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Sustainable Wheat Production in Arid Sandy Soils: Influence of Organic Fertilizers and Cultivation Timing on Growth and Yield

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Abstract

Wheat cultivation in arid desert soils, such as the nutrient-poor Arenosols of southern Libya, faces major constraints due to low fertility, limited organic matter, and extreme climatic conditions. This study evaluated the effects of fertilizer type and timing on the growth and yield of two durum wheat cultivars, *Karim* and *Dhahbi*, grown in virgin sandy soil filled in pots. The experimental design included three factors: (1) fertilizer type (raw and anaerobically digested manure from poultry and sheep, NPK fertilizer, and an unfertilized control), (2) sowing date (2, 10, 20 or 30 days after fertilization) and (3) cultivar (*Karim* and *Dhahbi*). All fertilizers were applied at a rate equivalent to 300 kg N ha^{-1}. The study aimed to assess how these factors and their interactions affected wheat growth and yield. Measured parameters included germination traits (germination speed, germination percentage, and time to final germination), growth characteristics (leaf area, plant height and number of tillers), and yield components (number of spikes, grains per spike, grain weight and biomass yield). Organic fertilization, especially with raw manure, delayed germination when sowing occurred immediately after application. However, sowing 20–30 days post-application reduced phytotoxic effects and improved germination. Sowing 2 or 10 days after fertilization, particularly with raw poultry manure or NPK, significantly enhanced plant height, tillering, biomass accumulation and grain weight, especially in *Karim*. Raw poultry manure consistently outperformed other manure treatments, achieving higher grain yields (12.4 g pot^{-1}). In contrast, sowing 20 or 30 days after fertilization significantly ($P < 0.05$) reduced the number of spikes, grains per spike, and grain weight. Overall, *Karim* demonstrated better adaptability under fertilized conditions, particularly when sowing 2 or 20 days after fertilization. These findings highlight the importance of optimizing fertilization timing and cultivar choice to enhance wheat productivity in arid, sandy environments. Sowing 2 or 20 days after fertilization with raw poultry manure appears to be a promising strategy for sustainable wheat production in desert farming systems.

Keywords: Cultivation date; Digested manure; Raw manure; Sandy soil; Wheat

Introduction

Southern Libya lies within the hyper-arid zone of the Sahara Desert, where annual rainfall typically measures less than 50 mm (FAO 2012; Zurqani *et al.* 2019). The region is characterized by sandy soil, particularly Arenosols, which have low fertility, poor water-holding capacity and limited organic matter (FAO 2001; Elaalem *et al.* 2021). These factors pose major challenges for agriculture, particularly for wheat (*Triticum aestivum* L.), which thrives in nutrient-rich soils. In addition, extreme temperatures and high evapotranspiration rates accelerate soil degradation and nutrient depletion, further reducing the productivity of these fragile ecosystems (Reynolds *et al.* 2007; Saad *et al.* 2011). The condition of this soil significantly affects agricultural practices and land use, posing considerable challenges for agriculture due to their limited capacity to support plant growth (Abagandura and Park 2016). This vast dry land area highlights the need for sustainable agricultural methods and a strong understanding of environmental factors that affect soil productivity. Despite the challenges associated with cultivating such land, including water scarcity and the

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high costs of land reclamation (Abagandura and Park 2016), efforts are being made to revitalize these areas for the cultivation of various crops, including forage and grain crops.

Wheat is a major cereal crop in Libya, cultivated on over 165,000 ha, with an annual production of around 200,000 tons (FAO 2021). However, yields remain far below potential due to poor soil fertility, which limits the availability of essential nutrients for optimal growth (Abubaker *et al.* 2020). To address this, farmers commonly apply chemical fertilizers, despite their high cost and limited contribution to improving long-term soil health. Moreover, excessive reliance on these inputs raises sustainability concerns such as soil acidification and water pollution (Savci 2012), highlighting the need for more sustainable fertilization practices.

Therefore, replacing chemical fertilizers with organic fertilizers is increasingly considered essential for enhancing soil properties, especially in arid and semiarid regions where the soil properties are poor (Abubaker *et al.* 2012; Liu *et al.* 2024). It has been reported in several studies that organic fertilizers can improve soil properties more effectively than chemical fertilizers (Herencia and Maqueda 2016; Luo *et al.* 2024; Xing *et al.* 2024). Organic fertilizers are recognized as an effective source of plant nutrients and can enhance soil structure, stimulate microbial activity, improve water retention, regulate pH, and increase crop yield (Gu *et al.* 2022; Zhou *et al.* 2022; Freitas *et al.* 2024). To effectively enhance soil productivity with organic fertilizers, several key factors must be considered, including the rate and timing of application (Delin and Engström 2010; Xing *et al.* 2024). The timing of application is closely linked to soil microbial activity, which plays a crucial role in the effectiveness of organic fertilizers in supporting plant growth. This is because microbial activity decomposes organic fertilizers, gradually releasing nutrients into the soil (Abdou *et al.* 2016; Zeiner *et al.* 2024). However, it should also be taken into consideration that the the soils in dry regions, which are poor in organic matter content, have weak biological activity. This may make the process of decomposition and nutrients release insufficient to support plant growth and yield (Thongjoo *et al.* 2005; Schimel 2018; Fujii *et al.* 2024). Therefore, organic fertilizers should be carefully applied to such soils to allow sufficient time for soil microorganisms to decompose the organic components and mineralize the nutrients before they become accessible to the crop.

Considering the unique challenges of arid environments and the nutrient release dynamics of organic fertilizers, it is critical to identify the optimal timing of crop cultivation following fertilizer application. Therefore, the objective of this study was to evaluate the growth and yield of two wheat cultivars when grown at different intervals after applying both raw and digested poultry and sheep manure to virgin sandy soil. We hypothesized that cultivation at specific intervals following manure application would enhance nutrient availability, leading to improved growth and yield, with the response varying depending on manure type and wheat cultivar.

Materials and Methods

Soil collection and characteristics

The soil used in this study was sandy soil collected from an arid area approximately 10 km west of Sebha City (located between latitudes 22°30′N and 30°00′N and longitudes 10°E and 18°E). The collection site had no prior history of cultivation or fertilization, ensuring minimal anthropogenic influence. Approximately 2 tons of soil were transported to the laboratory, air-dried, sieved through a 4-mm mesh, and stored at room temperature for further analysis. The physical and chemical properties of the soil are presented in Table 1, including soil texture (sand, silt and clay content), water-holding capacity, pH, organic matter (OM), total nitrogen (Tot N), total carbon (Tot C), total phosphorus (Tot P), total potassium (Tot K), sodium (Na), and calcium (Ca). The methods used in analysing soil properties are described in El-Zeadani *et al*. (2018).

Fertilizers

Two types of fertilizers were used in this study: organic and chemical fertilizers. The organic fertilizers were applied as separate treatments and consisted of raw poultry manure, anaerobically digested poultry manure, raw sheep manure, and anaerobically digested sheep manure, while the chemical fertilizer was applied separately as commercial NPK containing 12% nitrogen (N), 24% phosphorus (P_2O_5) and 12% potassium (K_2O). Approximately 50 kg of raw poultry and sheep manure were collected from local farms in Sebha City, manually cleaned to remove debris, and subdivided into small burlap sacks. The manure was then stored at room temperature under dry conditions until used. Digested manure was produced by anaerobic digestion of the collected raw poultry and sheep manure in a 30-liter airtight plastic container. The anaerobic digestion procedure followed the method described by Abubaker *et al*. (2017). The physical and chemical properties of both raw and digested manure, including dry matter (DM), pH, total nitrogen (Tot N), total carbon (Tot C), C : N ratio, total phosphorus (Tot P), and total potassium (Tot K) are presented in Table 2. Analytical methods used to determine these properties were based on the protocols outlined by El-Zeadani *et al*. (2018).

Experiment setup

The pot experiment was conducted outdoors under open-field conditions at the Scientific Research and Consultation Center of Sebha University, Libya. Treatments included four organic manure treatments (raw and digested poultry and sheep manure), two wheat cultivars (*Karim* and *Dhahbi*) and four sowing dates (2, 10, 20 and 30 days after fertilization). The experiment was laid out using completely randomized design in a factorial arrangement, with each

Table 1: Physical and chemical properties of the soil used in the experiment

Parameters	Values
Physical properties	
Sand (%)	69
Silt (%)	22
Clay (%)	9
Water-holding capacity (%)	21.7
Chemical properties	
pH	8.2
OM (%)	.001
Total N (%)	0.08
Total C (%)	0.9
Tot P (g kg^{-1} dw)	0.2
Tot K (g kg^{-1} dw)	0.06
Na (g kg^{-1} dw)	0.3
Ca (g kg^{-1} dw)	0.7

Table 2: Physical and chemical characteristics of raw and digested manures (poultry and sheep manure). Reported values are the average ± standard deviation (n = 3)

Parameters	Poultry manure	Digested poultry manure	Sheep manure	Digested sheep manure
DM (%)	91.2 ± 0.1	19.2 ± 0.9	91.7 ± 0.1	19.0 ± 0.2
pH	7.9 ± 0.2	7.8 ± 0.5	8.3 ± 0.4	7.4 ± 0.7
Tot N (g kg^{-1} dw)	36.1 ± 2	32.4 ± 1.5	16.2 ± 0.6	11.3 ± 0.4
Tot C (g kg^{-1} dw)	364 ± 13	340 ± 1	355 ± 6	378 ± 1
C/N	10	11	22	34
Tot P (g kg^{-1} dw)	15.8 ± 0.1	21.4 ± 0. 2	2.12 ± 0.02	2.59 ± 0.2
Tot K (g kg^{-1} dw)	18.8 ± 0.1	17.6 ± 0.4	13 ± 0.06	9.8 ± 0.8

treatment replicated four times. In addition, a control group of eight pots (four for *Karim* and four for *Dhahbi*) and an NPK treatment of eight pots (four for *Karim* and four for *Dhahbi*) were included, both applied only at the first sowing date. As outlined in Table 3, this setup resulted in a total of 12 treatment combinations, giving 144 pots overall.

Each treatment was conducted in cylindrical plastic pots with a diameter of 30 cm and a height of 50 cm. Initially, approximately 10 kg of sandy soil was filled into each pot. An additional 8 kg of soil, pre-mixed with the targeted fertilizers which are in Table 4, was then added as the top layer. All organic fertilizers were applied once before sowing at the beginning of the experiment as a basal dose.

As NPK fertilizer is a readily available nutrient source and served as the reference treatment in this study, it was applied after the plants had established to enhance nutrient uptake efficiency. To maximize nutrient use efficiency and minimize potential losses through leaching or volatilization, the total NPK dose was split into two equal applications: the first at 25 days after sowing and the second at day 60 after sowing. All fertilizer treatments were standardized to deliver the equivalent of 300 kg of total nitrogen per ha.

Soil moisture was maintained at approximately 70% of the water-holding capacity throughout the growing period. Moisture levels were monitored using the SQM-256 3-Way Soil Tester Kit, which also measures pH and light intensity.

Sowing and harvesting

Cultivation took place between mid-October and mid-November, with sowing on four dates: October 18, October 25, November 4, and November 14, which corresponded to 2, 10, 20 and 30 days after fertilization, respectively. The first set was sown 2 days after soil fertilization, the second after 10 days, the third after 20 days, and the fourth after 30 days.

Each pot was sown with 30 healthy, undamaged seeds at a depth of 0.5 cm. Twenty days after sowing; seedlings were thinned to 20 plants per pot to achieve a plant density equivalent to a seeding rate of 90 kg ha^{-1}, in line with standard field practices (Khan *et al.* 2002).

Prior to sowing, seed viability for the two durum wheat cultivars, *Karim* and *Dhahbi*, was assessed using the method described by Ellis *et al*. (1985). The germination rates were 89 ± 6% for *Karim* and 95 ± 3% for *Dhahbi*. Throughout the experiment, pots were maintained under open field conditions with natural daylight (11–13 hours), temperatures ranging from 10 to 31°C and relative humidity between 26% and 34%. The average growth duration across all cultivation dates was 115 ± 10 days, after which all plants were harvested.

Growth and yield characteristics

After sowing, the pots were monitored daily for 20 days to record seed germination. Based on the germination counts, several parameters were calculated: germination speed (GS), defined as the number of days required for seeds to germinate; final germination percentage (FGP); and time to final germination (TFG). The FGP and TFG were calculated following the methods described by Dastanpoor *et al*. (2013).

Plant height was measured using a ruler 90 days after sowing. The height of all plants in each pot was recorded, and the mean value was calculated. Before harvest, the number of tillers per treatment was recorded. Leaf area was determined using the procedures outlined by Chanda and Singh (2002) and Rehman *et al*. (2010). Ten leaves were randomly selected from each pot. Their length and width were measured with a ruler, and leaf area was estimated as length × width × 0.75.

At harvest, total biomass was separated into its components root, straw, and spikes. Each component was then weighed after oven-drying at 70°C for 48 h. Prior to drying, spike traits such as number and total spike biomass per pot, were measured. The spikes were dried at 60°C for 48 h, after which the grains per spike were counted and averaged per pot. Based on these measurements, the mean grain number per spike, total grain number per pot, and grain weight per pot were determined.

Statistical analyses

Data were analysed using the General Linear Model (GLM)

Table 3: Overview of the experimental treatments showing the combination of fertilizer type (raw and digested poultry and sheep manure, NPK fertilizer and unfertilized control), wheat cultivar (*Karim* and *Dhahbi*) and sowing date (2, 10, 20 and 30 days after fertilization). Each manure treatment was tested with both cultivars across four sowing dates, with four replications per date (4 treatments × 2 cultivars × 4 dates × 4 reps = 128 pots). In addition, unfertilized control and NPK treatments were included only at the first sowing date (2 cultivars × 4 reps × 2 treatments = 16 pots). This gave a grand total of 144 pots

No.	Variety	Fertilizer treatment	Abbreviations	Sowing date
1.	Karim	Control (no fertilization)	C_K	Only one sowing
2.		NPK	NPK_K	Only one sowing
3.		Raw poultry manure	PM_K	2, 10, 20 and 30 DAF
4.		Digested poultry manure	DPM_K	2, 10, 20 and 30 DAF
5.		Raw sheep manure	SM_K	2, 10, 20 and 30 DAF
6.		Digested Sheep manure	DSM_K	2, 10, 20 and 30 DAF
	Dhahbi	Control (no fertilization)	C_D	Only one sowing
		NPK	NPK_D	Only one sowing
7.		Raw poultry manure	PM_D	2, 10, 20 and 30 DAF
8.		Digested poultry manure	DPM_D	2, 10, 20 and 30 DAF
9.		Raw sheep manure	SM_D	2, 10, 20 and 30 DAF
10.		Digested Sheep manure	DSM_D	2, 10, 20 and 30 DAF

DAF = Days after fertilization

Table 4: Amounts of raw and digested poultry and sheep manures and NPK fertilizer required to supply 300 kg N ha^{-1}, along with their corresponding Tot N, Tot C, Tot P, Tot K and C/N ratio on a dry weight per pot basis

Fertilizer type	Amount of fertilizer (kg ha^{-1})	Amount of fertilizer (g pot^{-1})	Tot N added (kg pot^{-1})	Tot C added (kg pot^{-1})	Tot P added (kg pot^{-1})	Tot K added (kg pot^{-1})	C/N
Raw poultry manure	8321	59	2.1	21.5	0.9	1.1	10
Dig. poultry manure	9266	65	2.1	22.1	1.4	1.1	10
Raw sheep manure	18510	131	2.1	46.5	0.3	1.7	22
Dig. sheep manure	26491	187	2.1	70.7	0.5	1.8	33
NPK	2500	18	2.2	0	4.3	2.2	0

procedure in SPSS (Windows version 17), applying a three-way ANOVA followed by Tukey's Honestly Significant Difference (HSD) test for post-hoc comparisons. This approach was used to assess differences between treatments for various parameters, including germination speed (GS), final germination percentage (FGP), time to final germination (TFG), plant height, number of tillers, root biomass, straw biomass, spike biomass, total biomass, number of spikes, spike biomass, number of grains per spike, total grain number and grain weight per pot (grain yield). The main factors considered were cultivation date, fertilizer type, wheat variety, and their interactions, all as independent fixed factors. Statistical significance was determined at $P < 0.05$, unless otherwise specified. Results are presented as means (n = 4), with means followed by different letters in tables or figures indicating statistically significant differences.

Results

Fertilizer application and nutrient dynamics

Table 4 presents the quantities of raw and digested poultry and sheep manures, along with NPK fertilizer, required to supply 300 kg Tot N ha^{-1}. The application rates varied considerably: raw poultry manure required 8321 kg ha^{-1} (59 g pot^{-1}), digested poultry manure 9266 kg ha^{-1} (65 g pot^{-1}), raw sheep manure 18510 kg ha^{-1} (131 g pot^{-1}) and digested sheep manure 26491 kg ha^{-1} (187 g pot^{-1}). In contrast, NPK fertilizer supplied the nitrogen requirement at a much lower rate (2500 kg ha^{-1}, 18 g pot^{-1}). The total nitrogen supplied per pot was consistent across all treatments (2.1-2.2 kg pot^{-1}). However, other nutrient contributions varied: digested sheep manure delivered the highest total carbon (70.7 kg pot^{-1}), whereas NPK fertilizer provided the most phosphorus (4.3 kg pot^{-1}) and potassium (2.2 kg pot^{-1}). Manure treatments supplied lower amounts of phosphorus (0.3–1.4 kg pot^{-1}) and potassium (1.1–1.8 kg pot^{-1}). C/N ratios were highest in manure treatments, reflecting their high organic matter content, with raw and digested poultry manures having ratios of 10, raw sheep manure 22 and digested sheep manure 33. NPK fertilizer had a C/N ratio of 0.

Germination attributes

Table 5 shows germination speed (GS), final germination percentage (FGP) and time to final germination (TFG). The three-way interaction among cultivation date, fertilizer type, and cultivar was not significant. Significant two-way interactions ($P < 0.05$) were observed for cultivation date × cultivar and cultivation date × fertilizer type, both of which affected GS. For the main effects, cultivation date had a significant influence on all three parameters, whereas fertilizer type affected only GS. Neither fertilizer type nor cultivar significantly influenced FGP or TFG.

In the first sowing (2 days post-fertilization), both raw and digested manures significantly ($P < 0.05$) reduced GS compared with the control. Seeds in the manure treatments

Table 5: Germination speed (GS), final germination percentage (FGP) and the time to final germination (TFG) of two wheat varieties cultivated in sandy soil at different dates from soil fertilization

Time of sowing	Treatments	GS (days)	FGP (%)	TFG (days)
Control	C_K	5.6^{a}	99^{b}	12.3^{a}
	C_D	5.6^{a}	94^{b}	12.0^{a}
	NPK_K	5.7^{a}	97^{b}	12^{a}
	NPK_D	6.2^{a}	95^{b}	12.3^{a}
First cultivation date	PM_K	7.3^{b}	69^{m}	13.7^{a}
	DPM_K	7.3^{b}	93^{b}	12.7^{a}
	SM_K	8.0^{b}	64^{e}	13.3^{a}
	DSM_K	7.7^{b}	89^{b}	13.3^{a}
	PM_D	**7.7**^{b}	**87**^{b}	**13.7**^{a}
	DPM_D	8.3^{b}	79^{b}	**13.7**^{a}
	SM_D	8.0^{b}	76^{b}	14.0^{a}
	DSM_D	8.7^{b}	72^{y}	13.7^{a}
Second cultivation date	PM_K	7.3^{b}	98^{b}	12.0^{a}
	DPM_K	7.0^{c}	99^{b}	13.7^{a}
	SM_K	7.0^{c}	100^{b}	12.3^{a}
	DSM_K	7.0^{c}	98^{b}	11.0^{a}
	PM_D	7.0^{c}	94^{b}	12.7^{a}
	DPM_D	7.0^{c}	90^{b}	12.3^{a}
	SM_D	7.0^{c}	97^{b}	13.3^{a}
	DSM_D	7.0^{c}	98^{b}	10.7^{a}
Third cultivation date	PM_K	6.0^{a}	98^{b}	12.0^{a}
	DPM_K	5.7^{a}	94^{b}	11.3^{a}
	SM_K	6.3^{d}	97^{b}	11.3^{a}
	DSM_K	6.0^{a}	98^{b}	12.3^{a}
	PM_D	5.7^{a}	93^{b}	14.0^{a}
	DPM_D	6.0^{a}	92^{b}	12.0^{a}
	SM_D	6.0^{a}	93^{b}	13.3^{a}
	DSM_D	6.0^{a}	96^{b}	11.3^{a}
Fourth cultivation date	PM_K	6.3^{d}	93^{b}	9.7^{a}
	DPM_K	6.7^{e}	100^{b}	12.7^{a}
	SM_K	6.3^{d}	98^{b}	10.7^{a}
	DSM_K	6.3^{d}	92^{b}	12.3^{a}
	PM_D	6.0^{a}	94^{b}	11.3^{a}
	DPM_D	6.0^{a}	91^{b}	12.0^{a}
	SM_D	6.0^{a}	94^{b}	11.7^{a}
	DSM_D	6.0^{a}	96^{b}	11.7^{a}

Values represent the average ± standard deviation (n = 4). The same letters within the same column indicate no significant difference (Tukey *P = 0.05*)

Table 6: Leaf area, number of tillers, plant height and number of spikes of two wheat cultivars grown in sandy soil at different intervals following soil fertilization

Time of sowing	Treatments	Leaf area (cm^2)	Number of tillers	Plant height (cm)	Number of spikes (pot^{-1})
Control	C_K	4.9^{a}	15^{a}	36^{a}	5^{a}
	C_D	4.6^{b}	13^{b}	22^{b}	4^{b}
	NPK_K	24.5^{c}	20^{c}	59^{c}	19^{c}
	NPK_D	19.2^{d}	16^{a}	55^{d}	17^{d}
First cultivation date	PM_K	16.5^{e}	21^{c}	67^{e}	15^{d}
	DPM_K	16.7^{e}	21^{c}	68^{e}	16^{c}
	SM_K	17.8^{e}	10^{d}	50^{q}	14^{d}
	DSM_K	16.5^{e}	19^{c}	74^{e}	15^{d}
	PM_D	19.3^{d}	17^{e}	61^{c}	15^{d}
	DPM_D	18.7^{d}	18^{c}	55^{d}	15^{d}
	SM_D	24.0^{c}	16^{a}	56^{d}	11^{e}
	DSM_D	15.2^{f}	17^{e}	57^{d}	15^{d}
Second cultivation date	PM_K	15.4^{f}	28^{f}	69^{e}	22^{c}
	DPM_K	13.1^{g}	17^{e}	70^{e}	15^{d}
	SM_K	22.1^{h}	24^{f}	75^{e}	22^{c}
	DSM_K	10.6^{i}	15^{a}	68^{e}	15^{d}
	PM_D	26.9^{c}	25^{f}	66^{e}	16^{d}
	DPM_D	19.0^{d}	16^{a}	56^{d}	15^{d}
	SM_D	26.4^{c}	19^{c}	62^{c}	14^{d}
	DSM_D	16.4^{e}	16^{a}	56^{d}	15^{d}
Third cultivation date	PM_K	24.2^{c}	17^{e}	62^{c}	16^{d}
	DPM_K	13.2^{g}	15^{a}	65^{c}	15^{d}
	SM_K	19.9^{d}	15^{a}	62^{c}	12^{d}
	DSM_K	10.5^{i}	15^{a}	65^{c}	15^{d}
	PM_D	32.3^{c}	16^{a}	55^{d}	11^{d}
	DPM_D	17.8^{e}	16^{a}	56^{d}	13^{d}
	SM_D	30.1^{c}	15^{a}	59^{c}	7^{f}
	DSM_D	16.3^{e}	15^{a}	55^{d}	15^{d}
Fourth cultivation date	PM_K	22.7^{h}	15^{a}	66^{c}	13^{d}
	DPM_K	14.3^{f}	16^{a}	66^{c}	15^{d}
	SM_K	26.9^{c}	12^{b}	61^{c}	12^{d}
	DSM_K	14.9^{f}	16^{a}	63^{c}	16^{d}
	PM_D	22.7^{h}	18^{c}	55^{d}	6^{g}
	DPM_D	20.2^{d}	15^{a}	48^{k}	9^{h}
	SM_D	30.4^{c}	16^{a}	55^{d}	9^{h}
	DSM_D	22.8^{h}	15^{a}	52^{d}	10^{e}

Data are presented as mean ± standard deviation (n = 4). Values sharing the same letter within a column are not significantly different according to Tukey's test (*P = 0.05*)

took 7.3–8.7 days to germinate, whereas seeds in the control treatment germinated faster, with a mean germination time of 5.6 days, indicating that manure application delayed germination. In the second sowing, GS improved to approximately 7 days but remained slower than the control. By the third and fourth sowings, GS did not differ significantly from the control. Notably, GS in NPK-treated pots was similar to the control, likely because NPK was applied 25 days after sowing.

FGP was also significantly influenced by cultivation date and fertilizer type. High FGP values (94–99%) were observed in the control and NPK treatments. In contrast, raw poultry and sheep manure reduced FGP during the first sowing, particularly for *Karim* (64–69%), whereas *Dhahbi* was less affected. Digested manures resulted in higher FGP (72–93%), although values for *Dhahbi* remained low under digested sheep manure. From the second sowing onward, FGP exceeded 90 % across all treatments.

TFG showed minimal variation and no significant differences. Both cultivars reached final germination in approximately 12 days under control and NPK treatments. Organic fertilization slightly prolonged TFG (up to 14 days) in the first sowing, practically with SM. In later sowings, TFG declined, reaching 9.7 days under PM for *Karim*.

Growth characteristics

Table 6 shows the measured parameters. The three-way interaction among cultivation date, wheat variety, and fertilizer type was not significant. Significant two-way interactions (*P < 0.05*) indicated that these factors jointly influenced plant height, leaf area, and number of tillers. However, the number of tillers was not affected by the date × cultivar or cultivar × fertilizer interactions. For the main effects, plant height was unaffected by the date × cultivar interaction.

Plant height progressively increased in all fertilized treatments compared with the control. The tallest plants were observed in the NPK, PM, and DPM treatments, particularly in the *Karim* cultivar, whereas the control and SM treatments produced the shortest plants. Sowing 2 or 10 days after fertilization significantly ($P < 0.05$) increased plant height compared with sowing 20 or 30 days after fertilization. Poultry manure treatments generally produced taller plants than NPK, especially in *Karim*. Overall, *Karim* consistently exhibited greater plant height than *Dhahbi*.

Leaf area varied significantly according to fertilizer type, wheat variety, and sowing date. NPK produced the highest values, particularly in *Karim* (24.5 cm²), whereas control treatments had the lowest (4.6–4.9 cm²). At the first sowing date, SM increased leaf area in *Dhahbi* (24.0 cm²), while other treatments ranged from 15.2–19.3 cm². At the second sowing date, SM again resulted in high leaf area values (up to 26.9 cm²), whereas DSM reduced leaf area in *Karim*. During the third and fourth sowings, raw manure treatments produced greater leaf area than digested manure treatments, particularly in *Dhahbi*.

The number of tillers was significantly ($P < 0.05$) influenced by all three factors and their interactions (cultivation date, wheat variety and fertilizer type). NPK increased tillering compared with the control, with *Karim* producing more tillers (15–20 per pot) than *Dhahbi* (13–16 per pot). At the first sowing date, *Karim* showed the highest response under PM with 21 tillers, whereas SM resulted in the lowest count (10 tillers). *Dhahbi* exhibited intermediate tillering across all manure treatments. Maximum tillering was observed at the second sowing date, with *Karim* producing 28 tillers and *Dhahbi* 25. Tillering decreased in treatments sown 30 days after fertilization. Sowing 2 or 10 days after fertilization, particularly with raw manure, improved tillering, with *Karim* consistently outperforming *Dhahbi*.

Spike characteristics

Tables 6 and 7 summarize the spike characteristics of wheat. The three-way interaction among cultivation date, wheat variety, and fertilizer type significantly ($P < 0.05$) affected both the number of spikes and spike biomass. The number of spikes varied among treatments, with NPK producing the highest counts (*Karim*: 19; *Dhahbi*: 17), while the control yielded the lowest (Table 6). At the first sowing date, *Karim* produced 14–16 spikes per pot, whereas *Dhahbi* produced 11–15, with sheep manure reducing the number of spikes in *Dhahbi*. At the second sowing date, *Karim* achieved the highest spike number (22) under raw poultry and sheep manure treatments, while *Dhahbi* produced 14–16 spikes. The number of spikes declined during the third and fourth sowings, particularly in *Dhahbi* (6–11 spikes), whereas *Karim* remained relatively stable. Spike biomass was lowest in the control (< 1 g pot^{-1}) and highest in *Karim* under poultry manure (20.1 g pot^{-1}) and sheep manure (19.2 g pot^{-1}) at the second sowing date (Table 7). *Dhahbi* generally exhibited lower spike biomass, especially in later sowings. Sowing 20 days after fertilization with poultry manure enhanced spike development, particularly in the *Karim* cultivar.

Table 7: Root, straw and spikes biomass (g pot^{-1}) of two wheat cultivars grown in sandy soil at four sowing dates, after fertilization

Time of sowing	Treatments	Root biomass (g pot^{-1})	Straw biomass (g pot^{-1})	Spikes biomass (g pot^{-1})
Control	C_K	18 ^{k}	19.4 ^{e}	0.9 ^{a}
	C_D	16 ^{n}	19.2 ^{e}	0.8 ^{a}
	NPK_K	43 ^{s}	57.0 ^{b}	16 ^{b}
	NPK_D	45 ^{s}	54.0 ^{b}	15 ^{b}
First cultivation date	PM_K	45 ^{s}	60.7 ^{b}	18.2 ^{c}
	DPM_K	47 ^{s}	59.1 ^{b}	16.5 ^{c}
	SM_K	17 ^{j}	38.4 ^{t}	8.2 ^{d}
	DSM_K	24 ^{c}	54.0 ^{b}	14.0 ^{e}
	PM_D	51 ^{s}	68.3 ^{b}	12.5 ^{f}
	DPM_D	53 ^{s}	65.5 ^{b}	15.4 ^{b}
	SM_D	22 ^{c}	57.9 ^{b}	7.0 ^{g}
	DSM_D	28 ^{b}	68.3 ^{b}	10.9 ^{h}
Second cultivation date	PM_K	21 ^{k}	46.2 ^{t}	20.1 ^{c}
	DPM_K	38 ^{i}	42.4 ^{s}	15.9 ^{b}
	SM_K	20 ^{k}	47.0 ^{t}	19.2 ^{c}
	DSM_K	23 ^{c}	38.8 ^{h}	10.4 ^{h}
	PM_D	38 ^{i}	63.2 ^{b}	12.4 ^{f}
	DPM_D	38 ^{i}	47.6 ^{t}	11.5 ^{i}
	SM_D	22 ^{c}	54.6 ^{b}	12.7 ^{f}
	DSM_D	34 ^{x}	48.7 ^{t}	11.2 ^{i}
Third cultivation date	PM_K	27 ^{b}	39.2 ^{t}	8.2 ^{d}
	DPM_K	27 ^{b}	35.3 ^{r}	13.3 ^{f}
	SM_K	19 ^{k}	32.4 ^{r}	8.7 ^{j}
	DSM_K	24 ^{c}	31.1 ^{r}	9.6 ^{k}
	PM_D	20 ^{c}	44.2 ^{s}	7.3 ^{l}
	DPM_D	28 ^{b}	39.2 ^{t}	6.3 ^{m}
	SM_D	22 ^{c}	43.1 ^{s}	9.4 ^{k}
	DSM_D	40 ^{i}	38.4 ^{t}	7.3 ^{l}
Fourth cultivation date	PM_K	20 ^{k}	33.5 ^{r}	6.0 ^{m}
	DPM_K	25 ^{c}	34.0 ^{r}	11.0 ^{i}
	SM_K	17 ^{j}	34.2 ^{r}	9.5 ^{k}
	DSM_K	25 ^{c}	30.7 ^{r}	7.6 ^{l}
	PM_D	27 ^{b}	44.5 ^{s}	2.7 ^{n}
	DPM_D	30 ^{b}	37.0 ^{t}	3.0 ^{o}
	SM_D	21 ^{k}	48.9 ^{b}	4.1 ^{p}
	DSM_D	21 ^{k}	36.9 ^{t}	3.9 ^{p}

Values represent the average ± standard deviation (n = 4). The same letters within the same column indicate no significant difference (Tukey $P = 0.05$)

Biomass yield

The results for root, straw, and total biomass are presented in Table 7 and Fig. 1. All main factors (cultivation date, wheat variety, and fertilizer type) significantly ($P < 0.05$) influenced root, straw, and total biomass. The three-way interaction among cultivation date, wheat variety, and fertilizer type was not significant for straw biomass and total biomass. In contrast, significant two-way interactions ($P < 0.05$) were observed for most factor combinations, except for the date × wheat variety interaction, which did not affect straw biomass. Biomass peaked under NPK treatment and under poultry manures during the first sowing. In the first sowing, *Karim* produced 47 g pot^{-1} of root biomass (DPM_K) and 60.7 g pot^{-1} of straw biomass (PM_K), while *Dhahbi* recorded 53 g pot^{-1} of root biomass and 68.3 g pot^{-1} of straw biomass. *Karim* achieved the highest total biomass with PM (123.4 g pot^{-1}) and DPM (122.9 g pot^{-1}), whereas *Dhahbi* attained the highest total biomass with DPM (133.9 g pot^{-1}). The control consistently produced the lowest values.

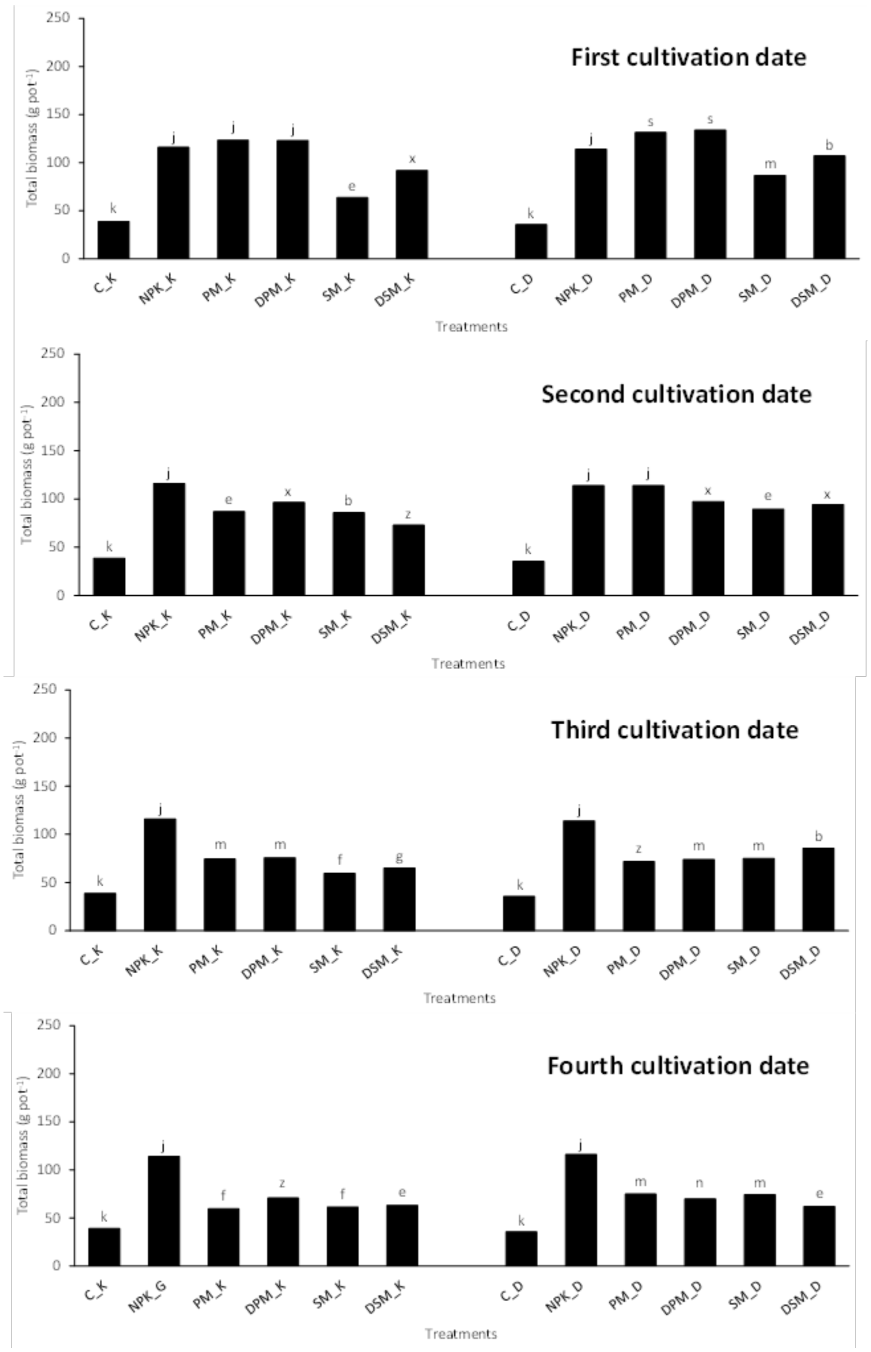

Fig. 1: Total biomass yield (sum of root, straw, and spike biomass) of two wheat cultivars grown at four cultivation dates with different fertilization treatments. Fertilizers comprised raw and digested poultry and sheep manure, and NPK, all applied at a rate equivalent to 300 kg Tot N ha^{-1}. Bars with the same lowercase letter do not differ significantly (Tukey's HSD, $P \leq 0.05$)

In the second sowing, overall biomass declined, although *Dhahbi* maintained a relatively high straw biomass (63.2 g pot^{-1}), while *Karim*'s root biomass decreased to 38.1 g pot^{-1} (DPM). Further decreases were observed in the third sowing. *Karim*'s root biomass dropped to 17.6–27.1 g pot^{-1}, while *Dhahbi* maintained moderate levels with digested manures (~30–40 g pot^{-1}). By the fourth sowing, biomass had reached its lowest levels.

Grain yield components

Grain yield components (number of grains per spike, total grain number and grain weight) are presented in Table 8. The three-way interaction among cultivation date, wheat variety, and fertilizer type significantly ($P < 0.05$) affected the number of grains per spike, total grain number, and grain weight. The results varied significantly ($P < 0.05$)

Table 8: Shown number of grains per spike, total grain number, and grain weight of two wheat cultivars cultivated in sandy soil at different dates from soil fertilization

Time of sowing	Treatments	Average number of grains per spike	Total grain number (pot^{-1})	Grain weight ($g\ pot^{-1}$)
Control	C_K	3^{a}	11^{a}	0.3^{a}
	C_D	2^{b}	6^{a}	0.2^{a}
	NPK_K	20^{c}	380^{b}	12.2^{u}
	NPK_D	19^{c}	323^{c}	11^{c}
First cultivation date	PM_K	22^{c}	350^{d}	12^{u}
	DPM_K	19^{c}	297^{c}	11.5^{c}
	SM_K	14^{d}	213^{e}	6.7^{o}
	DSM_K	19^{c}	292^{c}	9.0^{s}
	PM_D	22^{c}	230^{e}	8.1^{p}
	DPM_D	16^{e}	245^{c}	10.7^{c}
	SM_D	10^{f}	123^{f}	2.9^{d}
	DSM_D	11^{h}	166^{g}	6.0^{n}
Second cultivation date	PM_K	19^{c}	450^{h}	12.4^{u}
	DPM_K	21^{c}	314^{c}	11.4^{c}
	SM_K	23^{c}	479^{h}	11.7^{c}
	DSM_K	15^{e}	222^{e}	6.5^{n}
	PM_D	12^{g}	205^{e}	6.1^{n}
	DPM_D	11^{h}	161^{g}	7.2^{o}
	SM_D	12^{g}	189^{i}	6.3^{n}
	DSM_D	11^{h}	150^{g}	6.3^{n}
Third cultivation date	PM_K	15^{c}	245^{c}	4.6^{k}
	DPM_K	18^{c}	261^{c}	8.8^{s}
	SM_K	22^{c}	238^{c}	3.9^{h}
	DSM_K	14^{e}	208^{c}	5.6^{m}
	PM_D	12^{g}	146^{g}	2.8^{d}
	DPM_D	13^{g}	154^{g}	3.4^{g}
	SM_D	13^{g}	203^{c}	5.0^{l}
	DSM_D	11^{h}	144^{g}	3.1^{d}
Fourth cultivation date	PM_K	17^{c}	199^{e}	3.4^{g}
	DPM_K	16^{c}	240^{c}	7.6^{o}
	SM_K	19^{c}	232^{e}	5.2^{l}
	DSM_K	11^{h}	173^{g}	4.4^{k}
	PM_D	10^{j}	99^{j}	2.7^{d}
	DPM_D	7^{j}	73^{k}	2.0^{e}
	SM_D	7^{j}	69^{l}	1.9^{b}
	DSM_D	8^{k}	111^{m}	3.0^{d}

Values represent the average ± standard deviation (n = 4). The same letters within the same column indicate no significant difference (Tukey $P = 0.05$)

among the different treatments, cultivation dates, and wheat varieties. NPK and poultry manure generally produced the highest values, particularly in *Karim*. NPK increased the number of grains per spike (up to 20) and grain count (380 pot^{-1}), yielding 12.2 g of grain weight per pot. In the first sowing, PM and DPM produced high grain weight in both cultivars, with *Karim* reaching 12 g pot^{-1} (PM). Sheep manure resulted in lower grain weight, particularly in *Dhahbi*. In the second sowing, *Karim* produced the maximum grain count (479 pot^{-1}) and grain weight (12.4 g pot^{-1}) when supplied with SM and PM, whereas *Dhahbi* again exhibited lower performance. Grain weight declined further in the third and fourth cultivations. Digested PM supported moderate grain weight in *Karim* (8.8 g pot^{-1} in the third; 7.6 g pot^{-1} in the fourth sowings), while *Dhahbi*'s grain weight frequently fell below 5 g pot^{-1} under SM.

Discussion

This study demonstrates the complex interplay among cultivation date, fertilizer type, and wheat variety in shaping germination dynamics, vegetative growth, reproductive traits, and final yield of wheat grown in nutrient-poor, previously uncultivated sandy soils. The findings highlight the importance of both fertilizer application timing and cultivar choice for optimizing productivity under arid conditions.

Seed germination was strongly influenced by the timing of organic fertilizer application relative to sowing. When seeds were sown shortly after fertilization, particularly with raw poultry or sheep manure, germination speed and final germination percentage declined, while the time to germination increased. This inhibition is likely due to phytotoxic compounds such as ammonia, organic acids, and humic substances released during the early stages of organic matter decomposition (Lynch 1980; Bacilio *et al*. 2003; Bernal *et al*. 2009; Kaparaju *et al*. 2012; Kong *et al*. 2023). Similar effects have been reported in wheat and alfalfa, where immediate sowing after fertilization delayed germination (El-Zeadani *et al*. 2018; Abubaker *et al*. 2024). In contrast, improved germination performance was observed in the third and fourth sowings, suggesting that a lag period of 20–30 days allows sufficient microbial mineralization and volatilization of harmful compounds (Kuwatsuka and Shindo 1973; Hees *et al*. 2003; Fang *et al*. 2015). Compared with raw manure, digested manure caused only minor phytotoxic effects, likely due to the reduced levels of volatile compounds following anaerobic digestion (Tambone *et al*. 2010).

Vegetative growth traits such as plant height, leaf area, and tiller number were closely tied to both sowing date and fertilizer type. The most vigorous growth occurred in the first and second sowings, particularly for *Karim* under raw poultry manure, consistent with the rapid mineralization and high N-P-K content of this amendment (Eghball and Power 1999; Goyal *et al*. 1999; Geisseler *et al*. 2021). These results align with previous findings that poultry manure decomposition within 15 days can release nutrients essential for early plant growth (Bloukounon-Goubalan *et al*. 2019; Nabi 2023). In contrast, reduced growth under digested manure may reflect the accumulation of ammonium and dissolved organic carbon, which can constrain nitrogen availability through microbial transformations (Álvarez-Alonso *et al*. 2022). Growth also declined in later sowings, likely due to limited thermal time and reduced resource availability early in the season (Gomez-Macpherson and Richards 1995).

These vegetative responses translated into differences in reproductive development and yield components. Spike number and spike biomass were highest when sowing occurred 2 or 20 days after fertilization with raw poultry manure, particularly in *Karim*, reflecting a better match between nutrient release and reproductive demand (Ros *et al*. 2003). Digested manures also had moderate positive effects but were less effective than raw poultry manure, likely due to slower nutrient release. In some cases, the relatively small leaf area observed during the third and fourth sowings under manure treatments suggested delayed nutrient availability (Guo *et al*. 2019; Shaji *et al*. 2021), but this was insufficient to offset the declines in spike traits caused by late sowing. Biomass accumulation and grain yield followed a similar pattern, peaking in the first and second sowings under raw poultry manure. The high yield achieved with poultry manure was supported by improved vegetative growth, spike development, and grain filling efficiency, particularly in *Karim*. These findings support earlier reports that poultry manure can be as effective as inorganic fertilizers in enhancing yield (Abumere *et al*. 2019; Agbede 2021). In contrast, lower yields with digested manure may reflect nitrogen losses through volatilization or immobilization in sandy soils, where nutrient release does not always coincide with crop demand (Möller and Müller 2012). Yield components such as grain number per spike declined sharply under late sowing, most likely due to nutrient depletion *via* immobilization, denitrification, or volatilization (Samuel and Dines 2023; Priya *et al*. 2024). The consistent superiority of *Karim* over *Dhahbi* across most parameters underscores the importance of genotype in determining crop performance. *Karim* responded particularly well to poultry manure applied shortly before sowing, which may reflect higher nutrient uptake efficiency and greater sink strength compared to *Dhahbi* (Nsarellah *et al*. 2011; Mohammadi *et al*. 2012). Although Dhahbi has shown better performance in other environments (Ayed *et al*. 2022; Ghazouani *et al*. 2022), the contrasting results here highlight the strong influence of local conditions and management practices (Kong and Zhao 2023).

Despite the generally positive response to organic amendments, yields in this study were relatively low, though comparable to values reported for arid regions (Dadrasi *et al*. 2023; Razzaghi *et al*. 2024). The application rate of 300 kg N ha^{-1} may have been insufficient for uncultivated sandy soils. Previous studies have demonstrated that higher nitrogen rates, exceeding 450 kg N ha^{-1}, can substantially increase wheat yields (Abubaker *et al*. 2020). Future work should therefore assess higher application levels or complementary soil amendments to enhance fertility and water retention in these fragile soils.

Conclusion

This study demonstrates that sowing within 10 days after poultry manure application substantially enhances wheat performance in virgin sandy soils. Raw poultry manure was most effective, often outperforming mineral NPK fertilizer, while digested manure provided moderate benefits and sheep manure was generally less effective, particularly when applied close to sowing. The cultivar *Karim* showed greater adaptability and responsiveness to fertilization and sowing timing, making it well-suited for arid environments. These findings indicate that integrating timely sowing with appropriate manure management, preferably using raw or well-stabilized poultry manure, is a sustainable strategy to improve wheat growth and yield in nutrient-deficient sandy soils. Future studies should evaluate higher nitrogen rates, complementary organic amendments, and long-term soil fertility impacts to further strengthen resilient wheat production systems in marginal environments.

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Author Contribution

Jamal Abubaker conceived and designed the study, developed the experimental plan, conducted soil and fertilizer analyses, performed statistical analyses, prepared figures and drafted and revised the manuscript. Abusif Sonousi contributed to experimental design and implementation, data collection, table preparation, and result analysis. Mohemed Essalem assisted in the experimental design, data collection, and result analysis. Abdouslam M. Rassem contributed to the experimental work, measurements, data collection, and manuscript revision. Abdelsalam Abobaker participated in the experiment, performed measurements and contributed to manuscript writing. Hamzah Mohammed assisted in conducting the experiment and performing measurements.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data Availability

Data are available from the corresponding author upon reasonable request.

Ethics Approval

Not applicable to this paper.

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