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Research Paper

Optimization of yield and rooting behaviour of pearl millet (*Pennisetum glaucum*) in desert region through land configuration, *Mycorrhiza* and zinc fertilization

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ABSTRACT

Arbuscular *Mycorrhizal* fungi symbiosis holds promise for enhancing soil phosphorus (P) efficiency, providing a sustainable approach to maintain high yields while reducing P applications. These beneficial associations involving *Mycorrhiza* prove particularly valuable in improving zinc uptake in pearl millet (*Pennisetum glaucum* L.), especially in Zn-deficient soils. Roots perform diverse roles, including nutrient and water absorption, fostering symbiotic interactions with rhizospheric microorganisms, anchoring plants in the soil, and serving as storage organs. In the realm of planting techniques, the use of pits facilitates root expansion and nutrient uptake from fixed, saturated zones. In the study of 2020 and 2021 at Swami Keshwanand Rajasthan Agriculture University, Bikaner, we explored the combined effects of planting technique, Zn fertilization, and *Mycorrhiza* on pearl millet's yield attributes and root characteristics, evaluating 24 treatment combinations, including flat bed (S_1), ridge & furrow (S_2) and pit (S_3) planting techniques, *Mycorrhiza* control (M_0) and 8 kg/ha as basal (M_1), and zinc fertilization control (Z_0), 0.5% $ZnSO_4$ in two foliar sprays (Z_1), ZnSO4 @10 kg/ha basal + 0.5% foliar spray (Z_2), and $ZnSO_4$ @ 20 kg/ha basal (Z_3) in split plot design. Our findings revealed that, the pit planting technique, combined with *Mycorrhiza* and zinc sulphate fertilization, significantly increased plant stand (141.2 thousand/ha), root characteristics (Root volume: 42.93 cm^3), and yield attributes (effective tillers: 4.75, grain yield: 3.08 t/ha, and stover yield: 7.14 t/ha) by 12.72, 29.11, 137.53, 95.74 and 39.95% compared to flat bed sowing, respectively. These results underscore the immense potential of pit planting techniques for enhancing pearl millet productivity and quality by promoting robust root system development.

Key words: *Mycorrhiza,* Planting technique, Root parameters, Yield, Zinc

Pearl millet (*Pennisetum glaucum* L.), known as bajri or bajara, is renowned for its resilience to high temperatures and moisture stress, distinguishing it from other cereal crops. It's highly nutritious grain contains 12.4% moisture, 11.6% protein, 3-5% fat, 67% carbohydrates, 1.5-3% fiber, and 2.7% minerals (Sharma and Burark, 2015). This "nutri cereal" is a crucial source of quick sustenance in arid regions, often cultivated by economically disadvantaged farmers with limited access to technology (Ankit *et al.,* 2023). Pearl millet is a highly significant crop, covering approximately 30 million hectares in semi-arid tropical regions, with India and Africa contributing to a substantial 93.2% of global production. India, in particular, dominates this production, with 9.3 million hectares under cultivation and an annual output of 8.3 million tons, averaging 1436 kg per hectare (ICRISAT, 2022). Key pearl millet cultivating states in India include Rajasthan, Uttar Pradesh, Haryana, Gujarat, and Maharashtra. Rajasthan alone covers 4.32 million hectares, yielding 4.53 million tons with productivity of 1049 kg/ha (Anonymous, 2021). Efficient planting techniques are essential for optimizing resource utilization and yield (Bamboriya *et al.,* 2017a), as traditional methods such as broadcasting or row planting often result in low germination due to rapid soil moisture depletion. Pit planting stands out as a method with significant potential to maximize biological yield. Pit planting technology, initially successful in sugarcane cultivation, is being

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explored for various crops, including pearl millet, although further standardization is needed to fully realize its advantages. Traditional planting methods pose challenges to yield improvement. Pit planting has the potential to enhance pearl millet productivity. Additionally, *Mycorrhizal* fungi play a crucial role in nutrient uptake and soil stability, efficiently transporting phosphorus and forming symbiotic relationships with most plant species (Grover *et al.,* 2023). They exchange nutrients like phosphorus and water for carbohydrates, with some plants allocating over 50% of their carbohydrates to these fungi and other microbes. Nasim (2005) found that *Mycorrhizal* fungi-associated roots transport phosphorus over four times faster than non-associated roots. Zinc deficiency in plants, crucial for structural components and enzymatic cofactors, hampers yield and quality (Yogi *et al.,* 2023). Foliar zinc application enhances uptake efficiency, supported by studies (Ning *et al.,* 2009).

MATERIALS AND METHODS

The experiment was conducted at the College of Agriculture in Bikaner during the *kharif* season of 2020 and 2021. Bikaner is located at 28°4'21" North latitude and 73°20'17" East longitude, with an altitude of 235 meters above sea level, falling under Agro-climatic zone XIV (Western Dry Region) of India. In 2020, the temperature ranged from 30.4 to 41.8°C, while in 2021, it ranged from 25.5 to 42.3°C. Relative humidity fluctuated from 19.7 to 91.9% in 2020 and 32.4 to 93.6% in 2021. Rainfall during the *Kharif* seasons was 287.4 mm in 2020 and 246 mm in 2021, with 14 and 15 rainy days, respectively. Evaporation from an open pan evaporimeter Class A was 126.8 mm in 2020 and 202.2 mm in 2021 during the crop growing period. Bright sunshine hours ranged from 4.0 to 9.9 and 3.4 to 10.4 hours, with wind velocities of 2.8 to 12.7 and 2.8 to 17.9 km/hr in 2020 and 2021, respectively. The potential evapotranspiration (PET) in this region typically ranges from 1500-2000 mm annually. The soil in the experimental field was loamy sand, low in organic carbon and available nitrogen, medium in available phosphorus, and rich in available potassium. It had an alkaline pH and a low electrical conductivity. The experiment followed a Split Plot Design with 24 treatment combinations, replicated thrice, using plot sizes of 3.60 m × 4.50 m. The treatments comprised (A) three sowing methods in the main plot, (B) two *Mycorrhiza* levels in the sub-main plot, and (C) four zinc fertilization practices in the sub-plot, making twenty-four treatment combinations. Pearl millet variety 'MPMH-17' was used, initially sown in a nursery with a seed rate of 2 kg/ha, and then directly sown in the field at a rate of 4 kg/ha. Sowing in flat bed through the "pora" method and transplanting were done on 20 July 2020 and 29 July 2021, respectively. In flat bed seed sowing, spacing between rows and plants (R×P) was maintained at 45 cm × 15 cm, Ridge & furrow at 60 cm × 22.5 cm (R×P), and in pit technique at 60 cm × 45 cm (R×P). Healthy seedlings of approximately three weeks old were transplanted in experimental plots. Well-decomposed FYM (Farm Yard Manure) was applied at 9 t/ha along with fertilizers (60 kg N: 40 kg P: 20 kg K). Half the dose of nitrogen and the full dose of phosphorus and potassium were applied as a basal dose through urea, DAP (Diammonium Phosphate), and MOP (Muriate of Potash) just before sowing/treatment. The remaining half dose of nitrogen through urea was top-dressed in two splits, with the first $1/4^{th}$ at 30 DAS (Days After Sowing) and the remaining $1/4^{th}$ dose at 50 DAS/DAT (Days After Transplanting) with rains/irrigation.

Root dry weight

Root dry weight was observed from taken 5 randomly tagged plant root dug out from each plot followed by washing in water, airdrying and then oven drying. Weight of dry plant root was recorded individually.

Root volume

To assess root volume, well-washed roots from five plants in each plot were placed in a beaker filled with water up to a certain mark. After gently removing the roots from the beaker, the drop in the water level was measured and recorded as root volume in cubic centimetres (cm^3).

Root shoot ratio

The root-to-shoot ratio was determined by separately measuring the dry weights of roots and shoots from five plants in each plot. This ratio was recorded at 60 days after sowing/transplanting (DAS/DAT) stage.

Effective tillers

The number of fully developed ear heads on randomly selected five plants within each plot was counted. The average value of effective tillers per plant was computed as a representation of the total number of effective tillers for each treatment.

Weight of grains per ear head

Grains were separated from total ear heads and manually cleaned. The weight of these grains was recorded in grams (g) per ear head basis. The grain weight of the sample was divided by the total number of ear heads in a lot to calculate yield per plant basis.

Grain and stover yield:

Completely sun-dried ear heads from individual plot areas were weighed separately. After threshing, winnowing, and proper cleaning, the actual grain yield per plot was recorded and converted into grain yield in quintal per hectare (q/ha). The pearl millet stover, obtained after separating ear heads from the whole plant, was sun-dried for 15 days, weighed, and recorded as stover yield/plot, also converted into q/ha basis.

RESULTS AND DISCUSSION

In the study, the pit planting technique demonstrated the highest plant stand at 141.20 thousand plants per hectare, surpassing ridge & furrow planting by 6.25% and flat bed sowing by 12.07%. *Mycorrhiza* application, specifically at 8 kg/ha, significantly increased plant stand by 10.35% compared to the control. Among zinc treatments, ZnSO4 @10 kg/ha basal + 0.5% foliar spray led to the maximum plant population at 137.66 thousand plants per hectare, outperforming control, 0.5% ZnSO4 in two foliar sprays and $ZnSO_4$ @ 20 kg/ha basal by 2.40, 3.27 and 7.50%, respectively (Fig. 1). Optimal planting geometry is crucial for resource efficiency and yield maximization. *Mycorrhiza* enhances root absorption area, while zinc regulates auxin concentration and nitrogen metabolism, improving growth. Zinc application boosts mineral absorption, supported Kumawat *et al.,* (2015) in Fennel (*Foeniculum vulgare Mill*.), in dry lands.

Root parameters were explained in Table 1. Root dry weight was significantly affected by planting method, with pit planting yielding the highest root dry weight (9.80 g/plant) across both years. *Mycorrhiza* application also increased root dry weight by 9.32% in 2020, 24.97% in 2021, and 17.32% on average to over no application. Among zinc treatments, $ZnSO_4$ @10 kg/ha basal + 0.5% foliar spray resulted in the highest root dry weight, surpassing 0.5% $ZnSO_4$ in two foliar sprays and control by 2.06% and 4.07%, respectively, but was closely at par to $ZnSO_4$ @ 20 kg/ha basal in pooled data analysis.

Pit planting exhibited the highest root volume at 42.93 cm^3, significantly surpassing ridge & furrow and flat bed sowing by 11.23% and 29.04%, respectively, in pooled data analysis. *Mycorrhiza* application treatment also increased root volume significantly by 9.26% on average. Among zinc treatments, $ZnSO_4$ @10 kg/ha basal + 0.5% foliar spray resulted in the highest root volume (39.57 cm^3), outperforming other zinc application methods during both years and on average. Pit planting achieved the highest root-shoot ratio (0.322) at 60 DAS/T, significantly surpassing ridge & furrow planting by 11.81% and flat bed sowing by 55.56% on pooled data. *Mycorrhiza* application at 8 kg/ha produced the maximum ratio (0.293), significantly exceeding the control by 16.73% on pooled basis. $ZnSO_4$ @10 kg/ha basal + 0.5% foliar spray treat-

Table: 1. Effect of planting technique, *Mycorrhiza* and zinc fertilization on root dry weight, root volume and root shoot ratio at 60 DAS of pearl millet

Treatment	Root dry weight (g/plant)			Root volume (cm^3)			Root: shoot ratio		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
Sowing method									
S_1	5.97	6.58	6.28	31.77	34.77	33.27	0.217	0.196	0.207
S_2	8.21	9.31	8.76	37.39	39.39	38.39	0.299	0.276	0.288
S_3	9.40	10.20	9.80	42.34	43.53	42.93	0.342	0.303	0.322
SEm±	0.14	0.16	0.11	0.65	0.84	0.54	0.005	0.005	0.001
CD (P=0.05)	0.44	0.51	0.32	2.04	2.65	1.61	0.016	0.015	0.004
Mycorrhiza									
M_0	7.51	7.73	7.62	35.68	37.33	36.51	0.273	0.230	0.251
M_1	8.21	9.66	8.94	38.65	41.13	39.89	0.299	0.287	0.293
SEm±	0.11	0.13	0.09	0.53	0.69	0.44	0.004	0.004	0.001
CD (P=0.05)	0.36	0.41	0.25	1.67	2.16	1.32	0.013	0.012	0.003
Zinc fertilization									
Z_0	7.68	8.52	8.10	35.73	37.79	36.76	0.280	0.253	0.266
Z_1	7.84	8.68	8.26	36.81	38.88	37.84	0.285	0.258	0.272
Z_2	8.01	8.85	8.43	38.54	40.60	39.57	0.292	0.263	0.277
Z_3	7.90	8.74	8.32	37.59	39.66	38.63	0.288	0.259	0.274
SEm±	0.07	0.07	0.05	0.30	0.32	0.22	0.002	0.002	0.002
CD (P=0.05)	0.19	0.20	0.14	0.86	0.93	0.62	0.007	0.006	0.005

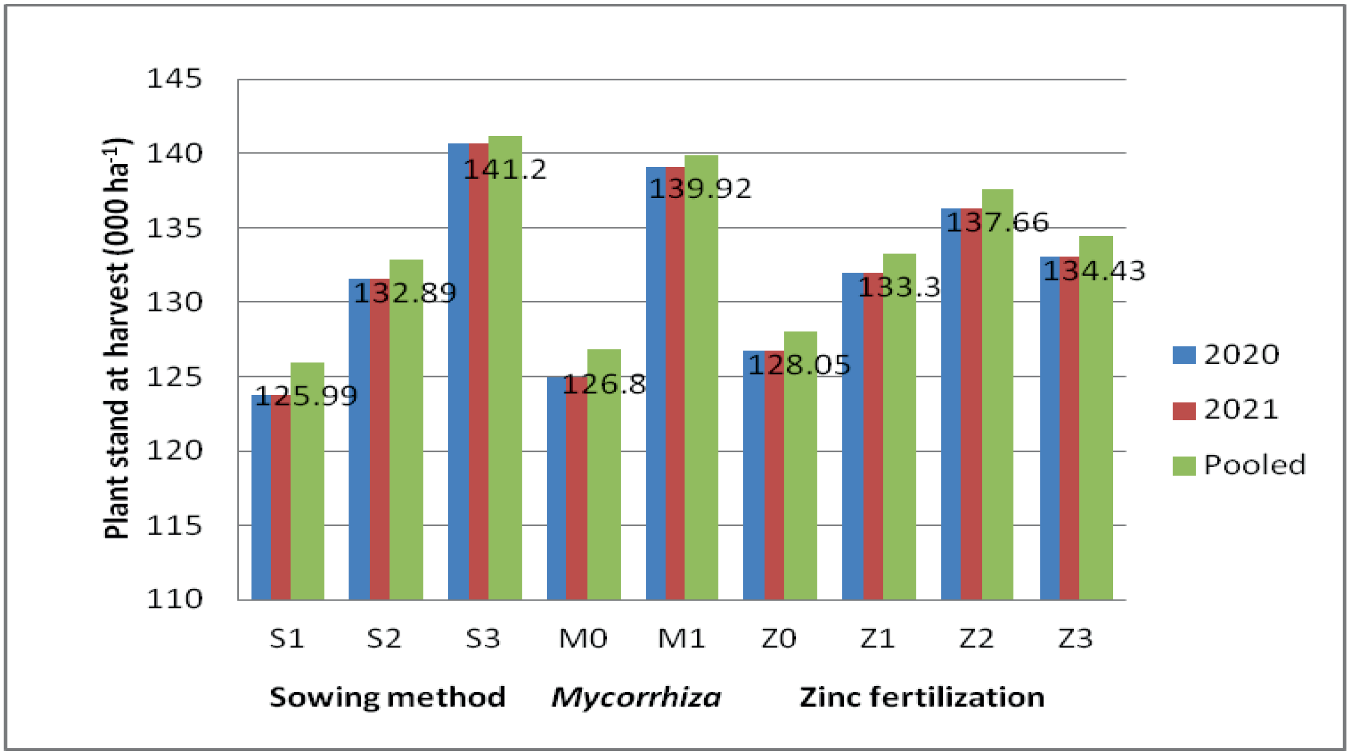

Fig. 1. Effect of planting technique, *Mycorrhiza* and zinc fertilization on plant stand at harvest of pearl millet

ment also resulted in high ratios (0.292, 0.263 & 0.277), significantly better than the no zinc fertilization and on at par with 0.5% $ZnSO_4$ in two foliar sprays and $ZnSO_4$ @ 20 kg/ha basal in 2020, 2021 and pooled data basis. The observed differences in plant growth are likely due to improved soil conditions and a robust root system, which create an environment conducive to nutrient uptake and light interception, thus promoting crop growth, as supported by Gul *et al.,* (2015). In contrast, direct seed sowing/flat bed resulted in lower growth parameters due to reduced light interception, fewer leaves per unit area, and limited soil moisture and nutrients, as reported by Nagarajan *et al.,* (2018). The increase in leaf number, area, root dry weight, and volume led to exponential growth, driven by enhanced solar light interception and increased photosynthesis rates, ultimately boosting plant height and biomass per plant. Pit planting techniques likely facilitated better light penetration to lower leaves due to lower plant density per unit area and efficient utilization of soil moisture and nutrients. Furthermore, the targeted nutrient supply in pit planting extended the roots into a larger soil volume compared to flat bed planting, where organic matter and fertilizer were mixed throughout the entire plot area. Pit planting's proximity of manure (FYM) and nutrients to the root rhizosphere benefited crop growth and mitigated the effects of dry spells, in line with studies by Maqsood *et al.,* (2006).

Pandey *et al.,* (2005) reported at IARI, New Delhi, demonstrating that in rye crops, the inoculation of arbuscular *Mycorrhiza*l fungi (AMF) led to remarkable increases in shoot (1.6-fold), root (1.7-fold), and total plant dry weight (1.8-fold) compared to uninoculated plants. In Kashmir, Mahdi *et al.,* (2011) reported significant improvements in various yield-contributing parameters of fodder maize with zinc application at 10 kg/ha, including plant height, chlorophyll content, the number of functional leaves per plant, stem diameter, leaf area, leaf-to-stem ratio (LSR), and final yield. Dadhich and Gupta (2004) noted that zinc application influenced plant morphology and growth parameters, such as leaves/plant, leaf area, stem girth, and tillers/plant, in pearl millet under the semiarid eastern plain zone of Rajasthan.

The yield attributes were show in Table 2. In 2020, 2021, and on pooled data, the pit planting technique resulted in the highest number of effective tillers per plant (4.75), significantly surpassing ridge and furrow (3.29) and flat bed sowing (2.66) by 44.38% and 137.50%, respectively. Ridge & furrow sowing also outperformed flat bed sowing, with 64.50% higher tiller count. *Mycorrhiza* application yielded the most effective tillers (3.81, 3.92, 3.87), significantly exceeding the control by 39.05%, 34.71%, and 37.23% in 2020, 2021, and on pooled data basis. Among zinc treatments, $ZnSO_4$ @10 kg/ha basal + 0.5% foliar spray had the highest tiller count (3.91), while control had the lowest (2.66), consistent across both years (2020 and 2021). On a pooled basis, pit planting (S_3) exhibited the longest ear head length (24.32 cm), significantly surpassing ridge & furrow and flat bed methods by 10.85% and 22.52%, respectively. In 2020, 2021, and on pooled data, *Mycorrhiza* application treatment produced the longest ear head length (22.96, 24.21, and 23.58 cm), significantly exceeding the control by 16.14, 14.20 and 15.08%, respectively. Among zinc treatments, ZnSO4 @10 kg/ha basal + 0.5% foliar spray treatment resulted in the maximum ear head length during both years and on a pooled basis (24.25 cm). Maximum grain weight per ear head was achieved in 2020 and on a pooled basis with pit planting (29.97 g and 30.57 g), significantly surpassing ridge and furrow and flat bed methods. In 2021, pit technique (31.17 g) significantly outperformed flat bed (21.51 g) by 44.90% and was similar to ridge and furrow (27.99 g). *Mycorrhiza* application treatment resulted in significantly higher grain weight per ear head (28.03 g, 28.86 g, and 28.44 g) compared to the control. Zinc application, especially $ZnSO_4$ @10 kg/ha basal + 0.5% foliar spray, consistently yielded higher grain weight/ear head during both years and in pooled analysis, remaining statistically on at par with $ZnSO_4$ @ 20 kg/ha basal. The significant improvements in yield-contributing characteristics with the pit planting technique can be attributed to its ability to maintain favorable soil moisture conditions for an extended period, promoting robust root growth. Enhanced root development allows better nutrient absorption through localized placement in pits, and improved air circulation and light interception create a conducive environment for plant growth and development, increasing leaf area for photosynthesis. Factors like adequate moisture, nutrient supply, aeration, and light penetration to lower leaves, combined with ideal plant architecture, contribute to efficient photosynthesis and resource distribution to developing sinks. Pit planting provides this environment, resulting in higher yield-contributing parameters and ultimately greater pearl millet yields. Ehsanullah *et al.,* (2017) also reported increased yield attributes in cotton with pit planting, consistent with findings from other researchers such as Amede and Taboge (2007). The pit technique's success may be attributed to reduced competition for water, nutrients, and solar radiation among individual or grouped plants within each pit. *Mycorrhiza* plays a crucial role in the growth of plants by surrounding and even entering their roots, providing essential nutrients like phosphorus and nitrogen, as well as water, in exchange for carbohydrates, typically sugars. Some plants allocate more than half of their carbohydrates to these fungi, recognizing their vital contributions to soil health. *Mycorrhiza* creates optimized growing conditions, improves soil characteris-

Table 2. Effect of planting technique, *Mycorrhiza* and zinc fertilization on total tillers, effective tillers and ear head length at maturity of pearl millet

Treatment	Effective tillers (Nos/ plant)			Ear head length (cm)			Grain weight/ear head (g)		
	2020	2021	Pooled	2020	2021	Pooled	2020	2021	Pooled
Sowing method									
S_1	1.96	2.03	2.00	18.81	20.89	19.85	20.21	21.51	20.86
S_2	3.23	3.36	3.29	21.46	22.41	21.94	26.79	27.99	27.39
S_3	4.64	4.86	4.75	23.82	24.82	24.32	29.97	31.17	30.57
SEm±	0.11	0.14	0.09	0.80	0.84	0.63	0.95	1.08	0.78
CD (P=0.05)	0.36	0.45	0.27	2.51	2.63	1.83	2.99	3.40	2.28
Mycorrhiza									
M_0	2.74	2.91	2.82	19.77	21.20	20.49	23.28	24.92	24.10
M_1	3.81	3.92	3.87	22.96	24.21	23.58	28.03	28.86	28.44
SEm±	0.09	0.12	0.08	0.65	0.68	0.51	0.78	0.88	0.64
CD (P=0.05)	0.29	0.37	0.23	2.05	2.15	1.49	2.45	2.77	1.86
Zinc fertilization									
Z_0	2.60	2.73	2.66	19.48	20.82	20.15	22.46	23.71	23.08
Z_1	3.15	3.29	3.22	20.80	22.14	21.47	24.40	25.59	24.99
Z_2	3.83	3.98	3.91	23.58	24.92	24.25	28.27	29.51	28.89
Z_3	3.52	3.66	3.59	21.61	22.95	22.28	27.50	28.75	28.13
SEm±	0.05	0.08	0.04	0.25	0.24	0.17	0.44	0.48	0.33
CD (P=0.05)	0.14	0.23	0.12	0.72	0.69	0.47	1.26	1.38	0.92

tics and quality, and enhances water availability. Poonia *et al.,* (2022) observed the highest yield attributes and yields in groundnut with the application of RDF + PSB @ 2.5 kg/ha+ AMF @ 4 kg/ha. Kanta (2019) reported increased effective tillers, ear head length, and grain weight per ear head in pearl millet with *Mycorrhiza* @ 12 kg/ha. Balanced nutrient availability from soil via inorganic sources enhances tiller production, chlorophyll content, and leaf expansion, providing more sites for photosynthesis. Choudhary *et al.,* (2014) found that Zn application to pearl millet increased ear head parameters significantly.

Prasad *et al.,* (2014) reported that N and Zn application in pearl millet increased tillers, panicles, panicle length, girth, and test weight. Kumar *et al.,* (2016) found that foliar $ZnSO_4$ application improved ear length and test weight. Khan *et al.,* (2008) noted that Zn application increased effective tillers in pearl millet. These studies collectively highlight the importance of *Mycorrhiza* and zinc in enhancing crop growth and yield attributes.

In the study, the pit planting technique resulted in the highest grain yield, reaching 3.08 t/ha, which was significantly greater by 27.91% and 95.73% compared to ridge & furrow and flat bed methods, respectively (Table 3). *Mycorrhiza* treatment at 8 kg/ha also led to a significant increase in grain yield (2.56 t/ha) compared to the control for both years and pooled analysis, with a 19.31% higher yield on average. Among zinc treatments, ZnSO4 @ 10 kg/ha basal + 0.5% spray produced the highest grain yield (2.76 t/ha), surpassing ZnSO4 @ 20 kg/ha basal, 0.5% ZnSO4 in two foliar sprays and control by 4.46, 22.05, and 59.47%, respectively, on a pooled basis.

Regarding stover yield, pit technique had the highest yield (7.14 t/ha), significantly exceeding Ridge & furrow and flat bed sowing by 12.75% and 39.95%, respectively in Table 3. Ridge and furrow planting also outperformed flat bed sowing by 24.12% on average. *Mycorrhiza* treatment at 8 kg/ha resulted in the highest stover yield during 2020, 2021, and on a pooled basis, with increases of 23.25%, 12.93%, and 17.68%, respectively, compared to the control. Among zinc treatments, $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray and $ZnSO_4$ @ 20 kg/ha basal had the highest stover yields, with control having the lowest on a pooled basis.

The significant improvement in yield-contributing factors observed under the pit planting technique can be attributed to several key factors. Firstly, the pit technique helps maintain favorable soil moisture conditions throughout the crop growing period, ensuring a longer duration of optimal moisture availability. This, in turn, promotes robust root growth, enabling the plant to absorb more nutrients efficiently due to their localized placement in the pits, aligned with specific treatment requirements.

Furthermore, the air circulation around each pit and the enhanced light interception provide a conducive

Table 3. Effect of planting technique, *Mycorrhiza* and zinc fertilization on grain and stover yield of pearl millet

Treatment	Grain yield (t/ha)			Stover yield (t/ha)		
	2020	2021	Pooled	2020	2021	Pooled
Sowing method						
S_1	1.48	1.67	1.57	4.60	5.61	5.10
S_2	2.10	2.71	2.40	6.10	6.57	6.34
S_3	2.72	3.43	3.08	6.82	7.46	7.14
SEm±	0.64	0.90	0.60	1.24	1.48	1.02
CD (P=0.05)	2.01	2.83	1.75	3.90	4.66	3.03
Mycorrhiza						
M_0	1.89	2.40	2.14	5.23	6.15	5.69
M_1	2.31	2.81	2.56	6.45	6.95	6.70
SEm±	0.52	0.73	0.49	1.01	1.21	0.83
CD (P=0.05)	1.64	2.31	1.44	3.19	3.80	2.46
Zinc fertilization						
Z_0	1.48	1.99	1.73	5.28	5.99	5.64
Z_1	2.01	2.52	2.26	5.69	6.40	6.05
Z_2	2.51	3.01	2.76	6.26	6.98	6.62
Z_3	2.39	2.90	2.64	6.12	6.83	6.47
SEm±	0.24	0.37	0.22	1.03	1.02	0.73
CD (P=0.05)	0.68	1.06	0.62	2.97	2.92	2.05

Table 4. Interaction effect of planting technique and zinc fertilization management on effective tiller at maturity of pearl millet

Treatment	Zinc level											
	2020				2021				Pooled			
Sowing method	Z_0	Z_1	Z_2	Z_3	Z_0	Z_1	Z_2	Z_3	Z_0	Z_1	Z_2	Z_3
S_1	1.13	2.00	2.59	2.13	1.20	2.07	2.66	2.20	1.16	2.03	2.63	2.17
S_2	2.34	3.16	3.83	3.58	2.47	3.29	3.96	3.71	2.41	3.22	3.90	3.64
S_3	4.31	4.32	5.07	4.85	4.52	4.53	5.32	5.07	4.41	4.42	5.19	4.96
S × Z (S at same level of Z)												
SEm±		0.11			0.14				0.09			
CD (P=0.05)		0.36			0.45				0.27			
Z × S (Z at same/ difference level of S)												
SEm±		0.10			0.13				0.08			
CD (P=0.05)		0.31			0.41				0.24			

environment for overall plant growth and development. Increased leaf area resulting from these conditions creates more sites for photosynthesis, ultimately leading to greater assimilation of carbon compounds and improved dry matter production, contributing to higher biological yield.

Studies by Gul *et al.,* (2015) in maize has reported similar trends, where ridge sowing or favorable soil conditions created by ridges resulted in better root development, increased moisture and nutrient uptake, larger leaf area index (LAI), and enhanced dry matter production, all contributing to higher biological yield. Kumar *et al.,* (2022) in pearl millet reported that transplanting of 4 plants/pit produced maximum grain yield (3.08 t/ha) and stover yield (6.60 t/ha) which was significantly higher over ridge and furrow and direct seeded treatment in arid region of Rajasthan.

Incorporating *Mycorrhiza* into the soil also plays a significant role in improving yield attributes and grain production. *Mycorrhiza* associations aid in nutrient uptake, especially phosphorus, and enhance photosynthesis, ultimately improving yield attributes such as effective tillers per plant, ear head length, and grain weight per ear head. This leads to increased ear head and grain yield. Kanta (2019) concluded that significantly higher grain yield and stover yield with *Mycorrhiza* @ 12 kg ha as compared to control in pearl millet.

Zinc application has shown positive effects on pearl millet and other crops, promoting growth and nutrient uptake. Kumar *et al.,* (2018) reported increased rice yields with foliar zinc application.

Effective tiller (S × Z)

The highest number of effective tillers per plant was consistently observed with the pit planting technique (S_3) across all fertilizer levels. Additionally, the combination of pit technique and $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray treatment resulted in significantly higher effective tillers compared to other combinations, closely followed by the combination of pit technique and $ZnSO_4$ @ 20 kg/ha basal treatment (Table 4). This approach involved sowing three-week-old seedlings in pits, which enhanced moisture retention and nutrient uptake, leading to improved yield parameters. These findings align with a study by Ehsanullah *et al.,* (2017) in cotton, which also reported increased yield attributes under pit planting conditions.

Grain yield (M ×Z)

The highest grain yield (2.93 q/ha) was achieved by the treatment combination of *Mycorrhiza* application and $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray which was

Table 5. Interaction effect of Mycorrhiza and zinc fertilization on grain yield of pearl millet on pooled basis

Treatment	Zinc level			
Mycorrhiza	Z_0	Z_1	Z_2	Z_3
M_0	1.47	2.08	2.59	2.42
M_1	1.99	2.44	2.93	2.86
M×Z (M at same level of Z)				
SEm±		0.34		
CD (P=0.05)		0.99		
Z×M (Z at same/ difference level of M)				
SEm±		0.48		
CD (P=0.05)		1.40		

statistically comparable to the *Mycorrhiza* application X $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray treatment (2.86 q/ha). These combinations outperformed the other *Mycorrhiza* and zinc treatments (Table 5). This aligns with a study by Ahmed *et al.,* (2019) in barley, which found increased grain yield and starch content with both *Mycorrhiza* and zinc fertilization.Top of Form

In conclusion, pit planting outperformed over ridge & furrow and flat bed methods, yielding the highest grain production, plant stand, root growth, and yield-related factors in pearl millet. This success stems from its capacity to maintain optimal moisture levels, stimulate robust root development, and create a conducive growth environment. *Mycorrhiza* application, notably at 8 kg/ha, and zinc fertilization, particularly with $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray, significantly boosted grain yield and yield-related traits. *Mycorrhiza* enhanced nutrient uptake and photosynthesis, resulting in more effective tillers, longer ear heads, and heavier grain per ear head. Zinc application positively influenced plant growth parameters.

The combined use of *Mycorrhiza* application and $ZnSO_4$ @ 10 kg/ha basal + 0.5% foliar spray achieved the highest grain production, emphasizing their synergistic role in pearl millet cultivation. This study underscores the importance of selecting suitable planting techniques and optimizing nutrient management to enhance pearl millet yields, ultimately improving food security in arid regions.

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