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Impact of Tillage Depth and Agricultural Gypsum Application on Sorghum Yield, Water Use Efficiency, and Soil Chemical Properties in Toshka, Egypt

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ABSTRACT

A field experiment was conducted during two successive growing seasons of 2020/2021 and 2021/2022, in non-saline soil, Toshka area, Aswan Government, south Egypt, in order to investigate the effect of tillage depth and agricultural gypsum application on Sorghum yield, water use efficiency, and soil chemical properties. The experiment was conducted using a randomized complete block design (RCBD) comprising four treatments and three replicates. Results indicated spectacular improvements in sorghum morphological and yield traits due to tillage and gypsum application. The DT+G treatment stimulated plant height by 7.35%, seed index by 44.23%, straw yield by 49.69%, and grain yield by 16.51% as compared to ST. Grain nitrogen content was the highest at 2.21% under DT+G, which reflects a 26.96% improvement, whereas the highest straw nitrogen content (1.25%) was achieved in ST+G treatment. Water use efficiency increased both due to deep tillage and the application of gypsum. Irrigation Water Productivity (IWP) was increased by 16.52% under ST+G to 0.34 kg m⁻³, while Crop Water Productivity (CWP) was increased by 18.65% under ST+G with a maximum of 0.47 kg m⁻³. At the same time, water consumptive use (CU) was reduced by 1.85% under DT+G, indicating improved water conservation. Physical properties of the soil were significantly improved. Available water content was increased by 36.90% (0–30 cm) and 17.97% (30–60 cm) by ST+G treatment compared to ST. In contrast, the field capacity and saturation percentages in gypsum treatments were elevated at a significant level. Also, the availability of nitrogen up to 13.70%, phosphorus 22.11%, and potassium 11.43% were increased to a significant level in treatment. Hence, the combined application of deep tillage and gypsum presents a quite practical and efficient method for enhancing sorghum yields, water use efficiency, and general soil fertility under hyper-arid conditions.

INTRODUCTION

The Toshka region, situated in the southwestern part of Aswan Governorate in southern Egypt, constitutes a cornerstone of Egypt's national desert land reclamation efforts. Geographically, it is located between latitudes 22°30' and 23°30' N and longitudes 31°00' and 32°30' E, constituting part of the Western Desert. The terrain remains predominantly flat to gently undulating, with soils varying from sandy to sandy loam. *These soils typically lack organic matter, exhibit poor structure, and retain little water, which creates a challenge for sustainable agriculture* [ElGhonomiey, 2006; Mohamed et al., 2019].

Climate-wise, Toshka lies in a hyper-arid zone, with extreme summer temperatures usually above 45°C, mild winters, and precipitation below 5 mm per annum. This causes a gigantic water deficit with high evaporation over 2,000 mm/year. Low relative humidity and frequent high winds heighten the potential danger of wind erosion with topsoil degradation. The conditions severely limit rain-based agriculture, and a total dependence on

irrigation becomes a must [Abd El-Aziz, 2018].

The Nile River is the primary source of water for agriculture in Toshka, supplied by way of the Sheikh Zayed Canal system from Lake Nasser. Irrigation water has comparatively good quality with low to moderate salinity, so that one can grow a wide range of crops under controlled conditions. Center pivot and drip irrigation are widely practiced to provide enhanced water use efficiency.

Toshka region is among the most promising agricultural lands in Egypt and has received great attention from the Egyptian government due to its immense possibilities of crop production on a larger scale and to narrow the national food gap. The government has, therefore, poured heavy investments into the development of infrastructure within the area, including road and transport systems and irrigation. Developing and promoting crop varieties of key crops like wheat, maize, sorghum, sunflower, legumes, and vegetables, among other strategic agricultural crops, has been awarded concerted efforts. [El-Shazly and Abd El Hady, 1977].

Despite these efforts, the region remains subject to significant agricultural constraints. Soil salinity, surface crusting, compaction layers, and nutrient deficiencies remain prevalent. High evaporation rates intensify salt accumulation, while poor soil permeability restricts water infiltration. In this context, integrated management practices are essential, combining mechanical interventions such as deep tillage with chemical amendments like gypsum to improve soil structure and fertility. Furthermore, selecting drought- and salt-tolerant crops such as *Sorghum bicolor* offers promising pathways for enhancing productivity and sustainability [ElGhonamey, 2006; Mohamed et al., 2019].

Given the challenges that soil salinity poses, it is of utmost importance to mitigate its negative impacts. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) has surfaced as an effective option to counteract the adverse effects of salinity on soil health. It is commonly accepted as one of the best and economical amendments for saline-sodic soils [Murtaza et al., 2013]. Gypsum can serve as a cheap calcium source to balance the $\text{Ca}^{2+}/\text{Na}^+$ ion ratio in the soils, thereby improving soil structure, water movement, and nutrient availability to plants. It appears that gypsum does much to improve soil properties such that plants can better acquire water and nutrients, which is very important in salt-affected soils [Murtaza et al., 2013]. Gypsum also supplies sulfur, a nutrient that helps in developing phytohormones, amino acids, and osmo-protectants to alleviate salt stress in plants [McKenna et al., 2019]. Calcium supplied by gypsum also helps to regulate the K^+/Na^+ balance within plant cells, which is essential for plant tolerance to salinity and efficient growth [Bello et al., 2021; Tian et al., 2024].

Therefore, this study aimed to: (1) evaluate the effects of tillage depth and agricultural gypsum application on sorghum yield and components quality; (2) assess the impact of these practices on water use efficiency indices (IWP and CWP); and (3) investigate changes in key soil physical and chemical properties under different tillage and gypsum treatments in the Toshka region.

MATERIALS AND METHODS

1. Study Site and Experimental Conditions

A field experiment was carried out in non-saline soil in the Toshka area, Aswan Government, south Egypt ($23^\circ 11' 35.03'' \text{ N}$ - $31^\circ 36' 50.25'' \text{ E}$) for two seasons, 2020/2021 and 2021/2022, to effect of tillage depth and agricultural gypsum application on Sorghum yield, water use efficiency, and soil chemical properties. The region experiences an arid climate with high temperatures, low relative humidity, and scarce rainfall. The evapotranspiration (ET_0) values for both growing seasons were calculated by using the data from a

weather station established at Toshka Station (Table 1), using the CROPWAT model (Smit, 1991) based on the FAO Penman-Monteith method.

2. Soil Characteristics

The samples were taken from 0-20 and 20-40 cm soil depths for chemical and physical analysis of the used soil were determined according to Black (1965) and Page et al. (1982), and the results obtained are presented in Table 2.

3. Experimental Design and Treatments

The experiment was conducted using a randomized complete block design (RCBD) comprising four treatments and three replicates. Each plot measured $29 \text{ m} \times 6 \text{ m}$, totaling 174 m^2 . The treatments were:

- ST: Surface tillage (15 cm depth) without gypsum.
- ST+G: Surface tillage with gypsum (7.5 t ha^{-1}).
- DT: Deep tillage (60 cm depth) without gypsum.
- DT+G: Deep tillage with gypsum (7.5 t ha^{-1}).

4. Crop Management

Sorghum (*Sorghum bicolor*, cv. Shandweel) was sown on July 20 and 25 in the 2020 and 2021 seasons, respectively. Fertilizer recommendations recommended by the Ministry of Agriculture for the area were adopted. Nitrogen was added at a rate of 85 kg/ha in three split dressings each growing season, a common practice to enhance nitrogen use efficiency and reduce leaching losses in sandy soils (Fageria and Baligar, 2005). Seeds were planted in rows spaced 75 cm apart with 18 cm between plants, at a seeding rate of 6 kg ha^{-1} . Irrigation was applied using a center-pivot system. The pivot speed and water flow rate were recorded to calculate the volume of irrigation water applied. Moisture readings were taken before and after irrigation for each cycle in all treatments during the season.

5. Water Use Efficiency Measurements

Actual water consumptive use (ET_a or Cu)

Water consumptive use was calculated using the following equation (Israelsen and Hansen, 1962).

$$\text{Cu} = \sum_{i=1}^n \frac{(\theta_2 - \theta_1)}{100} \times D_b \times D_i$$

Where:

Cu = Water consumptive use (cm), in effective root zone (100 cm).

D_i = Soil layer depth (20 cm).

D_b = Soil bulk density (g/cm^3), of the specified soil layer.

θ_1 = Soil moisture % before irrigation.

θ_2 = Soil moisture %, 24 hours after irrigation.

Irrigation water productivity

The Irrigation water use efficiency (IWUE) was calculated according to Du et al. (2017) using the following equations:-

$$\text{IWP} (\text{kg/m}^3) = Y/I$$

Where Y is the grain yield (kg ha^{-1}) and

I is the irrigation water applied ($\text{m}^3 \text{ ha}^{-1}$).

Table 1: The meteorological data of the experimental site during the two growing seasons 2020/2021 and 2021/2022.

YEAR	Months	Temperature (°C)		Relative humidity (%)	Wind speed (m/hr)	ET _a
		Maximum	Minimum			
2020	Jan	6.52	20.46	44.91	3.27	3.92
	Feb	8.61	23.86	37.32	3.24	4.83
	Mar	13.49	30.74	24.58	3.96	6.86
	Apr	17.26	33.9	20.29	3.4	8.22
	May	22.59	38.82	16.85	4.15	10.64
	Jun	24.98	41.05	15.96	3.76	10.88
	Jul	26.25	40.93	19.07	3.83	10.88
	Aug	26.86	41.31	20.78	4.03	10.90
	Sep	26.14	42.17	19.02	3.61	10.20
	Oct	22.95	38.11	22.83	3.98	9.20
	Nov	13.82	27.32	39.18	2.8	5.00
	Dec	12.05	26.73	36.7	2.96	4.80
2021	Jan	9.55	25.00	44.91	3.21	4.47
	Feb	10.22	25.35	37.32	3.64	5.37
	Mar	13.67	31.15	24.58	3.51	7.23
	Apr	17.93	35.68	20.29	3.70	8.87
	May	23.11	40.08	16.85	3.84	10.49
	Jun	25.64	41.49	15.96	3.07	9.89
	Jul	27.64	41.98	19.07	3.70	11.02
	Aug	27.18	42.18	20.78	3.86	10.85
	Sep	24.49	39.51	19.02	3.57	9.76
	Oct	21.2	36.58	22.83	3.48	8.17
	Nov	16.79	31.4	39.18	3.33	6.00
	Dec	10.18	23.67	36.7	3.52	4.80
2022	Jan	7.06	20.33	41.39	3.35	4.06
	Feb	7.85	23.74	36.56	3.42	5.00
	Mar	11.05	28.43	23.12	4.16	7.24

Table 2: Chemical and physical analysis of the soil of the experimental farm.

Soil property	Soil depth (cm)		Soil property	Soil depth (cm)	
	0 - 20	20 - 40		0 - 20	20 - 40
Sand %	78.40	73.40	SP	30.00	29.00
Silt %	5.00	10.00	FC %	16.00	15.00
Clay %	16.6	16.6	WP %	7.00	7.00
Textural Class	Sandy loam	Sandy loam	Bulk density (Mg m ⁻³)	1.41	1.40
pH (1: 2.5)	8.36	8.37	EC _e (dS m ⁻¹)	0.73	0.57
CaCO ₃ %	5.39	5.33	CEC (meq./ 100g)	12.01	18.64
OM (g kg ⁻¹)	3.10	2.40	Available N (ppm)	70.00	85.00
Available P (ppm)	9.88	7.65	Available K (ppm)	386.00	253.00

Crop water productivity

Crop water productivity (CWP) describes the efficiency of the water applied for yield production. It was calculated as described by Zwart and Bastiaansen (2004) as follows:-

$$CWP (kg m^{-3}) = Y / ET_a$$

ET_a is the seasonal Actual water consumptive use (m³ ha⁻¹)

6. Soil and Plant Analysis

Post-harvest soil samples taken from two depths (0–30 cm and 30–60 cm) and analyzed for:

- Field capacity, wilting points and available soil moisture were determined in the field (Michael, 1978).

- Available nitrogen (Jackson, 1973), Available phosphorus (Olsen et al., 1954) and Available phosphorus (Pase et al., 1982).

After harvest, some traits were recorded as follows:-

- Straw and grain yield (kg ha⁻¹).
- Plant height (cm).
- Seed index (g).
- N in straw and grain
- Plant samples were taken and washed with deionized water, oven-dried at 70°C, mill ground and kept for chemical analysis. Dried, ground plant material of 0.2 g was digested using 10 mL of a mixture of 7: 3 ratios of sulfuric to perchloric acids (Jackson, 1973).
- Total nitrogen was measured in the digested sample by distillation with 20 ml of 40% sodium hydroxide using a micro Kjeldahl's distilling unit.

7. Statistical analysis:

Two-way analysis of variance (ANOVA) and Duncan's multiple range test were used to determine the statistical significance of the difference between the treatments' effects on soil properties and yield data using COSTAT software, and $p < 0.05$ was considered statistically significant.

Relative change expresses the change between two values as a proportion of the initial value, often presented as a percentage.

Relative change formula :

$$RCh = \left(\frac{(X2 - X1)}{X1} \right) \times 100$$

Where:

RCh = Relative change

X1 = Initial value (surface tillage)

X2 = Final value

RESULTS

1. Effect of Tillage and Gypsum Application on Morphological Traits and Yield Components of Sorghum

Sorghum traits and their yield as affected by tillage and gypsum in the summer season of 2020 and 2021 are presented in Table 3. Sorghum traits and their yield were significantly increased due to tillage and gypsum application. The greatest value of plant height (137.00 cm) was recorded at deep tillage with adding gypsum (DT+G) in the 2nd season. The lowest value of plant height (126.74 cm) was recorded at surface tillage without gypsum application (ST) in the 1st season (Table 3). In both growing seasons, the relative change in plant height values was 1.99, 4.59, and 7.35 % for DT, ST+G, and DT+G treatments, respectively, compared to the ST treatment. The highest value of seed index (18.60 g) was recorded at deep tillage with adding gypsum (DT+G) in the 2nd season. The lowest value of seed index (12.45g) was recorded at ST treatment in the 2nd season (Table 3). In both growing seasons, the relative change in seed index values was 7.03, 27.38, and 44.23 % for DT, ST+G, and DT+G treatments, respectively, compared to the ST treatment. The highest value of straw yield (23.20-ton ha⁻¹) was recorded at the DT+G treatment in the 2nd season. The lowest value of straw yield (14.67-ton ha⁻¹) was recorded at ST treatment in the 2nd season (Table 3). In both growing seasons, the relative change in straw yield values was 19.23, 45.87 and 49.69% for DT, ST+G and DT+G treatments, respectively, compared to the ST treatment. The highest value of grain yield (2.52 ton ha⁻¹) was recorded at ST+G treatment in the 2nd season. The lowest value of grain yield (2.12 ton ha⁻¹) was recorded at ST treatment in the 1st season (Table 3). In both growing seasons, the relative change in grain yield values was 8.24, 16.51, and 8.34 % for DT, ST+G and DT+G treatments, respectively, compared to the ST treatment.

Table 3: Effect of tillage and gypsum application on sorghum yield and its components during both growing seasons.

Treatments	Plant Height (cm)		Weight of 100 Seeds (g)		Grain Yield (ton ha ⁻¹)		Straw Yield (ton ha ⁻¹)	
	2020	2021	2020	2021	2020	2021	2020	2021
ST	126.74d	127.70d	12.93d	12.45d	2.12c	2.13d	15.70d	14.67d
DT	129.30c	130.21c	13.77c	13.40c	2.43a	2.17c	18.23c	17.98c
ST+G	132.70b	133.43b	16.13b	16.20b	2.43a	2.52a	21.70b	22.60b
DT+G	136.15a	137.00a	18.60a	18.03a	2.26b	2.34b	22.26a	23.20a
	mean	R Ch	mean	R Ch	Mean	R Ch	mean	R Ch
ST	127.22	0.00	12.69	0.00	2.12	0.00	15.19	0.00
DT	129.76	1.99	13.58	7.03	2.30	8.24	18.11	19.23
ST+G	133.07	4.59	16.17	27.38	2.47	16.51	22.15	45.87
DT+G	136.58	7.35	18.32	44.32	2.30	8.34	22.73	49.69
S = surface	D = deep		T = tillage		G= gypsum			

2. Nitrogen Content in Sorghum Grain and Straw

Grain and straw nitrogen content as affected by tillage and gypsum in both growing seasons of 2020 and 2021 is presented in Table 4. The deep tillage and gypsum application treatments affected grain nitrogen content through both seasons. The highest value of grain nitrogen (2.21 %) was recorded at deep tillage with adding gypsum (DT+G) in the 2nd season. The lowest value of grain nitrogen (1.67%) was recorded at surface tillage (ST) without gypsum application in the 1st season (Table 4). In both

growing seasons, the relative change in grain nitrogen content values was 11.88, 18.26, and 26.96 % for DT, ST+G, and DT+G treatments, respectively, compared to the ST treatment. The highest value of straw nitrogen (1.25%) was recorded with ST+G treatment in the 2nd season. The lowest value of straw nitrogen (0.95%) was recorded with ST in the 1st season (Table 4). In both growing seasons, the relative change in straw nitrogen values was 19.27, 28.65, and 25.52 % for DT, ST+G and DT+G treatments, respectively, compared to the ST treatment.

Table 4: Effect of tillage practices and gypsum application on nitrogen content of grain and straw yield during both growing seasons.

Treatments	Grain N %		Straw N%	
	2020	2021	2020	2021
ST	1.67d	1.78d	0.95c	0.97d
DT	1.87c	1.99c	1.12b	1.17c
ST+G	1.92b	2.16b	1.22a	1.25a
DT+G	2.17a	2.21a	1.20a	1.21b
	Mean	R Ch	mean	R Ch
ST	1.73	0.00	0.96	0.00
DT	1.93	11.88	1.15	19.27
ST+G	2.04	18.26	1.24	28.65
DT+G	2.19	26.96	1.21	25.52

S = surface D = deep T = tillage G= gypsum

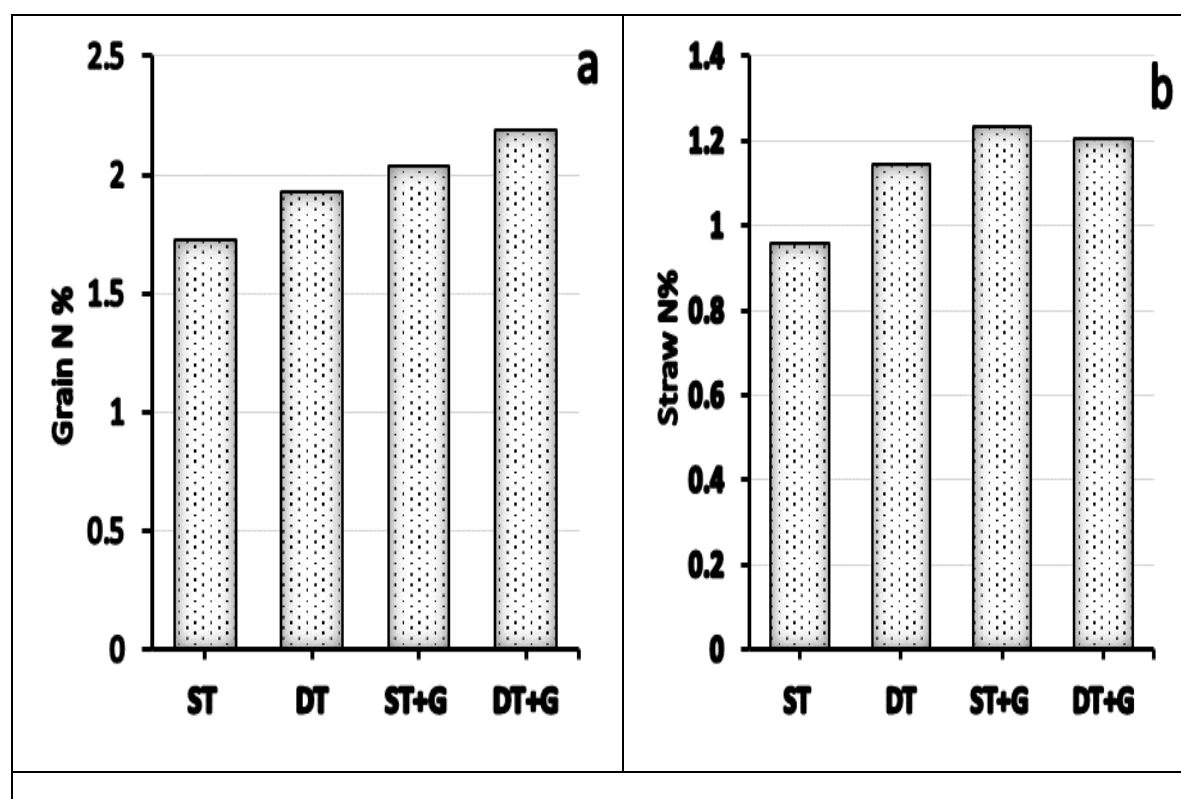


Fig. 1: Effect of tillage practices and gypsum application on nitrogen content of grain and straw yield during both growing seasons.

3. Effect of Tillage Practices and Gypsum Application on Water Use Efficiency in Sorghum Production

The effect of tillage practices and gypsum application on water consumptive use (CU), applied irrigation water (AIW), crop water productivity (CWP) and irrigation water productivity (IWP) through both growing seasons is shown in Table 5. The amounts of applied irrigation water were 7619 and 7522 m³ ha⁻¹ in the 1st and 2nd seasons, respectively. The water consumptive use (CU) of sorghum was decreased by agricultural practices (deep tillage and gypsum application) during both growing seasons. The highest value of CU (5528.57 m³ ha⁻¹) was recorded at surface tillage without gypsum application (ST) in the 2nd season. The lowest value of CU (5404.76 m³ ha⁻¹) was recorded at deep tillage with gypsum application (DT+G) in the 2nd season (Table 4). In both growing seasons, the relative change in CU values was 1.39, 1.81, and 1.85 % for DT, ST+G, and DT+G treatments, respectively, compared to ST treatment. The IWP was significantly increased due to tillage and gypsum practices. The highest value of IWP (0.34 kg m⁻³ water) was recorded at surface tillage with gypsum application (ST+G) in the 2nd season. The lowest value of IWP (0.28 kg m⁻³ water) was recorded at surface tillage without gypsum application (ST) in both growing seasons (Table 4). In both growing seasons, the relative change in IWP values was 8.20, 16.52 and 8.35 % for DT, ST+G and DT+G treatments, respectively, compared to ST treatment. The CWP was significantly increased due to the tillage and gypsum application through both growing seasons. The highest value of CWP (0.47 kg.m⁻³ water) was recorded at deep tillage with gypsum applied (ST+G) in the 2nd season. The lowest value of CWP (0.38 kg m⁻³ water) was recorded at surface tillage without gypsum application (ST) in the 2nd season (Table 4). In both growing seasons, the relative change in CWP values

was 9.75, 18.65, and 10.38 % for DT, ST+G and DT+G treatments, respectively, compared to the ST treatment.

4. Soil Water Retention Parameters as Influenced by Tillage Practices and Gypsum

The effects of tillage depth and gypsum application on soil moisture constants during the two growing seasons (2020 and 2021) are presented in Table 6. From the results, it was discerned that tillage and gypsum had a statistically significant effect on soil moisture parameters like saturation percentage, field capacity, wilting point, and available water for both the 0–30 cm and 30–60 cm soil depth layers. Summers represent the highest saturation percentages under surface tillage plus gypsum application (ST+G), with saturation percentage means of 36.75% in the 0–30 cm layer and 30.34% in the 30–60 cm layer, an increase of 26.72% and 13.74% relative to surface tillage (ST) alone. Deep tillage without gypsum (DT) also enhanced saturation values but to a lesser extent (4.02% and 8.12% increases for the two depths, respectively).

Field capacity values followed a similar trend, with ST+G treatment showing the highest means of 18.85% (0–30 cm) and 15.55% (30–60 cm), corresponding to relative increases of 32.42% and 13.50% compared to ST. Deep tillage treatments (DT and DT+G) also increased field capacity, though less markedly.

Wilting point percentages increased slightly under all treatments compared to ST, with ST+G demonstrating the largest relative increase (28.41% at 0–30 cm and 9.59% at 30–60 cm depths). Available water content, being one of the more important parameters for plant water availability, was found to be distinctly improved by gypsum application, with the surface soil under ST+G recording an increase of 36.90% and 17.97% at two depths, respectively, from the control.

Table 5: Effect of tillage practices and gypsum application on sorghum water relationships.

Treatments	AIW (m ³ ha ⁻¹)		CU (m ³ ha ⁻¹)		IWP (Kg m ⁻³)		CWP (Kg m ⁻³)	
	2020	2021	2020	2021	2020	2021	2020	2021
ST	7619	7522	5501.62	5528.57	0.28c	0.28c	0.39c	0.38d
DT	7619	7522	5451.55	5425.52	0.32a	0.29c	0.45a	0.40c
ST+G	7619	7522	5412.00	5419.05	0.32a	0.34a	0.45a	0.47a
DT+G	7619	7522	5421.86	5404.76	0.30b	0.31b	0.42b	0.43b
	Mean	R Ch	Mean	R Ch	mean	R Ch	mean	R Ch
ST	7570.50	0.00	5515.10	0.00	0.28	0.00	0.38	0.00
DT	7570.50	0.00	5438.54	-1.39	0.30	8.20	0.42	9.75
ST+G	7570.50	0.00	5415.52	-1.81	0.33	16.52	0.46	18.65
DT+G	7570.50	0.00	5413.31	-1.85	0.30	8.35	0.42	10.38
S = surface		D = deep		T = tillage		G= gypsum		

Table 6: Effect of agricultural practices on soil moisture constants during both growing seasons.

Treatments	Soil depth (cm)	Saturation percent %		Field capacity %		Wilting point %		Available water %	
		2020	2021	2020	2021	2020	2021	2020	2021
ST	0 -30	29.00	29.00	14.36	14.11	7.43	7.60	6.93	6.51
	30 -60	26.11	27.23	14.00	13.40	7.20	7.40	6.80	6.00
DT	0 -30	30.00	30.33	15.40	15.60	7.90	8.00	7.50	7.60
	30 -60	28.00	29.67	14.40	14.70	7.40	7.65	7.00	7.05
ST+G	0 -30	36.67	36.83	18.80	18.90	9.60	9.70	9.20	9.20
	30 -60	30.00	30.67	15.40	15.70	7.90	8.10	7.50	7.60
DT+G	0 -30	32.34	33.33	14.95	14.85	7.66	7.82	7.29	7.03
	30 -60	27.33	28.67	14.58	14.72	7.70	7.80	6.88	6.92
		mean	R Ch	mean	R Ch	mean	R Ch	mean	R Ch
ST	0 -30	29.00	0.00	14.24	0.00	7.52	0.00	6.72	0.00
	30 -60	26.67	0.00	13.70	0.00	7.30	0.00	6.40	0.00
DT	0 -30	30.17	4.02	15.50	8.89	7.95	5.79	7.55	12.35
	30 -60	28.84	8.12	14.55	6.20	7.53	3.08	7.03	9.77
ST+G	0 -30	36.75	26.72	18.85	32.42	9.65	28.41	9.20	36.90
	30 -60	30.34	13.74	15.55	13.50	8.00	9.59	7.55	17.97
DT+G	0 -30	32.84	13.22	14.90	4.67	7.74	2.99	7.16	6.55
	30 -60	28.00	4.99	14.65	6.93	7.75	6.16	6.90	7.81
S = surface		D = deep		T = tillage		G= gypsum			

Deep tillage with gypsum moderately improved soil moisture parameters as available water increased by 6.55% and 7.81% at 0-30 cm and 30-60 cm depths, respectively. Thus, gypsum application with surface tillage appears to be an effective way to improve soil moisture retention, leading to the potential improvement of water availability for sorghum growth under arid conditions.

5. Effect of Tillage Practices and Gypsum Application on Soil Nutrient Availability

During growing seasons, tillage treatments and gypsum application increase nitrogen (N), phosphorus (P), and potassium (K) availability, as shown in Figure 2 (a, b and c).

Tillage treatments and gypsum application pronounced increases in available nitrogen (N) for both growing seasons. The available N of the studied soil ranged from 55.62 to 65.55 mg kg⁻¹ in the surface layer and from 55.60 to 64.33 mg kg⁻¹ in the subsurface layer, which they are decreased with soil depth. The positive effect of tillage treatments and gypsum application on available N could be arranged in the descending order of ST+G > DT+G > ST. In both growing seasons, the relative change in N values was 12.87, 13.70 and 11.98% for DT, ST+G and DT+G treatments, respectively, compared to ST treatment regardless of their soil depth. Tillage treatments and gypsum application

pronounced increases in available phosphorus (P) in both growing seasons. The available P of the studied soil ranged from 10.87 to 13.93 mg kg⁻¹ in the surface layer and from 11.00 to 13.63mg kg⁻¹ in the subsurface layer, which they are decreased with soil depth. The positive effect of tillage treatments and gypsum application on available P could be arranged in the descending order of DT+G > ST+G > DT > ST. In both growing seasons, the relative changes in P values were 9.76, 13.15, and 22.11% for DT, ST+G, and DT+G treatments, respectively, compared to ST treatment regardless of their soil depth. Tillage treatments and gypsum application pronounced increases in available potassium (K) in both growth seasons. The available K of the studied soil ranged from 230.30 to 276.00 mg kg⁻¹ in the surface layer and from 247.70 to 265.30 mg kg⁻¹ in the subsurface layer, which they are decreased with soil depth. The positive effect of tillage treatments and gypsum application on available K could be arranged in the descending order of ST+G > DT+G > DT > ST. In both growing seasons, the relative change in K values was 5.18, 11.43 and 9.80% for DT, ST+G and DT+G treatments, respectively, compared to ST treatment regardless of their soil depth.

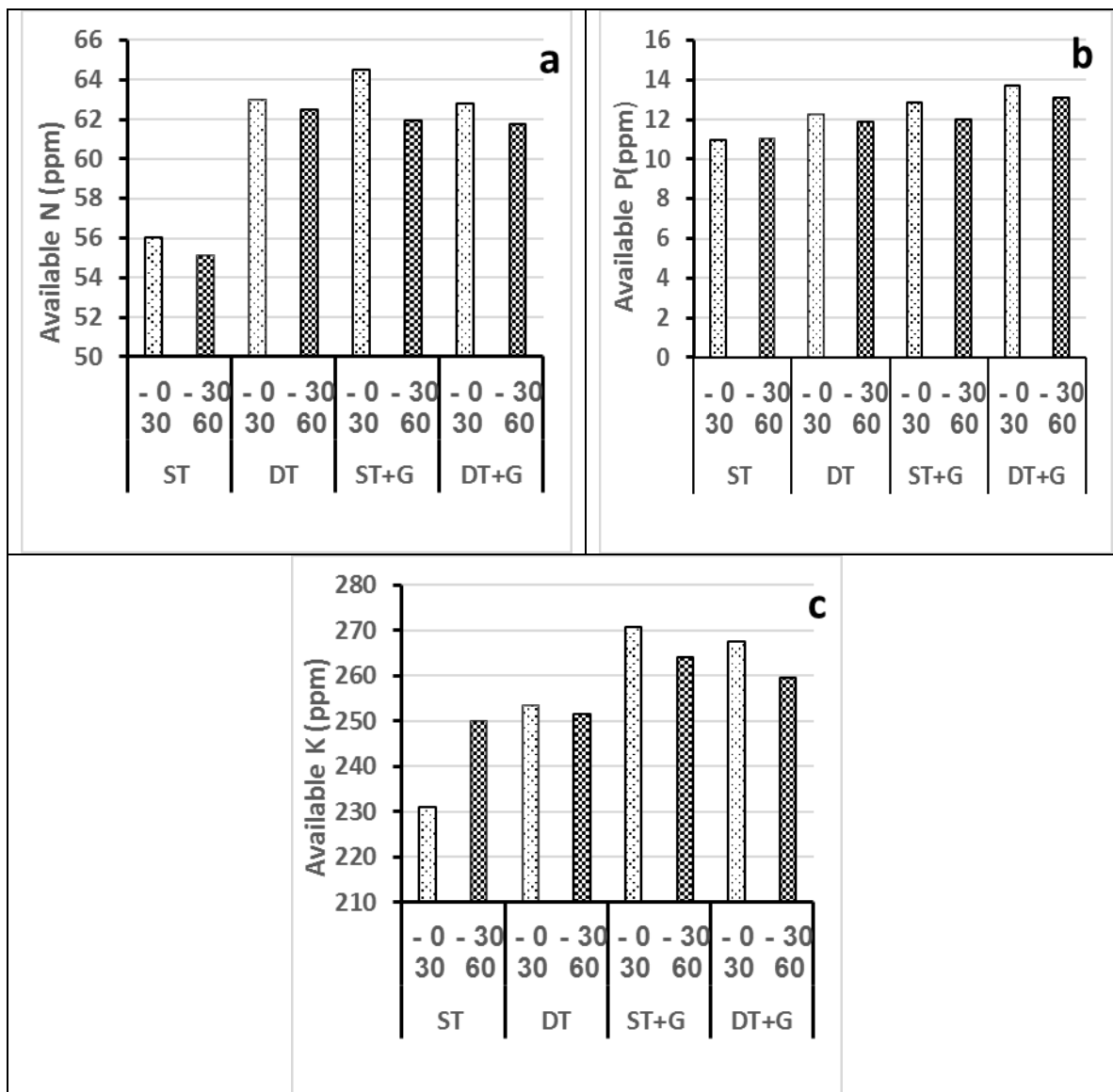


Fig 2: Effect of agricultural practices on available nutrients.

DISCUSSION

Under the harsh Toshka dry conditions, the deep tillage coupled with gypsum application leads to a significant enhancement of the morphological features and yield parameters of sorghum. The field results showed that plants grow higher and achieve higher straw and grain yields by deep tillage with gypsum against surface tillage without gypsum; other than that, there is also a fairly significant effect on the seed index. Such increments in plant height and seed indices reached a peak of 7.35% and 44.23%, respectively, while straw and grain yields saw 49.69% and 16.51% increases, respectively. These improvements were mainly attributed to increased aeration within the soil, better root penetration, and higher calcium availability, hence a

reduction in salinity stress and uptake of water and nutrients. Deep tillage essentially cuts through layers of compacted soil, allowing roots to spread out and water to flow deep into the soil, whereas gypsum works on improving the overall soil texture, equilibrating the ion composition in the soil with the availability of calcium and that of sulfur, which the two very crucial elements for stress tolerance of crops in saline-sodic soils. So, this combination provides better root environment, water use efficiency, and finally performance of crops (Caires et al., 2011; Somavilla et al., 2016 and El-Sanat et al., 2017)

Now, this is why one can safely state that there are high chances of crop improvement through the combined application of deep tillage and gypsum. The same author also assumed that though gypsum

can compensate for the deficiency of calcium in a short period, long-term amelioration of such conditions can only be achieved by frequent deep cultivation and incorporation of gypsum (Neogi et al., 2014 and Onunwa et al., 2021).

The results indicate that nitrogen concentration in sorghum grain and straw was significantly influenced by tillage depth and gypsum application. Greater nitrogen content in the grain under deep tillage with gypsum (DT+G), particularly during the second season of crop growth, can be attributed to improved root development, enhanced nutrient supply, and increased physical properties of the soil. Deep tillage would have encouraged deeper root penetration and maximized the volume of soil excavated by the roots, hence increasing the amount of nitrogen absorbed, especially in sandy soils where nutrient retention is usually low.

The 26.96% higher relative increase in grain nitrogen content of DT+G as compared to the surface tillage (ST) control treatment suggests a synergistic action of physical soil improvement and application of fertilizer. Application of gypsum as a soluble source of calcium and sulfur could have improved structural attributes of the soil, relieved compaction, and enhanced microbial numbers, all of which contribute to the mineralization and bioavailability of nitrogen (Chen and Dick, 2011; Gonzalez et al., 2022).

This concurs with Fageria and Baligar (2005), who re-stated that optimization of physical properties in the soil, in addition to balanced fertilization, is essential in attaining maximum efficiency in nutrient absorption in fine-textured soils. Similarly, Ahmed et al. (2019) reported that the use of gypsum in association with deep tillage significantly improved nitrogen in wheat under arid and semi-arid conditions through rooting expansion and better soil moisture levels. Interestingly, while DT+G improved grain nitrogen the most, the highest straw nitrogen content was observed under the ST+G treatment in the second season. This may reflect differences in nitrogen partitioning under varied soil management practices. Under surface tillage, gypsum may have increased nutrient availability primarily in the topsoil, favoring vegetative nitrogen accumulation, as noted by Shuangjie et al. (2018) in their study on nutrient partitioning in rice under different amendment treatments.

The overall improvements in nitrogen content across all improved treatments (DT, ST+G, and DT+G) relative to ST suggest that surface tillage without gypsum is suboptimal for nitrogen nutrition in sandy soils typical of arid regions. These results align with those of Xiao et al. (2025), who found that gypsum applications increased N availability and plant uptake in sandy loam soils through improvements in soil porosity and reduced leaching.

The present study demonstrates that tillage practices and the addition of gypsum significantly influenced water use dynamics and productivity in sorghum cultivation under dryland conditions. Deep tillage and/or the addition of gypsum reduced water consumptive use (CU) while concurrently enhancing both irrigation water productivity (IWP) and crop water productivity (CWP), implying improved water use efficiency, during both cropping seasons.

Minimum CU values were always obtained under deep tillage with gypsum (DT+G), while maximum CU was obtained under surface tillage (ST), particularly in the second season. One may infer that the deep tillage must have enhanced soil porosity and root zone depth, decreased surface evaporation, and increased water storage in the deeper soil layers. In parallel, gypsum might have benefited the soil structure and prevented sodium-associated crusting, hence reducing runoff losses, while infiltration was increased. This is in agreement with what Hamza and Anderson (2005) observed that through deep tillage and soil amendments, subsoil permeability and water holding capacity were improved in compacted soils (Chimonyo et al., (2016) ; De Barros et al., (2007) and Li et al., (2005).

Interestingly, while CU decreased, IWP and CWP were boosted significantly under ST+G and DT+G treatments. The highest IWP (0.34 kg m^{-3}) was achieved with surface tillage along with gypsum (ST+G), suggesting that even without deep tillage, the use of gypsum alone has the potential to enhance the plant water use efficiency, likely because of improved nutrient availability and reduced osmotic stress in the root zone. The improvement in CWP in ST+G (18.65%) and DT+G (10.38%) over ST control shows the role of gypsum in maximizing water productivity under rainfall-limited conditions.

These results are consistent with the work of Zwart and Bastiaanssen (2004), who established that physical or chemical soil condition improvement has important water productivity benefits, especially in semi-arid and arid regions. In addition, Du et al. (2010) pointed out that soil amendments and good tillage enhance the synchronization between crop water demand and soil water supply and therefore higher water productivity indices.

Interestingly, the improvement in IWP and CWP under DT and DT+G treatments also points to the advantage of deepening the root zone through tillage. This perhaps allows the crop to access deeper pools of moisture and reduces the number of irrigations required and thereby enhancing overall irrigation efficiency.

In summary, the combined application of deep tillage and gypsum appears to be a viable method for optimizing water use in sandy soils in dry

environments. While gypsum alone (ST+G) was very effective in increasing water productivity, deep tillage (with or without gypsum) also had substantial benefits, both through the conservation of water use and improving yield response per unit of water input. These findings warrant the inclusion of both mechanical (tillage) and chemical (gypsum) soil treatments in improving the sustainability of water-limited cropping systems (Moroke et al., (2011) and Dercas and Liakatas (2007)).

This research confirms that tillage depth and gypsum application exert a significant influence on soil moisture retention characteristics, particularly saturation percent, field capacity, wilting point, and available water in shallow and deeper soil layers. All these improvements are highly significant under the dryland environment, where water condition dominates for healthy crop growth (Chauvin et al., 2011).

Among the practices, surface tillage with gypsum (ST+G) always enhanced soil moisture properties more than any other practice. The considerable increases in saturation and field capacity for ST+G suggest that gypsum plays a critical role in building soil structure and porosity, and therefore, water-holding (Agbede (2006) and Adeyemo and Agele (2010). Deep tillage alone yielded moderate increases, likely due to mechanical loosening without the chemical benefit of gypsum.

Wilting point rise with all treatments, particularly with ST+G, may indicate higher water-holding at lower tensions in the soil due to improved soil texture and organic matter interaction (Habashy and Ewees, 2011). Increased water content directly benefits drought resistance in plants, and this parameter is generally ameliorated with gypsum application, mostly in the upper layers where root action is more impaired.

The results confirm the past observations that gypsum improves soil structure, reduces soil crusting, and consequently increases infiltration and water-holding capacity of degraded soils (Hamza and Anderson, 2005; Chen and Dick, 2011). Hence, the use of gypsum along with proper tillage practice may offer a sustainable way of improving soil moisture content and sustaining crop production in dryland scenarios.

The noted enhancement in soil nutrient availability as a result of tillage activities and gypsum application agrees with findings from previous studies emphasizing the importance of physical and chemical amendments to soil as factors for favoring the arid soils' nutrient dynamics. Tillage enhances aeration as well as breaks up clogged horizons, enhancing plant root infiltration and microbial activity that is accountable for propelling the nutrient mineralization and mobility in the soil profile (Lal, 2004).

The added availability of nitrogen, particularly under ST+G treatment, suggests that gypsum not only increases soil structure but potentially also has a role in minimizing losses of nitrogen to leaching and volatilization processes that are especially relevant in low cation exchange capacity sandy soils (Fageria and Baligar, 2005). The enhanced retention and mobility of ammonium ions by calcium from gypsum can be partially responsible for these benefits.

The availability of phosphorus was also greatly enhanced with tillage in addition to the application of gypsum. This could be attributed to the role of calcium ions in reducing the fixation of phosphorus, especially when exposed to alkaline conditions that are dominant in arid soils (Khasawneh and Doll, 1978). Ripping the soil matrix with deep tillage would likely enhance phosphorus diffusion and availability to roots. In addition, gypsum can also influence phosphorus availability indirectly by changing microbial activity and pH buffering (Chen and Dick, 2011).

As for potassium, its increase with gypsum application might be associated with increased root growth and porosity of the soil, which allows for increased K⁺ uptake and mobility in the soil solution. Gypsum is not a source of potassium itself, but its action to improve soil structure and reduce soil compaction can allow for an increase in the availability of the soil K reserves existing (Hamza and Anderson, 2005).

Generally, the results highlight the need for integrating soil physical and chemical management practices, particularly under arid and semi-arid environments. The sum of surface tillage plus gypsum was highest, which means that shallow intervention with coupled resultant chemical addition might be a cost-effective and sustainable means of maintaining soil fertility and productivity in sand soil

CONCLUSIONS

The research examined the impact of deep tillage in combination with gypsum application on sorghum growth, yield, nutrient concentration, and water use efficiency under dry conditions of the arid Toshka region. The results confirmed that gypsum deep tillage significantly enhanced morphological traits and yield attributes by up to 7.35% increment in plant height, 44.23% increment in seed index, 49.69% increment in straw yield, and 16.51% increment in grain yield compared to surface tillage without gypsum. Such improvements were attributed to increased soil aeration, root entry, and calcium availability, all of which collectively inhibited salinity stress and facilitated water and nutrient uptake. Grain and straw nitrogen content was enhanced through tillage depth and treatment with gypsum, with maximum grain nitrogen content

under deep tillage with gypsum (DT+G). This may have been due to enhanced root growth, physical soil status, and mineralization of nutrients by the availability of calcium and sulfur in gypsum. Maximum straw nitrogen was seen with surface tillage with gypsum (ST+G), which showed differential distribution of nitrogen under varied soil management systems. Water use efficiency was significantly enhanced with deep tillage and application of gypsum. Crop water productivity (IWP) and crop water productivity (CWP) improved under DT+G and ST+G treatments, whereas consumptive use (CU) decreased. Deep tillage increased porosity of the soil and water retention in lower layers, whereas Speckments provided improvement in soil structure, avoided crusting, and increased infiltration. The greatest IWP was observed in ST+G, noticeably indicating the remarkable effect of gypsum in enhancing water use by the soil even without deep tillage. Soil water-holding capacity, i.e., saturation, field capacity, wilting point, and available water, were improved strongly by the use of gypsum, especially under surface tillage. The effect of gypsum on the porosity and structure of soil led to increased water-holding capacity, which is needed most under dryland conditions. Deep tillage alone increased the said parameters moderately by physical loosening. The research also verified that tillage and gypsum application increased nutrient availability in the soil, such as nitrogen, phosphorus, and potassium. Gypsum reduced loss of nutrients and enhanced nutrient transport, and deep tillage promoted soil root penetration and microbial development. The soil physical and chemical amendments together offered an integrated strategy for enhancing the fertility of the soil and productivity of crops on dry sandy soils.

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الملخص العربي

تأثير عمق الحرث وتطبيق الجبس الزراعي على إنتاجية الذرة الرفيعة وكفاءة استخدام المياه والخصائص الكيميائية للتربة في توشكى، مصر

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تم إجراء تجربة حقلية خلال موسمين متتاليين 2021/2020 و 2022/2021 في تربة غير ملحية بمنطقة توشكى، محافظة أسوان، جنوب مصر، بهدف دراسة تأثير عمق الحرث وإضافة الجبس الزراعي على إنتاجية محصول الذرة الرفيعة، وكفاءة استخدام المياه، والخصائص الكيميائية للتربة.

نُفذت التجربة باستخدام تصميم القطاعات العشوائية الكاملة (RCBD) متضمنة أربع معاملات وثلاث مكررات. أظهرت النتائج تحسناً ملحوظاً في الصفات المورفولوجية والإنتاجية للذرة الرفيعة نتيجة الحرث العميق وتطبيق الجبس الزراعي. حيث أدت معاملة الحرث العميق مع الجبس (DT+G) إلى زيادة طول النبات بنسبة 7.35%، ومعامل البذور بنسبة 44.23%، وإنتاج القش بنسبة 49.69%، وإنتاج الحبوب بنسبة 16.51% مقارنة بمعاملة الحرث السطحي (ST). كما سُجل أعلى محتوى من النيتروجين في الحبوب بنسبة 2.21% تحت معاملة DT+G، بزيادة قدرها 26.96%، في حين تحقق أعلى محتوى نيتروجين في القش (1.25%) عند معاملة ST+G.

كما ازدادت كفاءة استخدام المياه نتيجة لكل من الحرث العميق وإضافة الجبس. إذ ارتفعت إنتاجية مياه الري (IWP) بنسبة 16.52% تحت معاملة ST+G لتصل إلى 0.34 كجم م⁻³، بينما زادت إنتاجية مياه المحصول (CWP) بنسبة 18.65% تحت نفس المعاملة لتصل إلى 0.47 كجم م⁻³ كحد أقصى. وفي الوقت نفسه، انخفض الاستهلاك المائي (CU) بنسبة 1.85% في معاملة DT+G، مما يدل على تحسن حفظ المياه.

أما الخصائص الفيزيائية للتربة فقد تحسنت بشكل ملحوظ، حيث زادت كمية الماء المتاح بنسبة 36.90% في الطبقة (30-0 سم) و 17.97% في الطبقة (30-60 سم) بمعاملة ST+G مقارنة بمعاملة ST. كما ارتفعت السعة الحقلية ونسبة الإشباع بشكل معنوي في معاملات الجبس. كذلك، زادت تراكيز العناصر الغذائية المتاحة في التربة بشكل ملحوظ، إذ ارتفع النيتروجين بنسبة 13.70%، والفوسفور بنسبة 22.11%، والبوتاسيوم بنسبة 11.43%. وبناءً على ذلك، فإن الجمع بين الحرث العميق وإضافة الجبس الزراعي يُعد وسيلة عملية وفعالة لتحسين إنتاجية الذرة الرفيعة، وكفاءة استخدام المياه، وخصوبة التربة بوجه عام تحت الظروف الجافة جداً.