



Optimizing Forage Yield, Quality and Water Use Efficiency in Pearl Millet through Planting Pattern and Nitrogen Management



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TWO FIELD experiments were conducted at the Experimental Farm of Sids, Agricultural Research Station, Beni-Suef, Egypt, through the summer seasons of 2022 and 2023 to evaluate three planting patterns (ridges, raised beds, and drilling) and five nitrogen fertilization treatments: B1 (90 kg N fed⁻¹ mineral fertilizer; control), B2 (bio-fertilizer + 90 kg N fed⁻¹), B3 (bio-fertilizer + 67.5 kg N fed⁻¹), B4 (bio-fertilizer + 45 kg N fed⁻¹), and B5 (bio-fertilizer + 22.5 kg N fed⁻¹) on productivity and some water relations of forage pearl millet (c.v. Shandweel.1). The experiment followed a Randomized Complete Block Design (RCBD) in strip plots with three replications, where planting patterns were assigned to vertical strips and fertilization treatments to horizontal ones. Results indicated that ridges pattern increased significantly total dry yield by 10.88% and 11.63% and the total protein yield by 12.65% and 12.96% as compared to raised beds and drilling patterns, respectively. Application of B2 increased significantly total dry yield by 2.25, 18.68, 32.69, and 49.60% and total protein yield by 4.69, 20.56, 35.16, and 52.16% as compared with the other fertilization treatments, respectively. The raised bed planting pattern saved approximately 19.49% and 19.55%, while the ridge planting pattern saved 11.43% and 11.23% of applied irrigation water compared to the drilling pattern in the 2022 and 2023 seasons, respectively. Ridges surpassed significantly beds and drilling patterns for water use efficiency by 7.33% and 17.28%, respectively. Ridges with B2 recorded the highest significant values for water productivity and water use efficiency of dry yield.

Keywords: Pearl millet, Planting pattern, Fertilization, Yield, Quality and Water relations.

Introduction

Egypt lies in a semi-arid region that suffers from water scarcity driven by climate change and population growth, which affects agricultural production (Salem and Shoman, 2021). Efficient forage crops, which hampers livestock production (Rady, 2018).

Addressing these challenges requires sustainable practices for irrigation and forage crop production. To meet animal feed demands, pearl millet drought-tolerant crop belonging to the Poaceae family. Its ability to thrive under adverse conditions such as high salinity, low soil fertility, and extreme Modern sustainable agriculture focuses on optimizing planting patterns and nitrogen management to enhance forage production and resource efficiency. Planting pattern is a critical factor influencing the growth, yield, and water use efficiency (WUE) of pearl millet (Bangar *et al.*, 2020). Some investigations found that planting

irrigation is crucial, as total irrigation demand could increase by 4–18% in absence of adaptation (Fader *et al.*, 2016; El-Marsafawy and Mohamed, 2021). Additionally, Egypt has a shortage of summer cultivation increased in recent years in Egypt, reaching 30.13 thousand feddan in 2021 (M. A. L. R., 2021). Pearl millet (*Pennisetum americanum* (L.) R. Br.), known as bajara, is a fast-growing,

temperatures makes it a key forage crop for arid and semi-arid regions (Ayub *et al.*, 2007 and Salem, 2020).

methods had an effect on pearl millet production and water use efficiency (WUE). Planting pearl millet on ridges improved stover yield and protein content in straw as compared to bed, seed drill, and broadcast planting patterns (Sharma *et al.*, 2018). In contrast, the row planting system of pearl millet resulted in higher stover yield as compared to the ridge and

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furrow method (Sagar *et al.*, 2017). The ridge planting pattern had the lowest consumptive use of water and the highest WUE for pearl millet as compared to the bed, seed drill, and broadcast patterns, respectively (Sharma *et al.*, 2015).

However, related studies in cereal crops such as corn and sorghum have shown that planting pattern can significantly influence crop yield, growth dynamics, and water use efficiency. The ridge planting method of corn increased biological yield as compared to other planting methods (broadcast, line, and raised bed) (Bakht *et al.*, 2011). The same trend was found for corn when sowing on ridges (Rehman *et al.*, 2011; Gul *et al.*, 2015 and Nassiri *et al.*, 2016). In contrast, corn performed better when sown on beds as compared to other planting patterns (ridges, flat, and drill) (Tanveer *et al.*, 2014 and Abu-Grab *et al.*, 2019). Also, Afzal *et al.* (2013) revealed that total dry forage yield and crude protein of sorghum increased under drilling patterns as compared to broadcast planting methods. Planting sorghum in rows enhanced dry forage yield and protein % (Manjunatha *et al.*, 2013 and Asim *et al.*, 2022).

Moreover, the uses of the raised bed pattern reduced irrigation and enhanced water productivity without any yield reduction. The applicant of the raised-bed technique saved 1600 m³ water ha⁻¹ in corn and 1500 m³ ha⁻¹ in wheat. Also, water productivity increased from 1.5 kg m⁻³ to 2.0 kg m⁻³ under the raised bed technique (Karrou *et al.*, 2012) in Egypt. Also, Abu-Grab *et al.* (2019) clarified that planting corn on beds decreased water use efficiency and increased crop water productivity as compared to the other planting patterns through Middle Delta region of Egypt. The same trend was found by Meena *et al.* (2015) in India that planting pattern of corn (furrow-irrigated raised bed) gave significantly the highest crop water productivity and the lowest water consumption compared to other planting patterns (flat bed and ridge and furrow). Meanwhile, furrow corn planting pattern improved water productivity by approximately 20% compared to traditional flat planting pattern (Wang *et al.*, 2011). Also, high water productivity for dry matter was obtained from the planting pattern (in-furrow) of corn. The planting pattern (in-furrow) saved 4.9% water. Furthermore, in-furrow planting pattern preserved more moist zones; therefore, the need for irrigation water is reduced as compared to the on-bed planting pattern (traditional), mentioned by Nassiri *et al.* (2016).

Nitrogen is a key but expensive input in crop production. Bio-fertilizers, which include microorganisms like (*Azotobacter*, *Cyanobacteria*, *Azospirillum* and *Pseudomonas*, *etc*) reduce the need for synthetic fertilizers; enhance soil fertility and lower pollution (George *et al.*, 1992 and Tantawey, 2001). Bio-fertilizers promote nutrient uptake, decompose organic matter, and improve plant stress resistance, making them essential for eco-friendly

farming (Malusa and Vassilev, 2014 and Kaur *et al.*, 2022). Combined inoculation of diazotrophic bacteria was: *Pseudomonas fluorescens*, *Azotobacter chroococcum*, *Azospirillum lipoferum* and *Acetobacter diazotrophicus*, one fungi: *Trichoderma viride* of pearl millet seed enhanced pearl millet performance and production as well as reduce 50% of mineral nitrogen application without any significant reduction of yield (Singh *et al.*, 2016; Singh, 2017; Singh *et al.*, 2017 and Singh *et al.*, 2018) in India as compared to the control (Un-inoculated seeds). Increasing dry forage yield and crude protein % of pearl millet significantly by applying 90 kg N ha⁻¹ as compared to nitrogen levels (0, 30, and 60 kg ha⁻¹); (Shekara *et al.*, 2019).

Integrated nutrient management (nitrogen fertilizer and bio-fertilizers) enhanced plant growth by supplying essential nutrients and resulted in high yield and quality. So, the combination of bio-fertilizers and mineral nitrogen (N) fertilizer had a markedly better yield as compared to using N fertilizer individually (Masaud, 2022). Moreover, Ibrahim *et al.* (2013) in Egypt revealed that a higher dose (120 kg N fed⁻¹) gave the tallest plant and the highest forage yield and crude protein yield of forage millet *cv.* Shandaweel-1 than nitrogen fertilizer treatments (0, 60, and 90 kg N fed⁻¹). Also, the results showed that the combination of *Cyanobacteria* and *Azospirillum* recorded the tallest plant by 2.5% and the highest total dry forage yield by 8% compared to the trusted level (120 kg N fed⁻¹). The results showed that treatment of 120 kg N fed⁻¹ gave protein yield similar to that gained from treatment of bio-fertilizers combined with 75% N fertilization (90 kg N fed⁻¹). They also revealed that treatment of bio-fertilizers save 25% of nitrogen with decreasing risk ecological effects, which found by mineral N-fertilizer. The incorporation of bio-fertilizer + 60 or 90 kg N fed⁻¹ recorded the tallest plants and the highest dry forage yield of fodder pearl millet (Habiba *et al.*, 2018 and Tomar *et al.*, 2019). Furthermore, Abdelaal and Habiba (2024) in Egypt mentioned that the treatment of (65 kg N fed⁻¹) + cereal in inoculation significantly outperformed the maximum plant height, dry forage yield, and crude protein % for three forage crops (millet, sudan grass, and teosinte).

These approaches ensure sustainable and cost-effective crop production and meet feed demands while protecting the environment. Accordingly, this work was conducted to assess the reply of growth, yield, quality, and water relations of forage pearl millet to planting pattern and evaluate the combination of different treatments of mineral N with bio-fertilization on forage pearl millet, *cv.* (Shandaweel-1), under Beni-Suief governorate conditions, Egypt, through the summer seasons of 2022 and 2023.

Materials and Methods

Experimental Location

Two field experiments were conducted at the Experimental Farm of Sids Agricultural Research Station, Beni-Suief Governorate, Middle Egypt (latitude 29° 04' N, longitude 31° 06' E, and 30.40 m above sea level) during the summer seasons of 2022 and 2023. The aim was to assess the effect of three planting patterns and nitrogen fertilization treatments, including bio-fertilizer, and their combinations on forage millet (*c.v.* Shandweel-1) productivity and water-related parameters. Some soil physical properties were determined according to Klute (1986), and some soil chemical properties of the experimental soil site according to Page *et al.* (1982) are listed in the following Table 1.

Experimental design

The experiment was conducted in a strip-plot layout within a randomized complete block design (RCBD) with three replications. The vertical (main) plots were assigned to three planting patterns: ridges, 60 cm between ridges and 30 cm between hills., raised beds: 120 cm wide with four rows spaced at 30 cm between rows and hills and drilling, 30 cm row spacing (traditional farmer practice), and the horizontal plots included five nitrogen fertilization treatments: B1: 90 Kg N fed⁻¹ mineral fertilizer only (control), B2: Bio-fertilizer + 90 Kg N fed⁻¹ fertilizer, B3: Bio-fertilizer + 67.5 Kg N fed⁻¹ fertilizer, B4: Bio-fertilizer + 45 Kg N fed⁻¹ fertilizer, and B5: Bio-fertilizer + 22.5 Kg N fed⁻¹ fertilizer.

Bio-fertilizer was N₂-fixing bacteria (*Azospirillum brasilense*) mixed with phosphate dissolving bacteria (*Bacillus megathium var. phosphaticum*) and potassium dissolving bacteria (*Bacillus circulans*) provided by the bio-fertilizer unit of the Bacteriology Research Dept., Land Water and Environment Research Institute, ARC. The inoculation was applied by treating pearl millet grains with a mixture of inoculum (Arabic gum 5%), which was used to stick the inoculant material to the grains just before sowing. Nitrogen was applied after 10 days from sowing and after each cut as urea (46.5% N). Grains of pearl millet (*c.v.* Shandweel.1) were sown on 5th and 7th June during the seasons of 2022 and 2023, respectively. Seeding rate was 16 kg fed⁻¹. Super phosphate (15.5% P₂O₅) was added at 150 kg fed⁻¹ to all the experimental plots after land preparation. Plants were cut three times on 23rd July, 24th August, and 27th September in the first season and on 26th July, 30th August, and 26th September in the second season.

Table 1. Physical and chemical properties of soil at Sids Agricultural Research Station during 2022 and 2023 seasons.

Soil properties	2022	2023
Physical analysis		
Coarse sand	0.36	0.55
Fine sand	18.73	15.17
Silt	29.12	31.09
Clay	51.79	53.19
Textural class	Clay	Clay
Chemical analysis		
PH (1:25)	7.80	7.90
EC (ds/m)	1.09	1.23
SP	0.50	0.55
Soluble anions (meq/l)		
Co⁻³	0.00	0.00
HCO⁻³	1.50	1.13
Cl⁻	5.50	4.24
SO⁼⁴	4.37	4.79
Soluble cations (meq/l)		
K⁺	0.42	0.35
Na⁺	4.45	3.66
Mg⁺⁺	2.50	2.81
Ca⁺	3.50	3.33
CaCO₃ %	3.78	3.25
Available nutrients (mg/kg soil)		
N	30	35
P	10.54	11.
K	176	210
Cu	0.54	0.59
Fe	2.96	3.33
Mn	1.30	1.83
Zn	1.18	1.42

Some traits recorded after each cut were a) plant height (cm) and b) dry forage yield (ton fed⁻¹) = fresh forage yield (ton fed⁻¹) × dry matter (%). Where dry matter % (DM %) was calculated by taking a plant sample (500 g) and weighing it fresh (g); afterward, samples were put in an oven and dried at 70°C to keep a stable weight, and the dried weight was recorded, and DM was calculated. c) Protein yield (kg fed⁻¹), where measured crude protein content was determined by total nitrogen by the micro-Kjeldahl method (A.O.A.C., 1995). Crude protein content was measured as follows: Crude protein % = total nitrogen × 6.25. Protein yield was determined as follows: Protein yield (kg/fed⁻¹) = dry forage yield × crude protein content. Chemical analysis was estimated at the 1st replication in the laboratory, but at the 2nd and 3rd replications in the 2nd season and the 3rd replications in the 1st season, the apparatus of NIR Spectra StarTM RTW¹ was used.

Water relations:

1. Amount of applied irrigation water (Q):

The amount of water added was determined found of the difference in soil average moisture content at 60 cm depth from soil samples was obtained prior irrigation and the soil moisture % at field capacity with an additional 10 % included to ensure a good uniform distribution of water through the plots according to (Hansen *et al.*, 1980) as follows:

$$D_i = \frac{F.C. - m}{100} \times B_d \times d$$

Where; D_i = applied water depth (cm), F.C. = soil moisture content at field capacity by weight %, m = average soil moisture content before irrigation by weight %, B_d = bulk density of the specified soil layer (g cm⁻³) and d = depth of soil layer (cm).

$$Q = R \times D_i$$

Where; Q = the volume of applied water in m³ and R = area that would be irrigated in m². The applied irrigation water was recorded and controlled for each plot by applying a water meter relevant to the irrigation pump.

2. Water saving percentage

Water saving percentage was measured describing by Molden (1997).

Total water for treatment m³ fed⁻¹

Water saving (%) = 100 - [----- X 100]

Total water for traditional method m³ fed⁻¹

3. Consumptive use (CU):

Consumptive use refers to the total volumes of water utilized by plant growth in a specific area, including the water lost through transpiration and plant tissue formation as well as water evaporated from adjacent soil (Doorenbos *et al.*, 1979). Water consumptive use was calculated at each irrigation time using the following equation:

$$Q_2 - Q_1$$

$$C.U. = \frac{Q_2 - Q_1}{B_d \times d} \times 100$$

Where; C.U. = actual water consumptive use in (cm), Q₂ = soil moisture % after 48 hours from irrigation, Q₁ = soil moisture % before irrigation, B_d = bulk density of the specified soil layer (g cm⁻³) and d = depth of soil layer (cm).

4. Water Productivity (WP):

Water productivity is measured as a ratio of product output over water input. Water productivity is calculated as kg of fresh or dry forage found per the unit of applied irrigation water. The water productivity was measured as described by FAO (2003) as follows:

$$WP \text{ (kg m}^{-3}\text{)} = \frac{\text{Total dry yield (kg fed}^{-1}\text{)}}{\text{applied water (m}^3\text{ fed}^{-1}\text{)}}$$

5. Water use efficiency (WUE)

The water use efficiency expressed as kg of forage per cubic meter of water consumed that was measured for each treatment according to Vites (1965):

$$WUE \text{ (kg m}^{-3}\text{)} = \frac{\text{Total dry yield (kg fed}^{-1}\text{)}}{\text{Consumptive use (m}^3\text{ fed}^{-1}\text{)}}$$

Statistical analysis

The data of each cut and total yield in every season were analyzed and described by procedures outlined by Steel *et al.* (1997) using the Mstat-C computer program (Freed, 2007). The differences between treatment means were compared by the least significant difference test (LSD) at 0.05 level of probability (Gomes and Gomes, 1984). Bartlett (1937) was employed to test the homogeneity of error variances across the two seasons before conducting combined analyses.

Results and Discussion

1. Planting pattern

Data presented in figure (1) showed the combined analysis in the 2022 and 2023 seasons regarding the influence of planting pattern on plant height of pearl millet. The ridge planting pattern significantly increased plant height at all three cuts. The tallest plants were recorded at the third cut (116.00 cm), followed by the first (105.77 cm) and second cuts (102.42 cm), respectively. No significant differences were observed between ridges and raised beds at the first cut. In contrast, the drilling pattern consistently produced significantly shorter plants across all cuts. Ridge planting enhances soil aeration, nutrient availability, and moisture retention, which promote cell division and elongation, thus increasing plant height. These results were in harmony with those reported by Manjunatha *et al.* (2013), Sagar *et al.* (2017), Bangar *et al.* (2020), and Deshmukh *et al.* (2013).

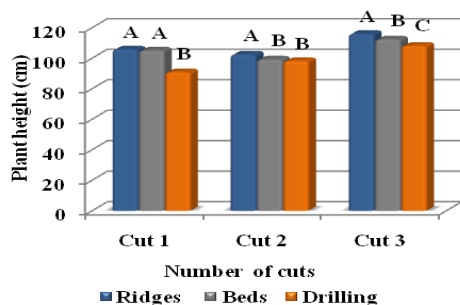


Fig. 1. The combined analysis of planting pattern effect on plant height (cm) at each cut across two seasons of 2022 and 2023.

Ridges produced the highest dry forage yield across all cuts (Fig. 2). Although there were no significant differences between ridges and drilling at the second and third cuts, ridge planting significantly increased total dry forage yield by 10.88% and 11.63% compared to raised beds and drilling, respectively. No significant difference was found between raised beds and drilling. Forage yield tended to decrease with successive cuts, possibly due to reduced regrowth vigor. The superior performance of ridge planting can be attributed to improved light interception, reduced intra-plant competition, and enhanced photosynthetic efficiency. Similar findings were reported by Bakht *et al.* (2011), Rehman *et al.* (2011), Gul *et al.* (2015), and Sharma *et al.* (2018).

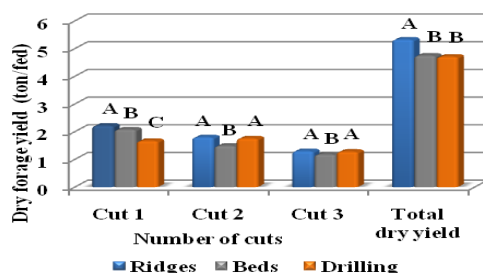


Fig. 2. The combined analysis of planting pattern effect on Dry forage yield (ton fed⁻¹) at each cut and their total yield across two seasons of 2022 and 2023.

Figure (3) clarified that ridges recorded the highest protein yield at the first and second cuts (255.94 and 187.43 kg/fed, respectively). Although no significant differences were observed between ridges and drilling at the second and third cuts, ridge planting significantly outperformed raised beds and drilling in terms of total protein yield by 12.65% and 12.96%, respectively. The increased protein yield is likely due to improved nutrient uptake and photosynthetic assimilation under favorable ridge conditions. These results align with those of Asim *et al.* (2022).

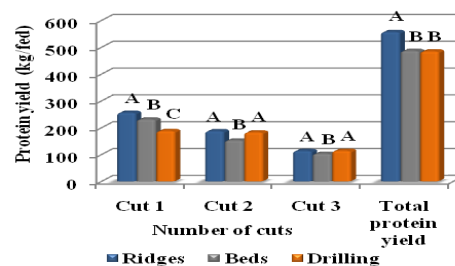


Fig. 3. The combined analysis of planting pattern effect on protein yield (kg fed⁻¹) of pearl millet at each cut and their total yield across two seasons of 2022 and 2023.

2. Fertilization treatments

Generally, all fertilization treatments influenced significantly plant height (Fig. 4). Treatment B2 (bio-fertilizer + 90 Kg N fed⁻¹) produced the tallest plants at the first cut, while B1 (mineral N 90 Kg fed⁻¹) surpassed others at the second and third cuts (125.50 cm). B5 (bio-fertilizer + 22.5 Kg N fed⁻¹) consistently resulted in the shortest plants across all cuts. Nitrogen enhances vegetative growth by promoting cell division and elongation, increasing auxin production, and improving chlorophyll content and photosynthesis rates. These findings are in agreement with previous reports by Meena *et al.* (2012), Ibrahim *et al.* (2013) and Shahin *et al.* (2013). Inoculated bacterial strains stimulate plant growth through the production of auxins, cytokinins, gibberellins, and vitamins, thereby enhancing growth (Togas *et al.*, 2017; Habiba *et al.*, 2018; Angel *et al.*, 2023; Abdelaal and Habiba, 2024).

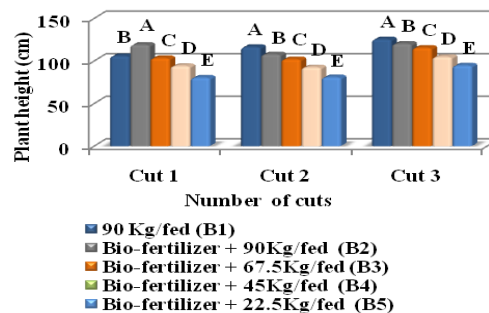


Fig. 4. The combined analysis of fertilization treatments on plant height (cm) of pearl millet at each cut across two seasons of 2022 and 2023.

Application of B2 gave significantly the highest dry yield at the 1st cut (Fig. 5). Meanwhile, adding B1 recorded the significantly the highest dry yield at 2nd and 3rd cuts. Application of B2 increased significantly the total dry yield by 2.25, 18.68, 32.69, and 49.60% as compared with B1, B3, B4, and B5, respectively. No significant difference was observed between B2 and B1 for total dry yield. Dry forage yield increased by increasing nitrogen rates and improved plant height and dry matter production. These results are recorded by Shekara *et al.* (2021) and Fakirah and Masaud (2022). Also, the

adding of bio-fertilizer to the mineral nitrogen application recorded an increase in the availability of nutrients, especially phosphorus and nitrogen, which accelerates the photosynthetic rate and facilitates the formation of carbohydrates, which increases the accumulation of dry matter production, as mentioned by Togas *et al.* (2017), Habiba *et al.* (2018), Fakirah and Masaud (2022), Vamsi *et al.* (2023), and Abdelaal and Habiba (2024).

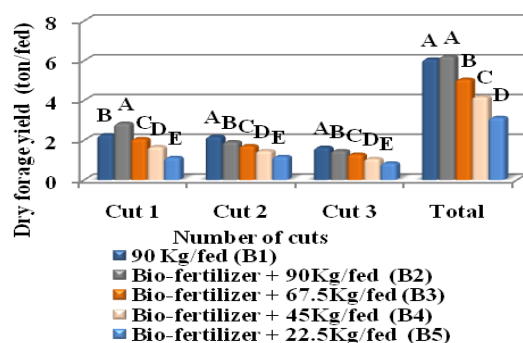


Fig. 5. The combined analysis of fertilization treatments on dry forage yield (ton fed⁻¹) of pearl millet at each cut and their total yield across two seasons of 2022 and 2023.

Adding B2 at the 1st cut and B1 at the 2nd and 3rd cuts gave significantly the highest protein yield of pearl millet (Fig. 6). Adding B2 surpassed significantly B1, B3, B4, and B5 for total protein yield by 4.69, 20.56, 35.16, and 52.16%, respectively. Increasing nitrogen fertilization increased the amount of nitrogen available in the rhizosphere, the primary compound of amino acids, increasing the amount of crude protein in fodder pearl millet. Similar outcomes were obtained by Togas *et al.* (2017), Khinchi *et al.* (2018), and Abdelaal and Habiba (2024).

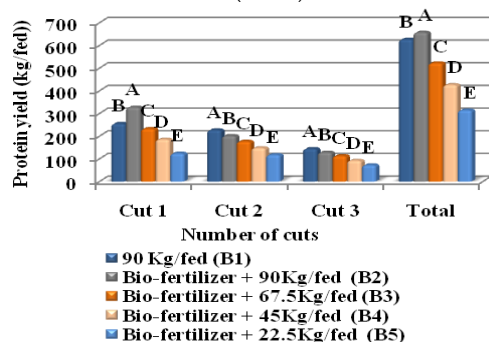


Fig. 6. The combined analysis of fertilization treatments on protein yield (kg fed⁻¹) of pearl millet at each cut and their total yield across two seasons of 2022 and 2023.

Increasing the nitrogen levels enhanced nutrient availability for pearl millet plants, improved soil fertility, and subsequently led to better pearl millet quality. These results were found by Saha and Mondal (2006), Ibrahim *et al.* (2013), Shivprasad and Singh (2017), and Aboelgoud *et al.* (2021). Furthermore, the application of bio-fertilizers such

as Cyanobacteria, Azospirillum, Pseudomonas, Serratia, Azotobacter, Bacillus, Klebsiella, and Anterobacter was recorded to support plant growth and quality because of their ability to produce secondary metabolites, fix nitrogen, enhance phosphate solubilization, and improve mineral uptake (Ibrahim *et al.*, 2013).

3. Interaction between planting pattern and fertilization treatments

Data in Table (2) clarified the impact of the combined analysis of planting pattern and fertilization treatments interaction on plant height of pearl millet at each cut over the 2022 and 2023 seasons. At first cut, no statistical differences were observed between planting pattern and fertilization treatments. Meanwhile, ridges and B1 interaction achieved significantly the tallest plant at the last two cuts. This finding was in agreement with Gul *et al.* (2015).

In contrast, the shortest plants were significantly obtained from the interactions of drilling and B5 and raised beds and B5 at the 2nd and 3rd cuts without significant difference between them.

Table 2. Mean performance of the combined analysis of the interaction between planting pattern and fertilization treatments on plant height (cm) of pearl millet at each cut across two seasons of 2022 and 2023

Planting pattern	Fer. treatment	Plant height (cm)		
		Cut 1	Cut2	Cut 3
Ridges	B1	109.17	119.33	130.17
	B2	128.17	107.33	125.00
	B3	108.50	104.75	118.83
	B4	97.83	95.17	107.00
	B5	85.17	85.50	99.00
Raised beds	B1	111.50	113.50	123.00
	B2	121.67	106.67	121.67
	B3	109.33	99.67	116.17
	B4	98.33	96.17	108.33
	B5	84.50	80.00	92.33
Drilling	B1	96.83	116.33	123.33
	B2	107.17	109.33	114.00
	B3	92.33	101.83	111.50
	B4	86.17	86.33	99.17
	B5	71.67	77.17	92.67
L.S.D (0.05) A*B		N.S	4.94	4.24

B1=90 Kg N fed⁻¹ fertilizer (control), B2= Bio-fertilizer + 90 Kg N fed⁻¹ fertilizer, B3= Bio-fertilizer + 67.5 Kg N fed⁻¹ fertilizer, B4= Bio-fertilizer + 45 Kg N fed⁻¹ fertilizer, B5= Bio-fertilizer + 22.5 Kg N fed⁻¹ fertilizer, and N.S= non significant.

Mean performance of Combined analysis of the interaction between planting pattern and fertilization treatments was significant on dry yield at all cuts and total dry yield of pearl millet except the third cut

across two seasons of 2022 and 2023 (Table 3). Ridges and B2 interaction recorded significantly the best dry yield (3.30 ton fed⁻¹) at the first cut. Meanwhile, ridges and B1 interaction achieved the highest dry yield (2.33 and 1.69 ton fed⁻¹) at the 2nd and 3rd cuts, respectively. But there were no significant differences between ridges and B1 and drilling and B1 at the 2nd and 3rd cuts.

These results were in harmony with those found by Rehman *et al.* (2011) and Gul *et al.* (2015) but it was disagree with Manea *et al.* (2015) and Bakry *et al.* (2023), who reported that raised bed planting pattern with higher rates of mineral nitrogen gave taller and higher maize yield. The highest total dry forage yield was significantly given by ridges and B2. The interactions of raised beds and B5, and drilling and B5, gave the lowest total dry yield during the study. The interaction between ridges and B2 increased total dry yield by 55.57% and 56.01% as compared with raised beds and B5 and drilling and B5 interactions, respectively.

Means of the interaction between planting pattern and fertilization treatments showed significant impacts on protein yield at all cuts and total protein yield of pearl except at the third cut across two seasons of 2022 and 2023 (Table 4).

Table 3. Mean performance of the combined analysis of the interaction between planting pattern and fertilization treatments on dry yield at each cut and total dry yield of pearl millet (ton fed⁻¹) across two seasons of 2022 and 2023.

Planting pattern	Fer. treatment	Dry yield (ton fed ⁻¹)			
		Cut 1	Cut2	Cut 3	Total
Ridges	B1	2.53	2.33	1.69	6.55
	B2	3.30	2.05	1.46	6.82
	B3	2.28	1.83	1.31	5.42
	B4	1.79	1.51	1.16	4.46
	B5	1.20	1.29	0.88	3.37
Raised beds	B1	2.39	1.91	1.54	5.84
	B2	2.87	1.62	1.42	5.92
	B3	2.18	1.47	1.25	4.89
	B4	1.74	1.40	0.93	4.07
	B5	1.21	1.07	0.76	3.03
Drilling	B1	1.85	2.30	1.68	5.83
	B2	2.36	2.06	1.48	5.90
	B3	1.73	1.82	1.28	4.83
	B4	1.46	1.46	1.09	4.01
	B5	0.96	1.16	0.88	3.00
L.S.D (0.05) A*B		0.17	0.11	N.S	0.25

B1=90 Kg N fed⁻¹ fertilizer (control), B2= Bio-fertilizer + 90 Kg N fed⁻¹ fertilizer, B3= Bio-fertilizer + 67.5 Kg N fed⁻¹ fertilizer, B4= Bio-fertilizer + 45 Kg N fed⁻¹ fertilizer, B5= Bio-fertilizer + 22.5 Kg N fed⁻¹ fertilizer, and N.S= non significant

Means of the interaction between planting pattern and fertilization treatments showed significant impacts on protein yield at all cuts and total protein yield of pearl except at the third cut across two seasons of 2022 and 2023 (Table 4). Ridges and B2 interaction produced significantly the highest protein yield (389.17 kg fed⁻¹) at the first cut. The interaction of ridges and B1 achieved significantly the highest protein yield (248.39 kg fed⁻¹) at the 2nd cut. This result was in disagreement with Shivprasad and Singh, (2017). The best total protein yield (739.79 kg fed⁻¹) was significantly obtained from the treatment (ridges and B2). The interactions of raised beds and B5 and drilling and B5 gave the lowest total protein yield (306.08 and 301.37 kg fed⁻¹) during the study, respectively. The interaction of ridges and B2 surpassed significantly drilling and B5 for total protein by 59.26%.

4. Water relations

4.1. Amount of water applied (m³ fed⁻¹) for each irrigation and water saving:

Results in Table (5) showed that the maximum amount of water applied was recorded by the drilling planting pattern (traditional A3), which achieved the maximum values of 4121 m³ fed⁻¹ and 4240 m³ fed⁻¹ in the 1st & 2nd seasons, respectively.

Table 4. Mean performance of the combined analysis of the interaction between planting pattern and fertilization treatments on protein yield at each cut and total protein yield (kg fed⁻¹) across two seasons of 2022 and 2023.

Planting pattern	Fert. treatment	Protein yield (Kg fed ⁻¹)			
		Cut 1	Cut2	Cut 3	Total
Ridges	B1	293.02	248.39	148.10	689.50
	B2	389.17	220.36	130.27	739.79
	B3	261.02	186.26	112.97	560.25
	B4	203.63	154.40	101.20	459.22
	B5	132.84	127.77	75.41	336.02
Raised beds	B1	264.75	194.04	137.48	596.26
	B2	323.29	168.62	122.74	614.66
	B3	243.16	151.30	108.91	503.37
	B4	190.74	141.21	80.36	412.30
	B5	133.51	107.31	65.25	306.08
Drilling	B1	208.01	238.13	147.89	594.03
	B2	269.23	216.13	132.49	617.85
	B3	193.26	192.89	117.09	503.24
	B4	162.70	148.48	96.12	407.30
	B5	106.14	118.21	77.01	301.37
L.S.D (0.05) A*B		21.98	11.92	N.S	32.65

B1=90 Kg N fed⁻¹ fertilizer (control), B2= Bio-fertilizer + 90 Kg N fed⁻¹ fertilizer, B3= Bio-fertilizer + 67.5 Kg N fed⁻¹ fertilizer, B4= Bio-fertilizer + 45 Kg N fed⁻¹ fertilizer, B5= Bio-fertilizer + 22.5 Kg N fed⁻¹ fertilizer, and N.S= non significant

Besides, the minimum amount of water applied was obtained from the raised bed (A2) pattern (3318 m³ fed⁻¹ and 3411 m³ fed⁻¹) in the 1st & 2nd seasons, respectively. Meanwhile, the ridges pattern (A1) recorded 3650 m³ fed⁻¹ and 3764 m³ fed⁻¹ in the 1st & 2nd seasons, respectively. The data in Table (5) provided evidence that raised beds (A2) could save about 19.49 and 19.55%, and ridges (A1) saved 11.43 and 11.23% of irrigation water applied in contrast to drilling (A3) in the 1st and 2nd seasons, respectively. The same conclusions were observed by Ahmad *et al.* (2010).

Increasing amount of irrigation water applied in treatment A3 compared with planting patterns (A1 and A2) because the wetted area of A3 is larger than the treatments A1 or A2. In treatments A1 and A2 water was primarily applied to the bottom of the furrows only, with only a small portion reaching the sides due to lateral flow.

Table 5. Amount of irrigation water used per irrigation number, total available water (m³ fed⁻¹) and water saving under planting pattern and nitrogen fertilization treatments during the summer season of 2022 and 2023.

Irri. event	Amount of irrigation water used per irrigation (m ³ fed ⁻¹)					
	Ridges (A1)		Raised bed (A2)		Drilling (A3)	
	1 st	2 nd	1 st	2 nd	1 st	2 nd
First	535	545	560	565	515	550
Second	402	425	381	395	431	450
Third	472	487	398	415	537	542
Fourth	470	493	406	415	541	547
Fifth	456	475	401	418	554	561
Sixth	428	439	395	416	524	552
Seventh	451	455	390	397	534	540
Eighth	436	445	387	390	485	498
Total	3650	3764	3318	3411	4121	4240
Saving water (%)	11.43	11.23	19.49	19.55	--	--

As a result, the wetted area in treatments A1 and A2 was less than the conventional method (A3). Furthermore, the number of furrow bottoms in treatment A2 was 50% less than treatment A1 by 50, further reducing the wetted area.

4.2. Seasonal consumptive use (CU):

Crop water consumptive use was estimated based on water bleeding from the root zone of the upper 60 cm soil depth. Results in Table (6) indicated that seasonal CU for pearl millet was influenced by planting patterns across both growing seasons. The highest CU was given from the drilling planting pattern (A3) in comparison to the ridges and raised beds planting patterns (A1 and A2). According to Doorenbos and Pruitt (1977), the soil water % decreases after irrigation or rainfall due to evapotranspiration. They further noted that the soil was dried; the rate of water declines as the water

moves through the soil. The impact of soil moisture on evapotranspiration depends on various factors, including crop type, soil properties, and soil water-holding capacity.

Regarding the effect of adopted N fertilization treatments on consumptive use, results in Table 6 revealed a gradual increase in CU as a result of increasing nitrogen levels when applied alongside bio-fertilizer. The highest values of CU (2956.43 and 3032.31 m³ fed⁻¹) were attained with the combination of B2 in the 2022 and 2023 seasons, respectively. The rise of the evapotranspiration rate explained the positive influence of nitrogen and bio-fertilizer application on growth, which led to an increase in plant canopy. As a result, the greater leaf area increased the transpiring surface, and that showed in higher overall water use during the season.

Table 6. Effect of planting pattern and nitrogen fertilization treatments on water consumptive use CU (m³ fed⁻¹) in 2022 and 2023 seasons.

Planting pattern (A)	Fertilization treatments (B)	Water consumptive use CU (m ³ fed ⁻¹)	
		First season	Second season
Ridges (A1)	B1	2877.24	2880.77
	B2	2916.25	2981.94
	B3	2749.95	2785.00
	B4	2615.27	2689.88
	B5	2487.66	2550.51
Mean		2729.27	2777.57
Raised (A2)	B1	2793.98	2826.32
	B2	2795.15	2879.14
	B3	2679.16	2715.98
	B4	2491.74	2524.55
	B5	2397.86	2415.54
Mean		2631.58	2672.31
Drilling (A3)	B1	3159.41	3121.85
	B2	3157.89	3235.86
	B3	2942.87	2971.06
	B4	2767.24	2795.25
	B5	2632.07	2658.97
Mean		2931.90	2956.60
Mean of Fertilizer	B1	2943.54	2942.85
	B2	2956.43	3032.31
	B3	2790.66	2824.01
	B4	2624.75	2669.89
	B5	2505.86	2541.67

B1=90 Kg N fed⁻¹ fertilizer (control), B2= Bio-fertilizer + 90 Kg N fed⁻¹ fertilizer, B3= Bio-fertilizer + 67.5 Kg N fed⁻¹ fertilizer, B4= Bio-fertilizer + 45 Kg N fed⁻¹ fertilizer, and B5= Bio-fertilizer + 22.5 Kg N fed⁻¹ fertilizer.

4.3. Water productivity (WP) and water use efficiency (WUE):

Water productivity (WP) (kg m^{-3} water applied) and water use efficiency (WUE) (kg m^{-3} water consumption) were significantly affected by the studied planting patterns (Fig. 7). The (WP) and (WUE) for dry yield were significantly obtained by ridges (A1). No significant differences were observed in water productivity (WP) between ridges (A1) and raised bed (A2) planting patterns. Water productivity was significantly increased for ridges by 21.53% over the drilling pattern. In related studies, the highest crop water productivity and the lowest water consumptive use of maize crop were significantly recorded from furrow-irrigated raised beds compared with other planting patterns mentioned by Karrou *et al.* (2012), Meena *et al.* (2015), Nassiri *et al.* (2016), and Abu-Grab *et al.* (2019). Meanwhile water use efficiency (WUE) of maize significantly decreased with reducing the amount of irrigation water from 2625 to 1575 $\text{m}^3 \text{fad}^{-1}$ (Kotb and Mansour, 2012).

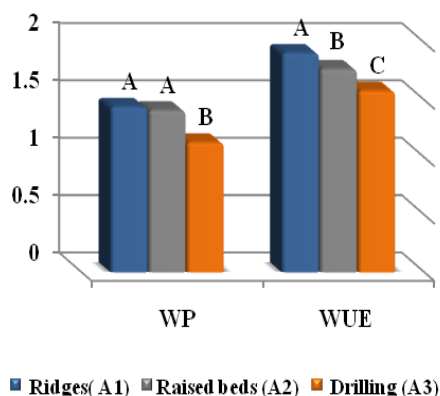


Fig. 7. Effect of planting pattern on water productivity (WP), (Kg m^{-3}) and water use efficiency (WUE), (Kg m^{-3}) for dry yield across combined analysis over two seasons of 2022 and 2023.

The combination of B2 provided significantly the highest water productivity of dry yield (Fig. 8). Water productivity of dry yield showed no statistical differences between B1 and the combination of B2. A mixture of B2 surpassed B1, B3, B4, and B5 by 2.40, 18.56, 32.93, and 49.70% for water productivity of dry yield, respectively.

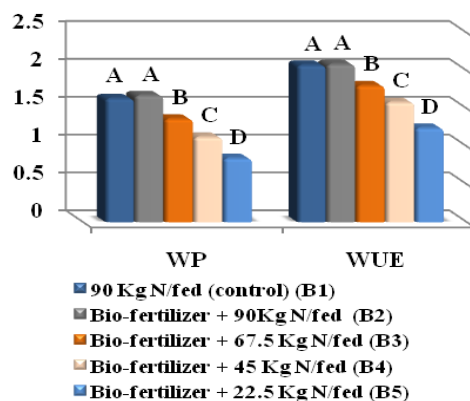


Fig. 8. Effect of fertilization treatments on water productivity (WP), (Kg m^{-3}) and water use efficiency (WUE), (Kg m^{-3}) for dry yield across combined analysis over two seasons of 2022 and 2023.

The interaction between ridges with B2 resulted in significantly the greatest water productivity of dry yield (Table 7). The improvement of dry yield is due to the increasing of nitrogen levels, which is included in the good root system and its high efficiency in absorbing soil nutrients, and minimizes nutrient loss through leaching (Leslie, 1981).

Table 7. Effect of planting pattern and fertilization treatment interaction on water productivity (WP) and water use efficiency (WUE) for dry yield across combined analysis over two seasons of 2022 and 2023.

Interactions	WP (Kg m^{-3})	WUE (Kg m^{-3})
A1 X B1	1.77	2.28
A1 X B2	1.84	2.31
A1 X B3	1.46	1.96
A1 X B4	1.20	1.68
A1 X B5	0.91	1.34
A2 X B1	1.73	2.08
A2 X B2	1.76	2.08
A2 X B3	1.45	1.81
A2 X B4	1.21	1.63
A2 X B5	0.91	1.26
A3 X B1	1.39	1.86
A3 X B2	1.41	1.84
A3 X B3	1.16	1.63
A3 X B4	0.96	1.44
A3 X B5	0.72	1.13
L.S.D A*B (0.05)	0.06	0.09

A1= Ridges, A2= Raised beds, A3= Drilling, B1=90 Kg N fed^{-1} fertilizer (control), B2= Bio-fertilizer + 90 Kg N fed^{-1} fertilizer, B3= Bio-fertilizer + 67.5 Kg N fed^{-1} fertilizer, B4= Bio-fertilizer + 45 Kg N fed^{-1} fertilizer, B5= Bio-fertilizer + 22.5 Kg N fed^{-1} fertilizer.

Ridges surpassed significantly raised beds and drilling patterns for (WUE) of dry yield by 7.33 and 17.28%, respectively (Fig. 2). The maximum WUE for dry yield was significantly observed by the combination of B2 (Fig. 3). No significant differences were observed for (WUE) between B1

and the combination of B2. Ridges with B2 interaction significantly outperformed the maximum WUE of dry yield without significant interaction between ridges and B1 (Table 7). The rise in (WUE) across different nitrogen levels may be more closely linked to the total dry matter yield obtained by Rostamza *et al.* (2011), Ajeigbe *et al.* (2018), and Nematpour *et al.* (2021).

Conclusion

Generally, the ridge planting pattern significantly increased total dry and protein yields compared to the raised bed and drilling patterns. Among fertilization treatments, the application of B2 (bio-fertilizer + 90 kg N fed⁻¹) significantly enhanced total dry and protein yields over B1, B3, B4, and B5. In terms of water management, the raised bed planting pattern saved approximately 19.49% and 19.55%, while ridges saved 11.43% and 11.23% of applied irrigation water compared to the drilling pattern in the first and second seasons, respectively. These savings are attributed to the higher consumptive use recorded under the drilling pattern. Ridge planting significantly increased water productivity of dry yield by 21.53% over drilling and improved WUE by 7.33% and 17.28% compared to bed and drilling patterns, respectively. Generally, the interaction between ridge planting and B2 produced the tallest plants and the highest total dry and protein yields, as well as WP and WUE values. Therefore, this combination is recommended to be a good practice to save water without yield reduction under water scarcity conditions. These findings underscore the importance of optimizing planting patterns and nitrogen management to improve forage productivity and resource use efficiency under limited water conditions. Further research is recommended to explore diverse planting configurations and innovative agronomic practices to enhance water savings and resilience under future climate change scenarios.

Consent for publication:

All authors declare their consent for publication.

Author contribution:

The manuscript was edited and revised by all authors.

Conflicts of Interest:

The author declares no conflict of interest.

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تعظيم الإنتاجية والجودة وكفاءة استخدام المياه في الدخن الحولي من خلال نظام الزراعة ومعاملات النيتروجين

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أجريت تجربتان حقليتان في مزرعة التجارب بسدس، مركز البحوث الزراعية، بنى سويف، مصر خلال الموسم الصيفي لعامي 2022 و2023 بهدف تقييم ثلاثة أنظمه للزراعة (الزراعة على خطوط والزراعة على مصاطب والزراعة بالتسطير) وخمس معاملات للتسميد النيتروجيني (90 كجم نيتروجين معدني/فدان (كنترول)، وتسميد حيوى +90 كجم نيتروجين/فدان، وتسميد حيوى +67.5 كجم نيتروجين/فدان، وتسميد حيوى +45 كجم نيتروجين/فدان، وتسميد حيوى +22.5 كجم نيتروجين/فدان) لتحسين إنتاجية الدخن العلفى وبعض العلاقات المائية. نفذت التجربة باستخدام تصميم القطاعات كاملة العشوائية بنظام الشرائح المتعامدة في ثلاثة مكررات.

حيث وزعت انظمة الزراعة فى الشرائح الرأسية ووزعت معاملات التسميد في الشرائح الأفقية. أظهرت النتائج أن الزراعة على خطوط حققت زيادة معنوية فى الحاصل الكلى من العلف الجاف بنسبة 10.88 و11.63% وحاصل البروتين الكلى بنسبة 12.65 و12.96% مقارنة بنظامين الزراعة على مصاطب وتسطير على التوالي. علاوة على ذلك، إضافة التسميد الحيوى +90 كجم نيتروجين/فدان أدت إلى زيادة معنوية فى حاصل العلف الجاف الكلى بنسبة 2.25 و18.68 و32.68 و49.50% وحاصل البروتين الكلى بنسبة 4.69 و20.56 و35.16 و52.16% على التوالي مقارنة بمعاملات التسميد الأخرى. كذلك وفرت الزراعة على مصاطب حوالى 19.49 و19.55% ووفرت الزراعة على خطوط حوالى 11.43 و11.23% من مياه الرى مقارنة بالزراعة تسطير فى مواسم 2022 و2023 على التوالي. كما تفوقت الزراعة على خطوط معنوياً عن نظامين الزراعة على مصاطب وتسطير بالنسبة لكفاءة استخدام المياه بنسبة 7.33 و17.28% على التوالي. أعطت الزراعة على خطوط مع إضافة التسميد الحيوى +90 كجم نيتروجين/فدان معنوياً أعلى إنتاجية للمياه وكفاءة استخدام للمياه بالنسبة لحاصل العلف الجاف.