

Effect of fertilizer combinations and planting spacing a sensor-controlled subsurface drip irrigation system on broad bean (*Vicia faba* L.) productivity

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Abstract: Crop productivity is negatively impacted by not adopting scientific principles of modern technological techniques, for the identifying purpose specifically the chemical fertilizers rationing through subsurface drip irrigation with sensors for ensures water availability. A two-year field experiment (2023-24 and 2024-25) was conducted in a farmer's field in the Al-Muradiyah Research Station Hilla City, Iraq. The experimental design was a split-plot RCBD with three replicates, the main plots consisted of four PD (20, 30, 40, 50 cm), and sub-plots consisted of three AFc (AFc0, AFc1, AFc2, AFc3) for the Luz-be-otono broad bean variety, via an AI-driven system controlled water and fertilizer delivery with precise planting distances, the results demonstrated that the AFc3 also surpassed AFc0, AFc1 and AFc2 in all growth and yield parameters: branches number (BN: 11.47 and 11.90 branch plant⁻¹), pods number in plant (PNP: 21.68 and 22.25 pod plant⁻¹), seeds number in pod (SNP: 5.56 and 5.85 seed pod⁻¹), 100-seed weight (100-SW: 138.91 and 140.78 g), seed yield per plant (SYP: 57.86 and 67.71 seed plant⁻¹), seed yield (SY: 5.47 and 5.66 tha⁻¹), protein ratio (PR: 25.10% and 25.52%) and carbohydrate ratio (CPR: 63.69% and 64.42%), for the study seasons 2023-24 and 2024-25. The PD of 50 cm significantly outperformed 20, 30 and 40 cm across all measured traits. Optimal results were achieved with the interaction of 50 cm and AFc3, highlighting this combination as the most effective for enhancing broad bean productivity under the studied conditions.

Keywords: broad bean, technologies, subsurface drip irrigation, sensor system, planting distances, fertilizers

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1 Introduction

Broad beans (*Vicia faba* L.) are one of the most important low-cost food sources, especially in poor countries, as they are considered an alternative to animal protein sources due to their high protein content of 40% and fiber content of 8.5% (Crépon et

al., 2010; Desouky et al., 2022; Ziche et al., 2023). It is an important crop that is encouraged to be cultivated due to their high nutritional value (Robinson et al., 2019; Khazaei and Vandenberg, 2020). The importance of broad bean cultivation is reflected in its soil properties improvement, both physical and chemical, through its contribution to

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fixing atmospheric nitrogen levels in symbiosis with bacteria. Therefore, it is preferable to cultivate it in crop rotations, especially when paired with soil-depleting crops that require fertile soil, to achieve high yields that cover production costs and raise the living standard for farmer's (Al-Hasany et al., 2020; Al-Falahi and Abdulkafoor, 2021). Broad bean cultivation still suffers from many problems, leading to a decrease in yield to unit area, among these problems most prominent, included crop management practices, the cultivation of strategic crops such as rice, wheat, and corn, and fertilization methods and timing according to the soil and the plant needs (Huthily et al., 2021). Broad bean plants are classified as nitrogen-fixing plants, therefore they play a key role in improving soil properties (Yucel 2013; Ali et al., 2019). The fertilization timing has a significant impact on growth characteristics that affect production (Alaamer et al., 2023a), the crop proper fertilization leads to a decrease in the percentage of flower drop, resulting in an increase in the final yield (Alaamer et al., 2023b; Alaamer et al., 2024a).

Study of Anaya et al. (2017) and Mahdi et al. (2021) have shown that the fertilizers use increases production costs and deteriorates soil condition; therefore, most studies have focused on improving crop characteristics according to scientific principles for adding fertilizers based on the soil needs and the plant in relation to the growth stages. Wafaa and Habib (2021). The use of different types of potassium fertilizers has a positively affected on the growth and productivity of the local variety, and enhances its ability to withstand water and environmental stresses. Kumar et al.(2020); Amanullah et al. (2022), potassium (K) plays a vital role in photosynthesis, its deficiency can cause significant disruptions in the nutrients distribution between the aerial and the plant root parts, especially during the early stages from plant growth. Plants deficient in nitrogen (N), are highly sensitive to light, exhibiting leaves yellowing and eventually wilting. Therefore, N and K fertilizers play a crucial role in

mitigating the stresses effects such as drought and important tolerance to high temperatures. Alsharifi et al. (2022b); Alaamer et al. (2024b), it has been shown that adding N fertilizers strengthens the root system and increases the plant's resistance to diseases and pests that make it vulnerable to damage in the various conditions it goes through during different growth stages. Ghali et al. (2020). Nitrogen is an indispensable mineral element, crucial for plant growth and development, maintaining adequate nitrogen levels in the soil is essential for the proper functioning for plants, its deficiency hinders overall plant growth (Barlóg et al., 2019; Kaleri et al., 2023; Dietrich et al., 2025). Mitigates the damage is distributing fertilizers in installments according to the plant's essential needs, thus eliminating the damage that causes groundwater pollution, adding high percentages of nitrogen fertilizer increases vegetative growth and lodging, consequently damaging the plant's flowers and reducing the yield.

Improvements in growth characteristics, including the branches number, seed weight, and total final yield, were observed when the application NK fertilizers rates were increased (Kakahy et al., 2013; Biri et al., 2024). Choosing the optimal spacing when planting plants according to precision agriculture improves growth characteristics related to reduced competition between plants for nutrient absorption. Furthermore, wider planting distances improve the plant's exposure to solar radiation, which is essential for photosynthesis, and this is reflected in improved vegetative growth characteristics (Cuccia et al., 2019; Manson et al.,2024). During the grain-filling stage, sufficient and appropriate water is required to sustain critical growth phases, water deficiency during these stages impairs plant growth and causes wilting, resulting in under ripe (empty) grains, which negatively impacts the final yield (Alaamer et al., 2026). Increasing the distance between planted plants had a positive effect on increasing growth characteristics and yield (Etemadi et al., 2018; Amer et al.,2025). The reason for the decrease in flower

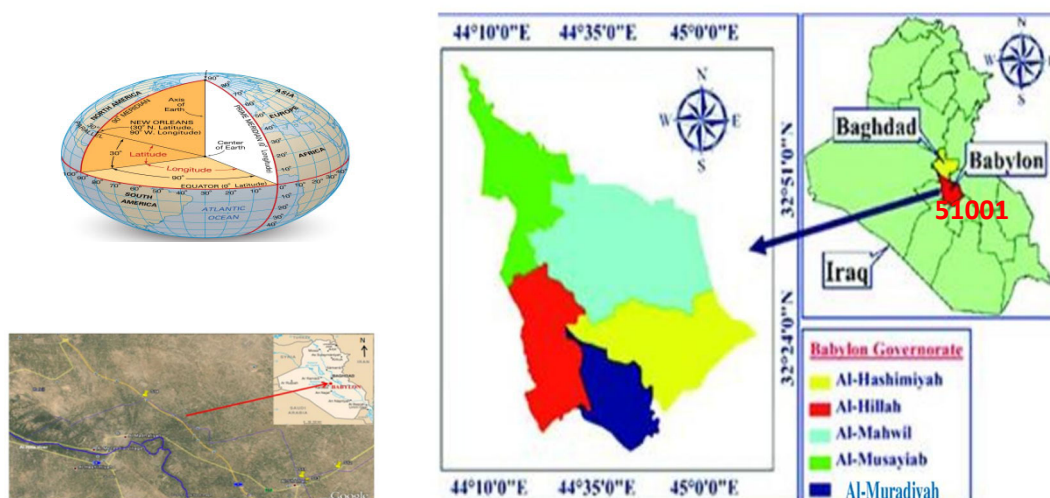
drop in broad bean plants resulting from the mineral fertilizers addition is that these fertilizers play a prominent role in providing the necessary nutrients for plant growth and changing the results distribution of carbon metabolism within the plant by altering the stems growth pattern, branches and the flowering duration (Guo et al., 2018; Barłóg et al., 2018; El Mokh et al., 2022). Most studies confirmed by researchers indicate that improving plant growth characteristics depends on the scientific basis of agricultural processes related to the chosen variety, the cultivation method, and its distances and depth (Shtewy et al., 2020; Alsharifi et al., 2022a). The competition method for nutrients is determined by the distance between plants and the way they are distributed per unit distance, which is affected by field and environmental factors and their influential role on vegetative growth, yield, and quality (Saad ,2015; Alatawi et al., 2024; Alsharifi et al., 2025). In this context, it must be considered that food

security is affected by the decrease in areas allocated for crop cultivation, which has reached its lowest level due to the water crisis. Therefore, adopting modern irrigation methods is necessary to support the large areas cultivation of arable land in a way that conserves water and makes it available for other crops planting . For this reason, the current study focused on the effect of fertilizer compounds applied through drip irrigation and surface watering on faba bean Luz-be-otono variety within different planting distance ranges.

2 Materials and methods

2.1 Experiment site

The Al-Muradiyah city is located approximately 15 km from the center, the Babil Governorate south in the Middle Euphrates region, at latitude 32.468191 north and longitude 44.5501935 east. It lies on the Euphrates River and is dedicated to cultivating broad beans (*Vicia faba* L) (Figure 1).



Administrative Map of Babylon city

Figure 1 Experiment site

2.2 Field soil preparation

A field experiment was conducted during the 2023-2024 and 2024-2025 winter growing season, before the implantation, soil samples were collected from nine randomly selected locations (0-20 cm depth) with three replicates each for comprehensive physicochemical analysis. The sampling area was determined based on experimental requirements, with

results presented in Table 1.

The soil was prepared by plowing using a chisel plow and the ploughman was set to a depth of 20 cm to stir it, smoothed and leveled using a laser leveling machine (Alsharifi et al., 2021a; Mankhi and Jebur, 2022; Merza et al., 2023), main pipes were extended on the experimental field sides, lines were made using a ditcher at a depth of 12 cm to extend the branch

pipes carrying the drippers and bury them according to planting distances, seeds were planted using a locally designed compound seeding machine with a distances of 20, 30, 40 and 50 cm between one line and another, at a rate of 75 kg ha⁻¹ for the broad bean Luz-be-otono variety. After completing the planting process, the pumps were installed and the main and sub-pipes wiring the drippers for the subsurface drip irrigation system were extended to a 12 cm depth and 2.8 cm towards the soil surface top, to achieve a moisture circle of 40 cm and 2 cm from the surface dry soil from top. And with a distance of 10 cm between each sub-pipes line, from the wilting point up to the field capacity value, which is the most

suitable soil moisture of 95%, allowed for the plant during the growing season (Alsharifi et al., 2021b; Alaamer et al., 2026). The irrigation process is carried out automatically according to the plant's need through sensors that give a signal to operate the irrigation system and when the saturation stage is reached, the sensors give a signal to stop the irrigation system and this process is repeated throughout the growing season until harvest (Alaamer and Alsharifi, 2021). The dripper discharge was 12 L h⁻¹ with the operating pressure was 150 kPa, Figure 2, the irrigation process continued to achieve a germination rate of 96% and a germination speed of 84%, for broad bean Luz-be-otono variety.

Table 1 Soil characteristics of physical and chemical

Soil Depth (cm)		Properties
10 -20	0- 10	
153	143	Sand
444	488	Silt
403	369	Clay
silty clay loam		soil texture
0.109	0.133	Mean Weight Diameter (mm)
1.37	1.35	Bulk Density (Mg m ⁻³)
6.42	6.98	pH
292.52	335.55	Total Carbonate (g kg ⁻¹)
2.73	3.25	Organic matter (g kg ⁻¹)
3.86	2.77	Ec Soil dSm ⁻¹
2.65	49.35	True Density (Mg m ⁻³)
		porosity %
		field capacity %
		Soil water infiltration value
1.0 mm hr ⁻¹	31.39	Ec Water dSm ⁻¹
0.8	0.8	Chemical properties of irrigation water
< 10		SAR
1.4 meq . l ⁻¹		HCO ₃ ⁻
7.2		pH
< 450 ppm		TDS
27.33	27.51	CEC Cmole ⁽⁺⁾ kg ⁻¹
	9.44	Na
	10.51	K
	19.30	Mg ⁺⁺
	38.60	Cl ⁻
Meq . L ⁻¹	20.40	SO ₄ ⁼
	17.20	Ca ⁺⁺
	43.89	Ca+Mg

2.2.1 Study factors

i) Main factor; Planting distances (PD)

is 20, 30, 40 and 50 cm, it was measured using an Invar tape (Alsharifi et al., 2021a; Alsharifi et al., 2022a)

ii) Secondary factor; Added fertilizers (AF)

The experiment examined three nitrogen (N: 0, 70, 90, 110 kg N·ha⁻¹) and three potassium (K: 0, 55, 75, 95 kg K·ha⁻¹) levels in a fertilizer composition, denoted as AF0 (control), AF1(70 kg N + 55 kg K ha⁻¹), AF2 (90 kg N + 75 kg K ha⁻¹) and AF3 (110 kg N + 95 kg K ha⁻¹).

2.2.2 Characteristics studied

2.2.2.1 Branches number (BN)

Calculated it one week before the harvest, for each plant, with five randomly selected plants per experimental unit (Zörb et al., 2013 Lombardo et al., 2016; Alaamer et al., 2022).

2.2.2.2 Pods number in plant (PNP)

The Equation (1) is used to calculate the parameter (Mitiku and Wolde, 2015; Wahbi et al., 2016; Liu et al., 2021).

$$P_{NP} = \frac{\sum PN}{NPSR} \quad (1)$$

Where,

P_{NP} , pods number in plant (pod plant⁻¹);

$\sum PN$, Total number of pods;

$NPSR$, Number of plants selected at random.

2.2.2.3 Seeds number in pod (SNP)

It is calculated using the Satack device used for the threshing and counting process (Equation (2)) (Alsharifi et al., 2021b; Alsharifi et al., 2024)

$$S_{NP} = \frac{N_{SP}}{N_{PP}} \quad (2)$$

Where,

S_{NP} is the seed number in pod (seed pod⁻¹);

N_{SP} is the number of seeds per plant;

N_{PP} is the number of pods per plant.

2.2.2.4 100-seeds weight (100- SW)

A random sample of (100 seeds) was taken from each experimental unit (Aljibouri and Alsharifi, 2019), it was sorted using a Satack device (Aljibouri et al., 2022; Ajmi et al., 2023) and weighed using a precision balance (accuracy ± 0.01 g).

2.2.2.5 Seed yield per plant (SYP)

It can be calculated from the Equation (3) (Al Barri and Shtaya, 2013; Gezahegn et al., 2016 ; Sandhu et al., 2019).

$$S_Y = (PNA \times ANS \times SWA) \quad (3)$$

Where,

S_Y is the seed yield (seed plant⁻¹);

PNA is the pods number average (pods plant⁻¹);

ANS is the seeds number average (seed pod⁻¹);

SWA is the seed weight average

2.2.2.6 Seed yield (SY)

Calculated based on the average yield of ten randomly selected plants per experimental unit, multiplied by the plant density (Equation 4) (Alaamer et al., 2023b; Alsharifi et al., 2025).

$$SY = G_p \times PD \quad (4)$$

Where,

SY is the grain yield (t ha⁻¹);

G_p is the grain rate per plant (kg);

PD is the plant density ha⁻¹.

2.2.2.7 Carbohydrate ratio (CR)

It was calculated from the Equation 5.

$$CHp = \frac{VSCS}{0.2g} \times 25 \quad (5)$$

Where,

CHp is the carbohydrate percentage (%);

$VSCS$ is the value from the standard curve for sucrose.

2.2.2.8 Protein ratio (PR)

It was calculated as Equation 6.

$$P_P = \frac{V H_2SO_4 (s) - V H_2SO_4 (B) \times N H_2SO_4 \times E \times 6.25}{Wts} \quad (6)$$

Where,

P_P is the protein percentage (%);

$V H_2SO_4 (s)$ = Vol H₂SO₄ for the model,

$V H_2SO_4 (B)$ = Vol H₂SO₄;

For the plank, $N H_2SO_4$ = Acid standard H₂SO₄ , E, Nitrogen equivalent (0.014);

Wts , Sample weight.

2.2.3 Statistical analysis

The experimental data were analyzed using GenStat 18th edition (VSN International) with a split-plot arrangement in a randomized complete block design (RCBD). Treatment means were compared using Least Significant Difference (LSD) test at $\alpha = 0.05$ significance level.

3 Results and discussion

3.1 Vegetative growth characteristics

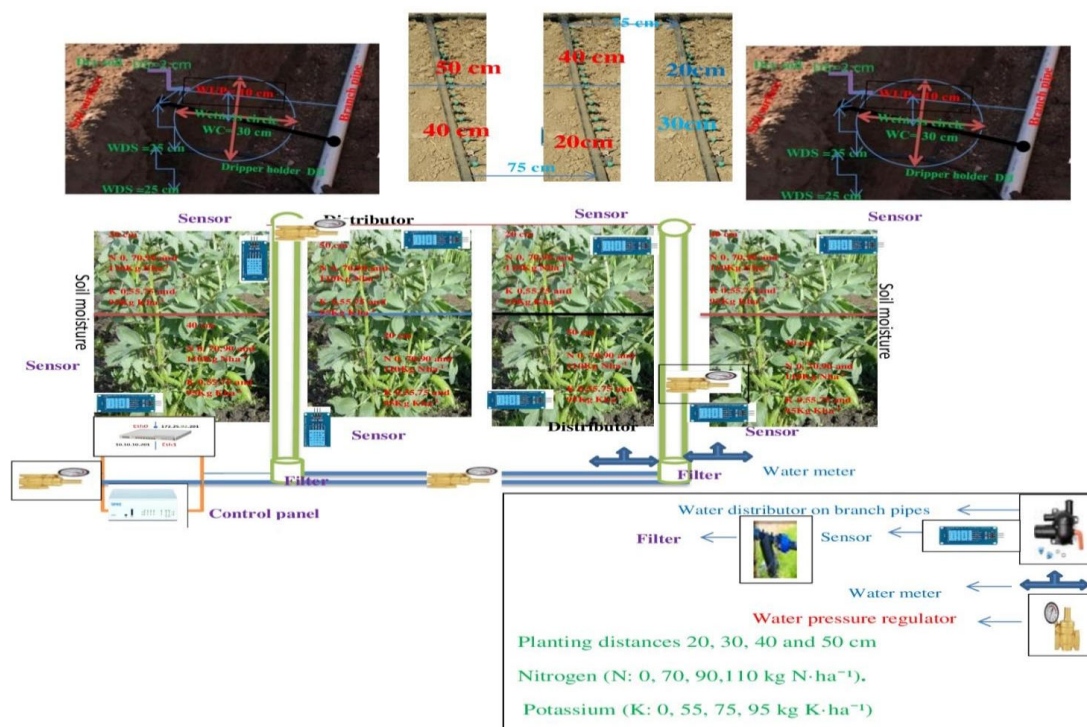
There was a highly significant effect due to the interaction between the planting distances and the added fertilizer combination N-K on the vegetative growth characteristics (Tables 2 and 3). The AFc3

was significantly superior to the other levels of AFc1, AFc2 and AFc0. While the PD of 50 cm was significantly superior to the other distances 20, 30 and 40 cm in all studied parameters. All the interactions were significantly different and the best results BN: 12.78 and 13.10 branch plant⁻¹, 26.21 and 26.69 pod plant⁻¹, 6.47 and 6.78 seed pod⁻¹, have come from the overlap between PD of 50 cm and AFc3, for the study seasons 2023-24 and 2024-25.

The statistical analysis revealed significant effects ($p < 0.05$) (Table 2). From Figure 3A, it is obvious that there were significant differences in the planting distances on the branches number. The PD of 50 cm registered the highest average 11.05 and 11.56 branch plant⁻¹, while the treatment PD of 20 cm gave the lowest average, 8.11 and 8.61 branch plant⁻¹, respectively for two seasons 2023-24 and 2024-25. The spacing between plants is closely linked to photosynthesis. Increasing the distance between plants improves their exposure to solar radiation, which positively impacts vegetative growth. Mahdi et al., (2021); Alaamer et al. (2023a) confirmed that photosynthesis have a significant effect on plant growth characteristics, it is noted from Figure 3B.

The treatment PD of 50 cm recorded the highest average of 22.01 and 22.62 pod plant⁻¹, surpassing 40

cm of 18.37 and 18.90 pod plant⁻¹, and the treatment 30 cm of 16.62 and 17.19 pod plant⁻¹, while the treatment 20 cm recorded the lowest average of 13.18 and 13.78 pod plant⁻¹, respectively for two seasons, vegetative growth traits improve with increased spacing between plants, following precise scientific principles of uniform planting distances. This, in turn, stimulates plant growth through root development and all nutrients absorption with less competition (Desouky et al., 2023; Biri et al., 2024). They confirmed that PD has a significant effect on plant traits, as it appears from the results of the statistical analysis for Figure 3C, there is a highly significant effect for planting distances on seed number in pod, that there are significant differences between all treatments. The treatment PD of 50 cm on record the highest average of 5.40 and 5.74 seed pod⁻¹, surpassing PD 40 of 4.88 and 5.07 seed pod⁻¹, PD 30 cm of 4.59 and 4.90 seed pod⁻¹, while the treatment PD of 20 cm recorded the lowest average of 4.19 and 4.38 seed pod⁻¹, respectively for two seasons. The competition for nutrients is determined by the distance between plants and how they are distributed within a unit area, which is influenced by field and environmental factors and, in turn, has a direct impact on the vegetative crop growth (Etemadi et al., 2018).



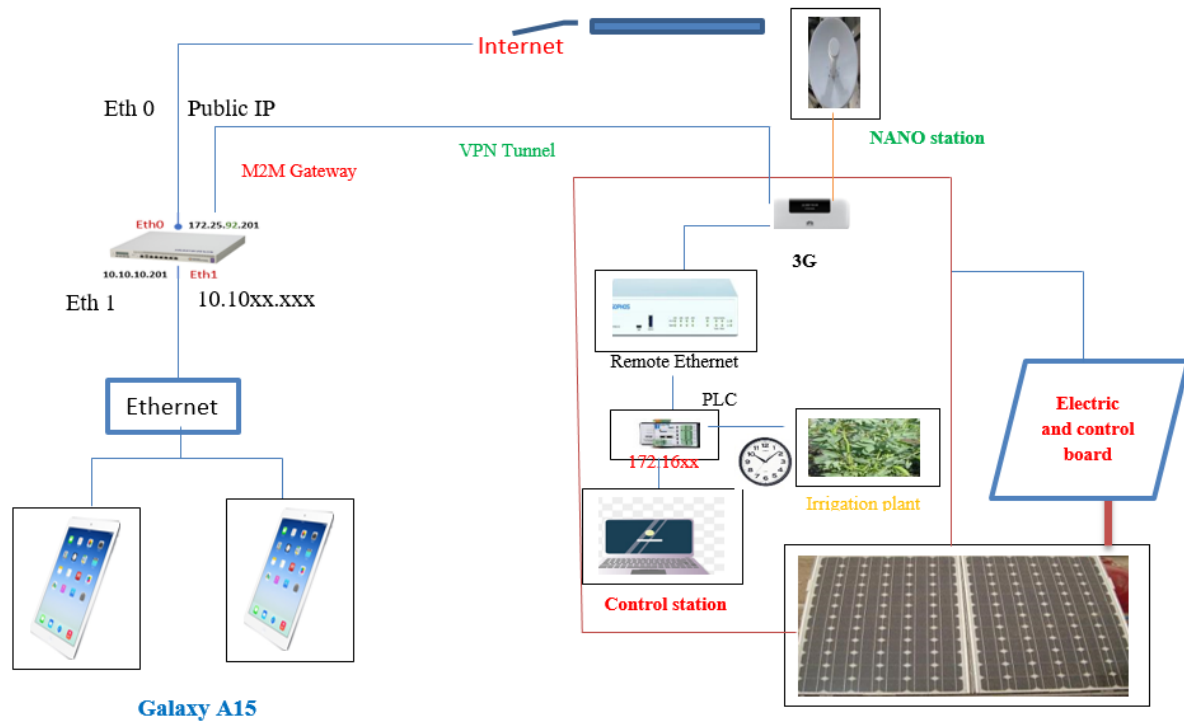


Figure 2 The experiment general structure

Table 2 Effects of PD and AFc on vegetative growth parameters.

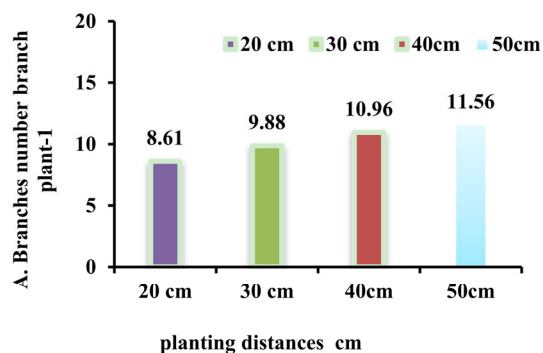
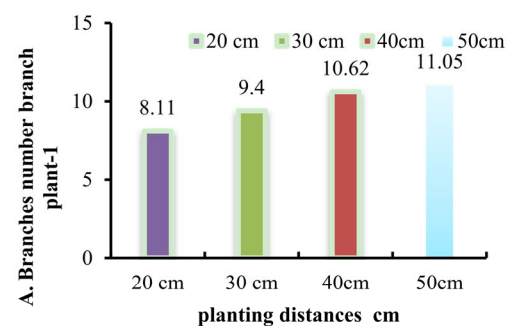
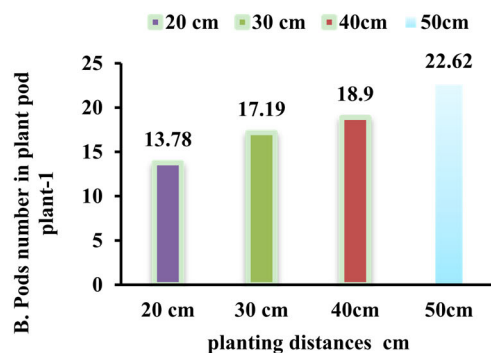
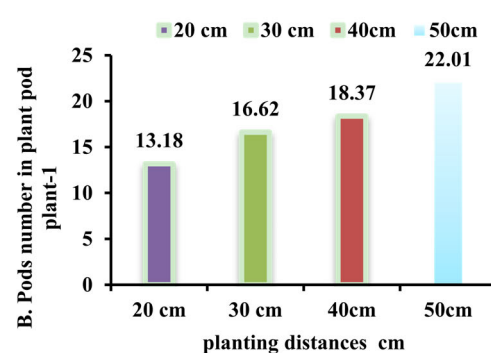
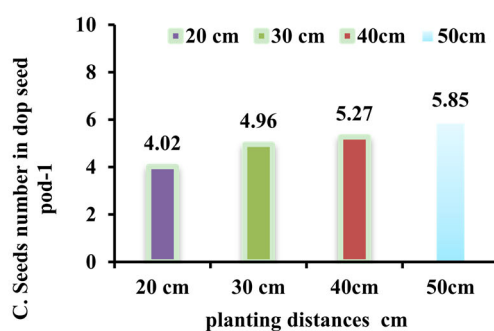
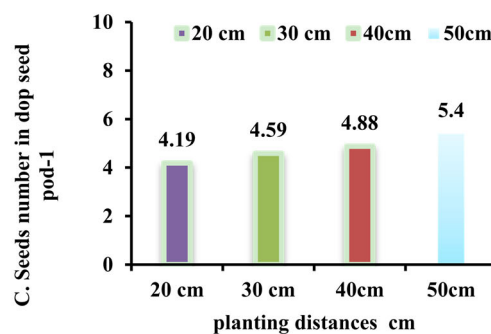
2023-2024					2024-2025				
PD	cm	AFc			PD	cm	AFc		
		kg ha ⁻¹					kg ha ⁻¹		
		BN	PNP	SNP			BN	PNP	SNP
20	AFc0	6.13	7.44	3.51	20	AFc0	6.74	8.32	3.76
	AFc1	7.86	13.75	4.04		AFc1	8.09	14.53	4.25
	AFc2	8.43	14.82	4.26		AFc2	9.06	15.07	4.49
	AFc3	10.01	16.72	4.49		AFc3	10.55	17.19	5.02
	AFc0	7.94	9.12	3.65		AFc0	8.22	9.55	3.89
30	AFc1	8.55	16.47	4.67	30	AFc1	9.12	17.06	4.92
	AFc2	10.04	19.80	4.98		AFc2	10.66	20.11	5.12
	AFc3	11.06	21.11	5.07		AFc3	11.52	22.04	5.68
	AFc0	8.55	10.92	3.76		AFc0	9.42	11.13	3.98
	AFc1	10.52	18.43	4.96		AFc1	10.37	19.15	5.03
40	AFc2	11.43	21.36	5.02	40	AFc2	11.61	22.21	5.36
	AFc3	12.01	22.76	5.77		AFc3	12.42	23.10	5.92
	AFc0	9.03	12.37	4.04		AFc0	9.94	13.43	4.43
	AFc1	10.81	24.54	5.13		AFc1	11.08	28.85	5.66
	AFc2	11.60	25.01	5.95		AFc2	12.11	25.52	6.11
50	AFc3	12.78	26.21	6.47	50	AFc3	13.10	26.69	6.78
	Means PD					Means PD			
	20	8.11	13.18	4.19		20	8.61	13.78	4.38
	30	9.40	16.62	4.59		30	9.88	17.19	4.90
	40	10.62	18.37	4.88		40	10.96	18.90	5.07
	50	11.05	22.01	5.40		50	11.56	22.62	5.74
Means AFc					Means AFc				
	AFc0	7.91	9.96	3.74		AFc0	8.58	10.61	4.02
	AFc1	9.43	18.29	4.70		AFc1	9.67	18.89	4.96
	AFc2	10.38	20.25	5.05		AFc2	10.86	20.73	5.27
	AFc3	11.47	21.68	5.56		AF3	11.90	22.25	5.85
L.S.D=0.05					L.S.D=0.05				
	PD	0.106	0.035	0.065		PD	0.044	0.137	0.045
	AFc	0.107	0.037	0.049		AFc	0.031	0.075	0.033
	PD* AFc	0.204	0.070	0.101		PD* AFc	0.065	0.175	0.068

Note: Planting distances; PD, Added fertilizers; AFc, Branches number; BN, Pods number in plant; PNP, Seeds number in pod; SNP .

Table 3 Variance analysis for vegetative growth and yield parameters

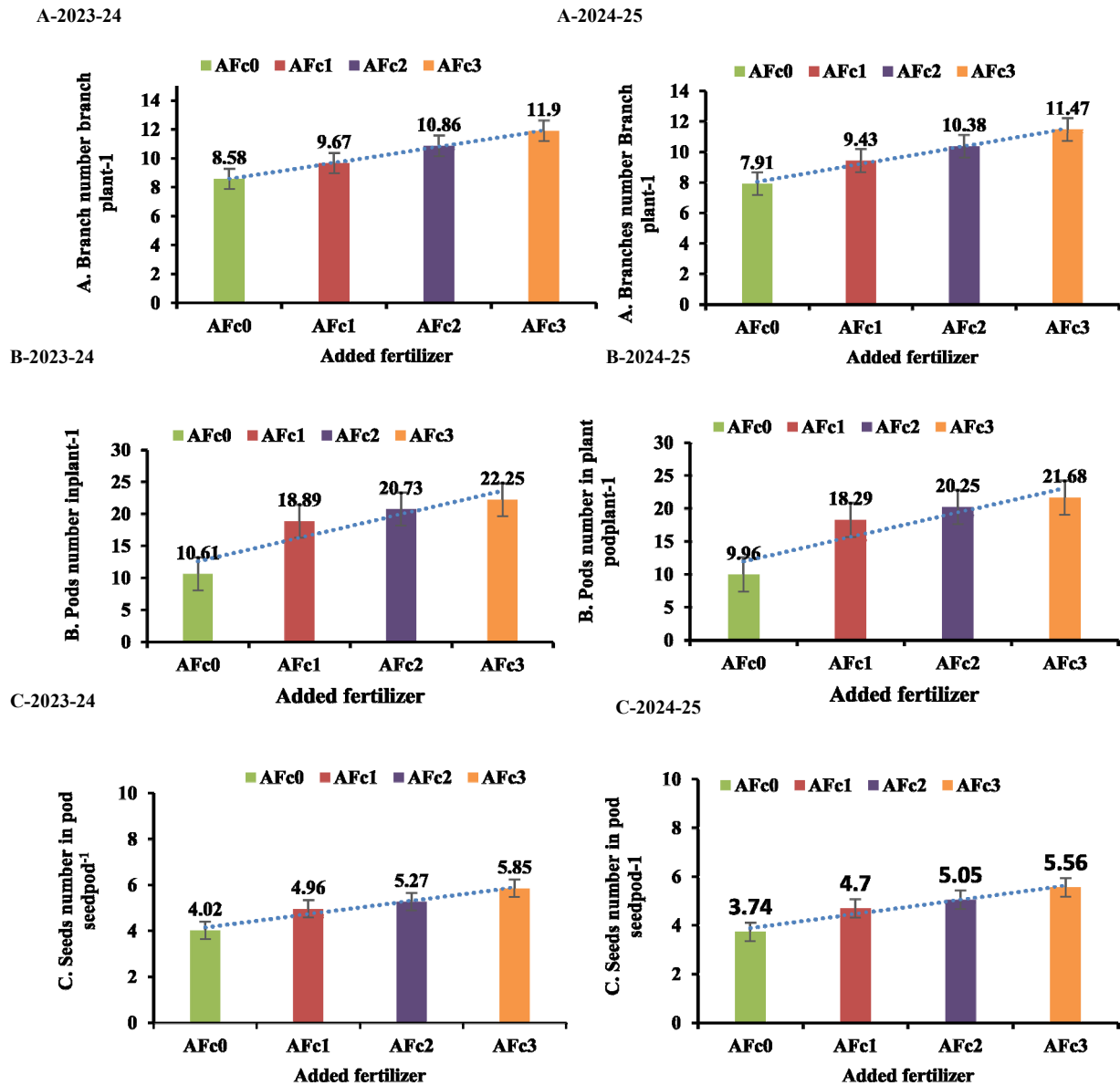
2023-24									
Source		Vegetative growth characteristics			Yield characteristics		Carbohydrate and protein ratios		
Source	df	Branch number	Pods number in plant	Seed number in pod	100 –seed weight	Seed yield per plant	Seeds yield	Protein ratio	Carbohydrate ratio
PD	3	1853.64**	1291.05**	725.92**	5022.37**	4381.24**	11993.91**	291.71**	793.50**
AFc	3	1682.48**	1688.5**	2086.91**	24100.53**	18075.30**	3288.90**	2895.66**	5877.75**
PD*AFc	9	17.31**	2423.93**	66.25**	341.99**	233.70**	552.95**	37.04**	84.42**
2024-25									
Source		Vegetative growth characteristics			Yield characteristics		Carbohydrate and protein ratios		
Source	df	Branch number	Pods number in plant	Seed number in pod	100 –seed weight	Seed yield per plant	Seeds yield	Protein ratio	Carbohydrate ratio
PD	3	10335.44**	8585.73**	1813.87**	47586.25**	4.355E+0**	6458.66**	1548.56**	1378.05**
AFc	3	17715.73**	40559.26**	4510.02**	16499.66**	1.157E+0**	3195.15**	8396.13**	1088.05**
PD*AFc	9	69.46**	575.31**	81.14**	254.57**	1318.30**	388.22**	127.14**	1290.86**

Note: PD = planting distances. AFc – added fertilizer combination. ** Significant at 0.01 level. * Significant at 0.05 level.

A-2023-24**A-2024-25****B-2023-24****B-2024-25****C-2023-24****C-2024-25**

(A) branches number, (B) pods number in plant, (C) seeds number in pod

Figure 3 Effect of the planting distances on vegetative growth characteristics



(A) branches number, (B) pods number in plant, (C) seeds number in pod

Figure 4 Effect of the added fertilizer combination on vegetative growth characteristics

The statistical analysis revealed significant effects ($p < 0.05$) of both planting distances and N-K fertilization on branches number. From Table 3, there is a highly significant effect for AFc, that there are significant differences between all treatments. It is noted from Figure 4A. The treatment AFc3 recorded the highest average of 11.47 and 11.90 branch plant⁻¹, surpassing AFc2 of 10.38 and 10.86 branch plant⁻¹, AFc1 of 9.43 and 9.67 branch plant⁻¹, while the treatment AFc0 recorded the lowest average of 7.91 and 8.58 branch plant⁻¹, respectively, for two seasons 2023-24 and 2024-25. Added fertilizers play a pivotal role in plant growth and development, and

maintaining their concentration in the soil is crucial for completing plant functions and thus improving normal growth conditions (Kakahy et al., 2013; Biri et al., 2024). These results indicate that the increase in branch number is attributed to the availability of essential nutrients in the soil, which promotes plant growth and development. Statistical analysis of the data in Figure 4B revealed that the AFc factor had a highly significant effect on pod number per plant. Among the treatments, AFc3 produced the highest values (21.68 and 22.25 pods plant⁻¹), followed by AFc2 (20.25 and 20.73 pods plant⁻¹) and AFc1 (18.29 and 18.89 pods plant⁻¹) for the two seasons,

respectively. The control treatment AFc0 yielded undesirable results for this study of 9.96 and 10.61 pod plant⁻¹, for two seasons. While the statistical analysis revealed significant effects ($p < 0.05$) from Figure 4C. For AFc factor was a highly significant effect on seeds number in pod, the AFc3 registered the highest average 5.56 and 5.85 seedpod⁻¹, surpassing AFc2 of 5.05 and 5.27 seed pod⁻¹, AFc1 of 4.70 and 4.96 seed pod⁻¹, while the treatment AFc0 gave the lowest average of 4.19 and 4.38 seed pod⁻¹,

respectively. For two seasons, the reason for this is that adding fertilizers promotes root expansion in the soil, increasing the branches number and thus helping the plant absorb nutrients from the soil, thereby increasing the seeds number in pod (Liu et al., 2021). This evolution renowned to afflicted AFc with water allocation, which improved nutritious uptake over ticklish growth stages (flowering and grain filling) while lessen inter-plant rivalry.

Table 4 Effects of PD and AFc on broad bean yield parameters

PD cm	AF kg ha ⁻¹	2023-2024			PD	AF kg ha ⁻¹	2024-2025		
		100-SW	SYP	SY			100-SW	SYP	SY
20	AFc0	65.77	18.54	2.71	20	AFc0	66.26	18.88	2.78
	AFc1	90.13	26.43	3.42		AFc1	91.80	27.33	3.55
	AFc2	111.28	36.10	4.09		AFc2	112.43	37.81	4.22
	AFc3	122.55	55.15	4.36		AFc3	123.52	56.29	4.51
30	AFc0	72.44	21.37	2.94	30	AFc0	74.18	22.21	3.02
	AFc1	104.33	34.54	3.81		AFc1	105.60	35.17	4.07
	AFc2	124.14	53.64	4.58		AFc2	125.19	53.95	4.89
	AFc3	137.95	66.58	5.09		AFc3	141.81	67.46	5.17
40	AFc0	81.59	23.47	3.06	40	AFc0	84.34	23.88	3.21
	AFc1	128.69	44.80	3.46		AFc1	131.06	45.74	5.20
	AFc2	141.62	56.93	5.06		AFc2	143.92	56.08	5.88
	AFc3	143.10	71.06	5.57		AFc3	145.24	71.97	5.89
50	AFc0	99.03	34.52	5.24	50	AFc0	98.08	36.16	5.62
	AFc1	143.53	55.17	6.04		AFc1	145.92	56.04	6.26
	AFc2	145.75	67.82	6.52		AFc2	146.21	68.38	6.92
	AFc3	151.30	73.95	6.87		AFc3	152.56	75.13	7.08
Means PD					Means PD				
20		97.43	34.05	3.64	20		98.50	35.08	3.77
30		109.71	44.03	4.11	30		111.70	44.70	4.29
40		123.75	49.07	4.29	40		126.14	49.42	5.04
50		134.91	57.86	6.17	50		135.69	58.93	6.47
Means AFc					Means AF				
AFc0		79.71	24.47	3.49	AFc0		80.72	25.28	3.66
AFc1		116.67	40.23	4.18	AFc1		118.59	41.07	4.77
AFc2		130.70	53.62	5.06	AFc2		131.94	54.06	5.48
AFc3		138.91	57.86	5.47	AFc3		140.78	67.71	5.66
L.S.D=0.05					L.S.D=0.05				
PD		0.797	0.519	0.035	PD		0.259	0.052	0.051
AFc		0.491	0.392	0.038	AFc		0.602	0.049	0.041
PD* AFc		1.083	0.802	0.071	PD* AFc		1.061	0.095	0.082

Note: 100-seeds weight ;100-SW, Seed yield per plant; SYP, Seed yield; SY.

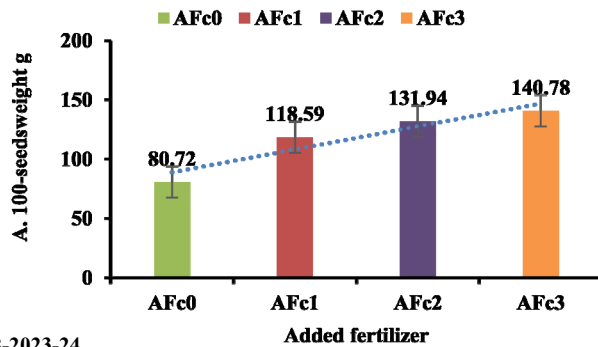
3.2 Yield characteristics

There was a highly significant effect due to the

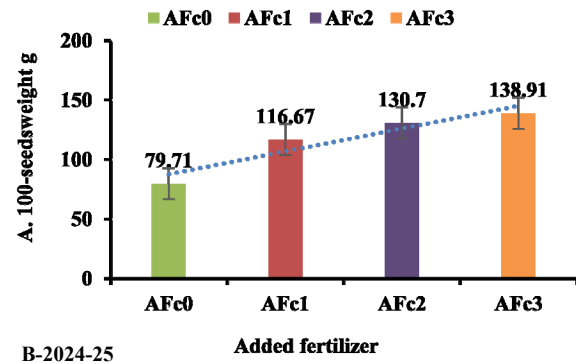
interaction between the planting distances and the added fertilizer combination N-K on the vegetative growth characteristics (Table 3 and 4). The AFc3 was significantly superior to the other levels of AFc1, AFc2 and AFc0. While the PD of 50 cm was significantly superior to the other distances 20, 30 and

40 cm in all studied parameters. All the interactions were significantly different and the best results: 151.30 and 152.56 g, 73.95 and 75.13 seed plant⁻¹, 6.87 and 7.08 tha⁻¹, have come from the overlap between PD of 50 cm and AFc3, for the study seasons 2023-24 and 2024-25.

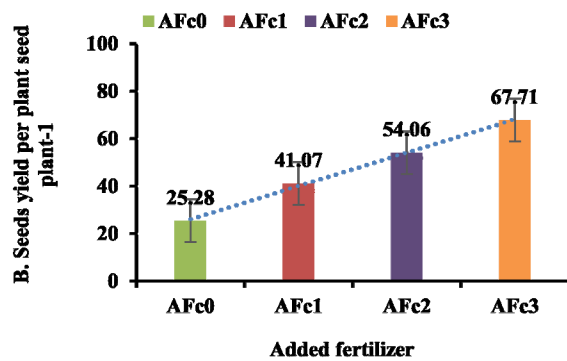
A-2023-24



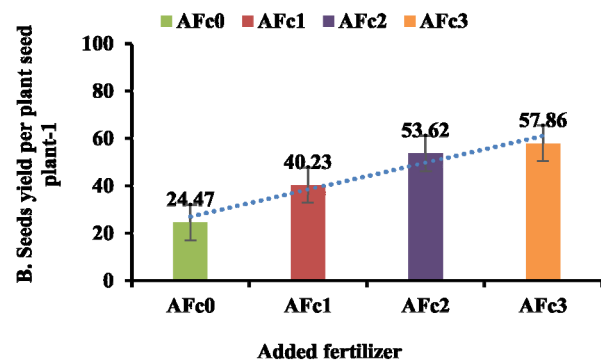
A-2024-25



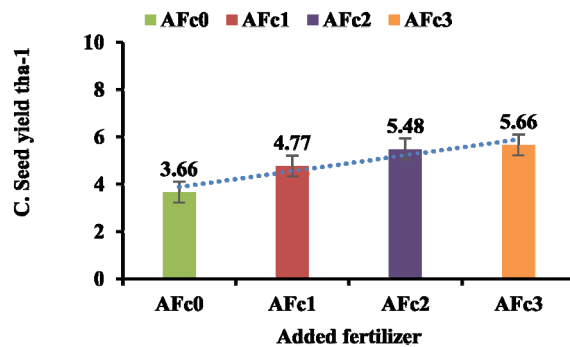
B-2023-24



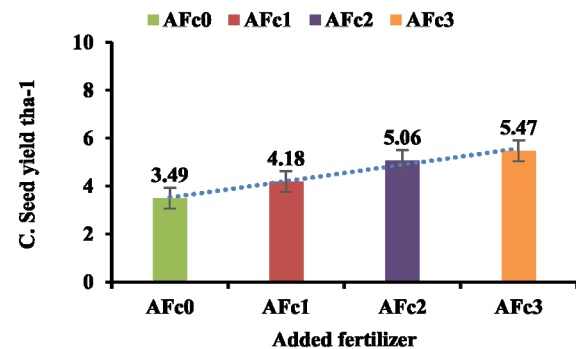
B-2024-25



C-2023-24



C-2024-25



(A)100-seed weight, (B)seed yield per plant , (C)seed yield

Figure 4 Effect of the added fertilizer combination on yield characteristics

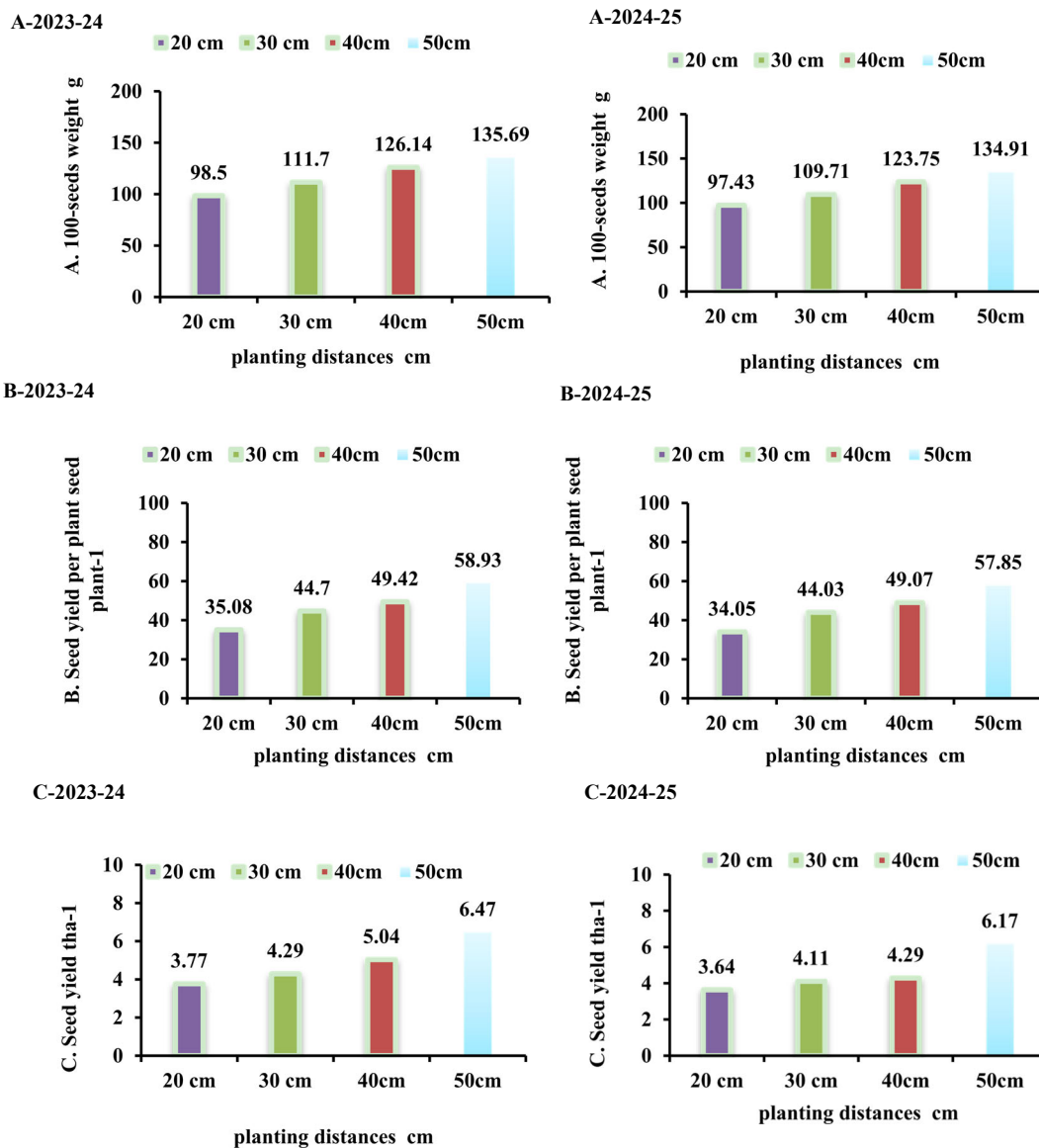
The statistical analysis revealed significant effects ($p < 0.05$) of PD and AFc on yield parameters that there are significant differences between all treatments. It is noted from Figure 4A, factor was a highly significant effect for AFc3 on the 100SW, the best results of 138.91 and 140.78 g, surpassing AFc2 of 130.70 and 131.49 g, and AFc1 of 116.67

and 118.59 g respectively. The control treatment AFc0 yielded undesirable results for this study of 79.71 and 80.72 g respectively, for two seasons. An increase in the flowers number occurs when appropriate fertilizers proportions are added according to the needs of the soil and the plant, fertilizer plays a vital and effective role in increasing

the carbonation efficiency, which positively impacts flowering, thus reducing flower drop and improving crop quality (Kumar et al., 2020).

The results shown of the statistical analysis for the Figure 4B. factor was a highly significant effect for AFc on the seed yield per plant, the best results of 57.86 and 67.71 seed plant⁻¹, 53.62 and 54.06 seed plant⁻¹, 40.23 and 41.07 seed plant⁻¹, for AFc3, AFc2 and AFc1 respectively. The control treatment AFc0 yielded undesirable results for this study of 24.47 and 25.28 seed plant⁻¹, for two seasons. While the statistical analysis revealed significant effects ($p < 0.05$) from Figure 4C. For AFc factor was a highly

significant effect on seed yield, the AFc3 registered the highest average 5.47 and 5.66 tha⁻¹, surpassing AFc2 of 5.06 and 5.48 tha⁻¹, AFc1 of 4.18 and 4.77 tha⁻¹, while the treatment AFc0 gave the lowest average of 3.49 and 3.66 tha⁻¹, respectively for two seasons. Fertilizers work to create a hormonal nutritional balance that positively affects the flower buds development. This makes the plant more tolerant for growing conditions (Ali et al., 2019), this is what Alaamer et al. (2026) confirmed that adding mineral fertilizers in proportions according to the soil's needs improves the plant's vegetative condition and increases the final yield.



(A)100-seed weight, (B)seed yield per plant , (C)seed yield

Figure 5 Effect of the planting distances on yield characteristics

The statistical analysis revealed significant effects ($p < 0.05$) of PD and AFc on yield parameters that

there are significant differences between all treatments. It is noted from Figure 5A, factor was a

highly significant effect for PD of 50 cm on the 100SW, the best results of 134.91 and 135.69 g, surpassing PD of 40 cm; 123.75 and 126.14 g, and PD of 30 cm; 109.71 and 111.70 g. While a PD of 20 cm gave the fewest results of 97.43 and 98.50 g. From Figure 5B. factor was a highly significant effect for PD on the seed yield per plant, the best results of 57.85 and 58.93 seed plant⁻¹, 49.07 and 49.42 seed plant⁻¹, 44.03 and 44.70 seed plant⁻¹, for 50, 40 and 30 cm, respectively. The control treatment PD of 20cm yielded undesirable results for this study of 34.05 and 35.08 seed plant⁻¹, for two seasons 2023-24 and 2024-25. While the statistical analysis revealed significant

effects ($p < 0.05$) from Figure 5C. For PD factor was a highly significant effect on seed yield, the PD of 50 cm registered the highest average 6.17 and 6.47 tha⁻¹, surpassing PD of 40cm; 4.29 and 5.045 tha⁻¹, PD of 30cm; 4.11 and 4.29 tha⁻¹, while the treatment PD of 20 cm gave the lowest average of 3.64 and 3.77 tha⁻¹, respectively for two seasons. Choosing the optimal spacing when planting plants using precision farming methods improves growth characteristics associated with reduced competition between plants for nutrient absorption (Shtewy et al., 2020; Alaamer et al., 2026). They confirmed that increasing the distance between planted plants improves the final product quality.

Table 4 Effects of PD and AFc on carbohydrate and protein ratios

2023-2024				2024-2025			
PD	AF Kg ha ⁻¹			PD	AF Kg ha ⁻¹		
		PR	CHR			PR	CHR
20	AFc0	20.11	55.94	20	AFc0	20.86	56.19
	AFc1	21.13	57.22		AFc1	21.73	57.67
	AFc2	23.09	61.05		AFc2	23.31	61.56
	AFc3	24.55	62.25		AFc3	24.85	62.92
30	AFc0	20.60	56.64	30	AFc0	20.29	56.93
	AFc1	22.59	60.45		AFc1	22.85	61.04
	AFc2	23.73	62.43		AFc2	24.07	62.95
	AFc3	24.61	63.05		AFc3	24.96	63.92
40	AFc0	21.06	57.06	40	AFc0	21.84	57.28
	AFc1	23.51	61.85		AFc1	23.92	62.21
	AFc2	24.59	63.02		AFc2	24.95	63.89
	AFc3	25.14	64.42		AFc3	25.39	64.90
50	AFc0	21.54	58.11	50	AFc0	22.05	58.89
	AFc1	24.57	62.48		AFc1	25.07	63.10
	AFc2	25.36	63.63		AFc2	26.15	64.52
	AFc3	26.11	65.03		AFc3	26.90	65.94
Means PD				Means PD			
	20	22.23	59.11		20	22.69	59.58
	30	22.88	60.64		30	23.20	61.21
	40	23.57	61.58		40	24.02	62.07
	50	24.40	62.31		50	25.04	63.11
Means AFc				Means AFc			
	AFc0	20.83	56.94		AFc0	21.41	57.32
	AFc1	22.95	60.50		AFc1	23.39	61.01
	AFc2	24.20	62.53		AFc2	24.62	63.23
	AFc3	25.10	63.69		AFc3	25.52	64.42
L.S.D=0.05				L.S.D=0.05			
	PD	0.189	0.169		PD	0.090	0.013
	AFc	0.100	0.112		AFc	0.056	0.027
	PD* AFc	0.237	0.241		PD* AFc	0.124	0.049

Note: Protein ratio ; PR, Carbohydrate ratio; CHR

3.3 Carbohydrate and protein ratios

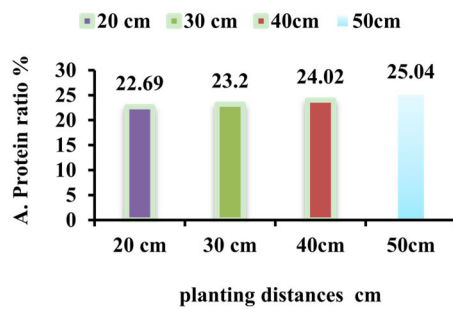
There was a highly significant effect due to the interaction between the PD and the AFc on the carbohydrate and protein ratios. Table.4 The AFc3 was significantly superior to the other levels of AFc1,

AFc2 and AFc0. While the PD of 50 cm was significantly superior to the other distances 20, 30 and 40 cm in all studied parameters. All the interactions were significantly different, and the best results were 26.11% and 26.90%, 65.03% and 65.94%

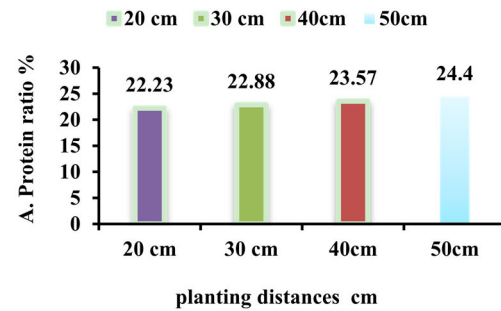
respectively, for protein and carbohydrate, have come from the overlap between PD of 50 cm and AFc3, for the study seasons 2023-24 and 2024-25.

As shown in Figures 6A and 6B, PD and AFc had significant effects ($p < 0.05$) on carbohydrate and protein ratios. The 50 cm distance produced superior ratio metrics were 24.40% and 25.04%, 62.31% and 63.11%, for protein ratios and carbohydrate, as

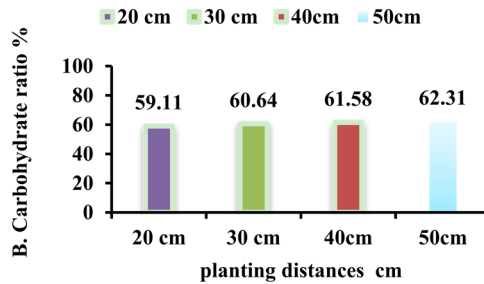
A-2023-24



A-2024-25



B-2023-24



B-2024-25

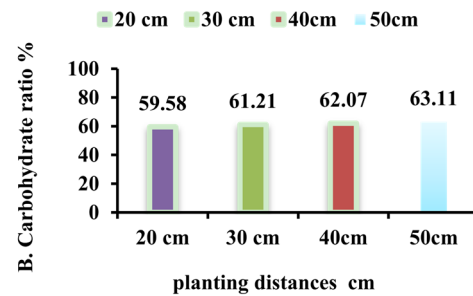
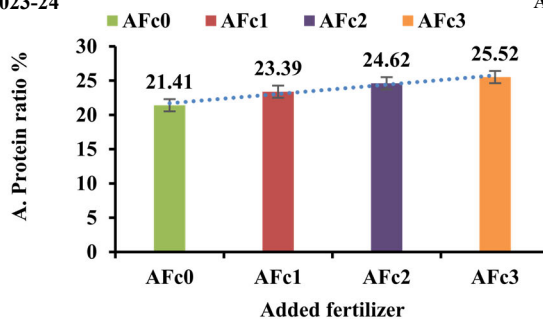
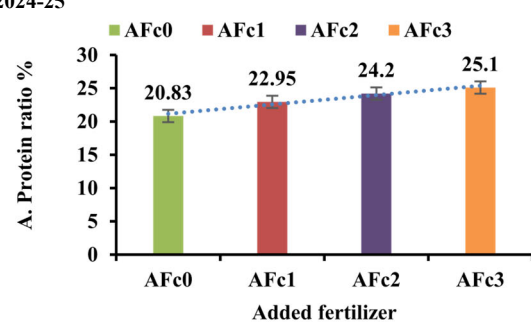


Figure 6 Effect of the planting distances on protein ratio (A), and carbohydrate ratio (B)

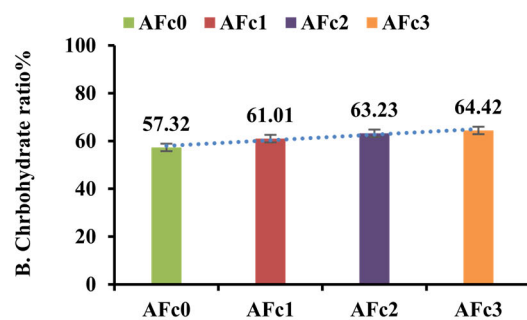
A-2023-24



A-2024-25



B-2023-24



B-2024-25

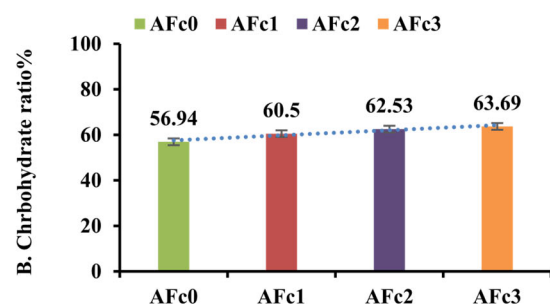


Figure 7 Effect of the added fertilizer combination on protein ratio (A), and carbohydrate ratio (B)

The statistical analysis revealed significant effects ($p < 0.05$) from Figure 7A. For AFc factor was a highly significant effect on protein ratio, the AFc3 registered the highest average 25.10% and 25.52%, surpassing AFc2 of 24.20% and 24.62%, AFc1 of 22.95% and 23.39%, for AFc3, AFc2 and AFc1 respectively, while the treatment AFc0 gave the lowest average of 20.83% and 21.41%, respectively for the two seasons. As shown in Figure 7B, AFc had a highly significant effect on carbohydrate ratio ($p < 0.05$). AFc3 recorded the highest average value of 63.69% and 64.42%, followed by AFc2 with 62.53% and 63.23%, and AFc1 of 60.50% and 61.01%, while the treatment AFc0 gave the lowest average value of 56.94% and 57.32%, respectively for two seasons (Lombardo et al., 2016; Robinson et al., 2019).

4 Conclusion

The PD of 50 cm was significantly better than other 20, 30, and 40 cm in all studied conditions. The N-K of AF3 (110 + 95), was significantly superior to the other two AFc1 (70+55) and AFc2 (90+75) The results showed better conditions for the overlap between the AFc3 and PD of 50 cm in all study conditions.

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