	46.97	45.99	46.97	46.35
30/11	42.30	43.37	44.12	44.37	43.54
20/12	40.63	42.49	41.05	42.49	41.67
Means	43.23	43.95	44.24	45.20	
LSD $_{0.05}$		P = 1.65	M = 1.83		**P × M = NS**

LSD: least significant difference; NS: not significant.

Table 5. Effect of planting dates, mannitol and their interaction on the number of capsules per plant

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	24.77	25.52	27.19	28.60	26.52
10/11	30.12	32.48	32.78	35.39	32.69
30/11	20.64	22.32	24.02	26.59	23.39
20/12	17.14	21.10	22.92	24.39	21.39
Means	23.17	25.35	26.73	28.74	
LSD $_{0.05}$		P = 0.94	M = 1.33		**P × M = 3.20**

LSD: least significant difference; NS: not significant.

Number of seeds per capsule (seeds $capsule^{-1}$)

The results presented in Table 6 indicate a significant effect of planting dates, mannitol concentrations and their interaction on the number of seeds per capsule in the flax crop. The planting date of November 10 significantly outperformed the other dates, recording the highest mean of 8.60 seeds $capsule^{-1}$; this is attributed to the favourable climatic conditions associated with this date, which aligned well with the critical stages of flowering and

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capsule formation. Conversely, delaying planting until December 20 resulted in the lowest mean for this trait, at 6.92 seeds capsule^{-1}. Regarding the mannitol treatment, increasing concentrations led to a significant, direct improvement in the number of seeds per capsule, peaking at a concentration of 9 g L^{-1} with a mean of 8.57 seeds capsule^{-1}. The optimal positive interaction was observed with the combination of the November 10 planting date and the 9 g L^{-1} concentration, which achieved the highest yield of 9.60 seeds capsule^{-1}; this significantly outperformed the control treatment (late planting date without mannitol), which yielded the lowest value of 6.11 seeds capsule^{-1}.

Table 6. Effect of sowing dates, mannitol and their interaction on the number of seeds per capsule (seeds capsule^{-1})

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	7.19	7.22	8.13	8.80	7.83
10/11	7.45	8.43	8.91	9.60	8.60
30/11	7.07	7.35	7.95	8.23	7.65
20/12	6.11	6.68	7.22	7.66	6.92
Means	6.95	7.42	8.05	8.57	
LSD $_{0.05}$		P = 0.504	M = 1.03	**P × M = 2.98**	

LSD: least significant difference; NS: not significant.

1000-seed weight (g)

Statistical analysis of the 1000-seed weight trait in the flax crop (Table 7) revealed significant independent effects for both sowing dates and mannitol concentrations, whereas the interaction effect between them was not significant. The sowing date of November 10th yielded the best result, recording the highest mean seed weight of 7.47 g significantly outperforming the other dates, while the mean dropped to a minimum of 6.89 g for the late sowing date of December 20. This outcome is attributed to the fact that earlier sowing provided an optimal vegetative growth period, enhancing photosynthetic efficiency and net dry matter accumulation, as well as effectively directing assimilates toward the sink (seeds); in contrast, later sowing dates suffered from a shortened grain-filling period. On the other hand, foliar spraying with mannitol resulted in a significant, linear improvement in seed weight; the highest concentration (9 g L^{-1}) yielded the highest significant value, with an average of 7.59 g compared to the control treatment (6.65 g). This reflects mannitol's physiological role as an osmoprotectant and antioxidant, contributing to the maintenance of cell membrane integrity and the continuity of metabolic activities during seed development and embryo formation.

Seed yield (t ha^{-1})

The results show that significant differences in growth characteristics and yield components were reflected in the total crop yield due to variations in planting dates. Table 8 shows that the November 10 planting date resulted in the highest yield (1.64 t ha^{-1}), while the later planting date (December 20) yielded the lowest average total yield (1.02 t ha^{-1}). The reason for the higher total yield of the November 10 planting date is attributed to the optimal temperature and humidity conditions during the vegetative growth, flowering and seed-setting stages. This provided an ideal photosynthetic period and avoided the heat stress or extreme cold associated with later planting dates, such as December 20. This positively impacted nutrient translocation efficiency and increased seed yield. These results are consistent with previous findings, which confirmed that planting dates have a direct impact on seed yield and that late planting negatively affects production (17–20).

The increased response to increasing mannitol spray concentrations led to a rise in seed yield. After the control treatment recorded a seed yield of 0.87 t ha^{-1}, this yield gradually increased with each increase in mannitol concentration, reaching its highest average yield (1.63 t ha^{-1}) at the highest concentration (9 g L^{-1}). Mannitol plays a significant role in promoting plant growth (Tables 1–5) by increasing its tolerance to biotic and abiotic stresses, due to its low molecular weight (12). These compounds are also a major source of carbon and aid in carbohydrate synthesis and production, which is reflected in increased yield components (Tables 6 and 7) and, consequently, seed yield (13). The interaction between planting dates and mannitol concentrations had no significant effect, indicating the independence of each factor in influencing seed yield.

Table 7. Effect of sowing dates, mannitol and their interaction on 1000-seed weight (g)

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	6.73	7.16	7.29	7.74	7.23
10/11	6.97	7.38	7.62	7.92	7.47
30/11	6.62	7.08	7.18	7.51	7.09
20/12	6.29	6.95	7.14	7.19	6.89
Means	6.65	7.14	7.31	7.59	
LSD $_{0.05}$		P = 0.12	M = 1.007	**P × M = NS**	

LSD: least significant difference; NS: not significant.

Table 8. Effect of planting dates, mannitol and the interaction between them on seed yield (t ha^{-1})

Planting dates (P)	Mannitol concentration (M)				Means
	0 g L^{-1}	3 g L^{-1}	6 g L^{-1}	9 g L^{-1}	
20/10	0.81	1.09	1.15	1.37	1.11
10/11	1.02	1.78	1.81	1.96	1.64
30/11	0.96	1.51	1.80	1.89	1.54
20/12	0.69	0.92	1.20	1.29	1.02
Means	0.87	1.33	1.49	1.63	
LSD $_{0.05}$		P = 0.09	M = 0.06	**P × M = NS**	

LSD: least significant difference; NS: not significant.

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Conclusion

The study demonstrated that determining the appropriate planting date has a direct impact on the success and performance of flax production within the arid and semi-arid conditions of central Iraq. The planting date of November 10 proved optimal in achieving the highest crop response under the environmental conditions of the season. Furthermore, the study showed that the foliar application of the sugar alcohol mannitol, particularly at the concentration of 9 g L^{-1}, had a positive effect on improving crop growth and yield indicators and enhancing tolerance to environmental variations.

Authors' contributions

MIA, HHH, HMSK and UHM conducted the experiment and collected the data. MIA and AFZA performed the statistical analysis. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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