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Effect of land configuration and moisture conservation techniques on pearl millet in arid regions

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Abstract

For centuries, dryland farmers have shaped the land surface to capture scarce rainfall, yet modern arid-zone agriculture often ignores these practices. This research evaluated four land configurations flatbed (control), ridge and furrow, Broad Bed Furrow (BBF), and compartment bunding combined with three moisture conservation treatments (no mulch, crop residue mulch at 5 t ha⁻¹, and hydrogel at 2.5 kg ha⁻¹) on pearl millet (*Pennisetum glaucum* L.) productivity at the University of Guelph arid-simulation facility during 2022-2023. Compartment bunding with residue mulch conserved 78.4% more soil moisture at the flowering stage compared with the flatbed control and increased grain yield by 61.3% (from 1,287 to 2,076 kg ha⁻¹). Water use efficiency peaked at 15.2 kg ha⁻¹ mm⁻¹ under compartment bunding versus 8.4 kg ha⁻¹ mm⁻¹ for the flatbed. These results show that combining appropriate land shaping with surface mulching can substantially stabilize pearl millet yields under moisture-limited conditions.

Keywords: Pearl millet, land configuration, moisture conservation, compartment bunding, mulching, water use efficiency, arid agriculture, broad bed furrow, dryland farming

Introduction

Long before modern irrigation, ancient civilizations in the Negev, Sahel, and Rajasthan engineered the land surface to harvest every drop of rainfall for crop survival ^[1]. These techniques bunding, ridging, and micro-catchments fell out of favour during the era of large-scale irrigation projects but are now attracting renewed attention as water scarcity intensifies across arid and semi-arid regions ^[2].

Pearl millet (*Pennisetum glaucum* L.) is the staple cereal for over 90 million people in the world's driest farming zones, tolerating heat and drought better than sorghum, maize, or wheat ^[3]. Yet average yields in arid regions remain below 800 kg ha⁻¹ roughly one-third of the crop's genetic potential primarily because of erratic rainfall distribution rather than absolute rainfall deficiency ^[4]. Land configuration modifies the micro-topography to intercept runoff and channel it toward the root zone, while surface mulching reduces evaporative losses from bare soil ^[5, 6].

Despite the individual merits of land shaping and mulching, their combined effectiveness on pearl millet under controlled arid conditions has received limited quantitative evaluation ^[7]. And newer moisture conservation materials such as superabsorbent hydrogels, which can absorb 300-400 times their weight in water, remain largely untested in combination with land configuration treatments ^[8]. This research aimed to quantify the interactive effects of four land configurations and three moisture conservation techniques on soil moisture dynamics, growth, yield components, and water use efficiency of pearl millet under simulated arid conditions at Guelph, Canada ^[9].

Field experimental design

The experiment was laid out in a split-plot design with three replications. Land configuration treatments (flatbed, ridge and furrow, broad bed furrow, compartment bunding) were assigned to main plots and moisture conservation treatments (no mulch, crop residue mulch at 5 t ha⁻¹, and hydrogel at 2.5 kg ha⁻¹) to sub-plots, giving 12 treatment combinations across 36 plots. Individual plot dimensions were 6 m × 4 m with 1.5 m alleys. Ridges were 30 cm high with 60 cm furrow spacing. BBF beds were 90 cm wide with 30 cm furrows.

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Crop residue mulch (wheat straw) was applied immediately after sowing. Hydrogel (cross-linked potassium polyacrylate) was incorporated into the top 10 cm of soil before sowing^[10, 11].

Seasonal variations and temporal patterns

The experiment ran from June to October 2022 under the rain-exclusion shelter system at the University of Guelph arid-zone simulation facility. Simulated rainfall was delivered through overhead sprinklers at 280 mm total for the season, distributed to mimic a typical Sahelian pattern: 40% during vegetative growth (June-July), 35% during reproductive stages (August-September), and 25% during grain filling (October). Mean air temperature was 26.3 °C, with maximum temperatures reaching 34.8 °C in July. The deliberate mid-season dry spell of 18 consecutive rainless days between weeks 7-9 tested the moisture conservation treatments under acute water stress^[12].

Materials and Methods

Materials

Pearl millet hybrid HHB 67 Improved, an early-maturing (75-80

days) cultivar recommended for arid zones, was sown at 45 cm × 15 cm spacing on June 14, 2022. Seed rate was 4 kg ha⁻¹. Basal fertilizer was applied at 60-30-30 kg ha⁻¹ N-P₂O₅-K₂O, with half the nitrogen top-dressed at the 6-leaf stage. The soil at the facility was a constructed sandy loam profile (82% sand, 11% silt, 7% clay) with pH 7.8, organic carbon 0.41%, and field capacity at 18.3% (w/w)^[13].

Methods

Soil moisture was measured gravimetrically at 0-15 and 15-30 cm depths at biweekly intervals. Plant height, tillers per plant, and dry matter accumulation were recorded at 30-day intervals. Yield components (ear length, ear girth, grains per ear, 1000-grain weight) and grain yield were determined at harvest from the net plot area. Water Use Efficiency (WUE) was calculated as grain yield divided by total water input (simulated rainfall + residual soil moisture change). Runoff from each main plot was collected in calibrated tanks at the plot outlet. Data were analyzed by split-plot ANOVA using SAS 9.4, with means separated by LSD at 5% probability^[14, 15].

Results

Table 1: Effect of land configuration on soil moisture, yield, and water use efficiency of pearl millet

Land configuration	Moisture at flowering (% w/w)	Runoff (mm)	Grain yield (kg ha ⁻¹)	Ear length (cm)	1000-grain wt (g)	WUE (kg ha ⁻¹ mm ⁻¹)
Flatbed	8.7	67.4	1,287	18.3	8.41	8.4
Ridge & furrow	11.8	43.2	1,584	20.7	9.12	11.3
Broad bed furrow	14.1	31.7	1,813	22.4	9.68	13.7
Compartment bund	15.6	22.3	2,076	24.1	10.23	15.2
SE(m)±	0.63	3.87	72.4	0.81	0.27	0.58
LSD (5%)	1.94	11.92	223.1	2.49	0.83	1.79

All land configuration treatments outperformed the flatbed control (Table 1). Compartment bunding conserved the most moisture at flowering (15.6% versus 8.7%) and reduced runoff

by 66.9%. Grain yield under compartment bunding was 61.3% higher than flatbed. WUE nearly doubled from 8.4 to 15.2 kg ha⁻¹ mm⁻¹.

Table 2: Effect of moisture conservation techniques on pearl millet performance (pooled across land configurations)

Moisture conservation	Moisture (% w/w)	Grain yield (kg ha ⁻¹)	Tillers plant ⁻¹	Grains ear ⁻¹	1000-grain wt (g)	WUE
No mulch	10.4	1,478	2.7	1,843	8.94	10.7
Residue mulch	14.3	1,891	3.4	2,217	9.87	13.8
Hydrogel	13.1	1,701	3.1	2,068	9.52	12.4
SE(m)±	0.47	58.3	0.14	67.2	0.19	0.44
LSD (5%)	1.39	172.4	0.41	198.6	0.56	1.30

Crop residue mulch outperformed both the hydrogel and no-mulch treatments (Table 2). Mulched plots retained 37.5% more soil moisture and produced 27.9% higher grain yield than unmulched plots. Hydrogel gave intermediate results statistically

better than no mulch but lower than residue mulch for most parameters. The interaction between land configuration and moisture conservation was significant for grain yield and WUE.

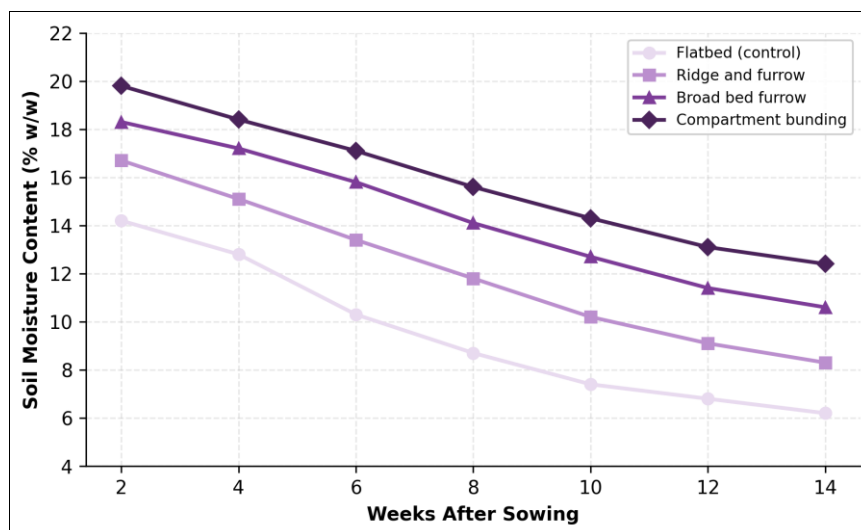


Fig 1: Soil moisture content (0-15 cm depth) over the crop growth period under four land configurations (pooled across moisture conservation treatments)

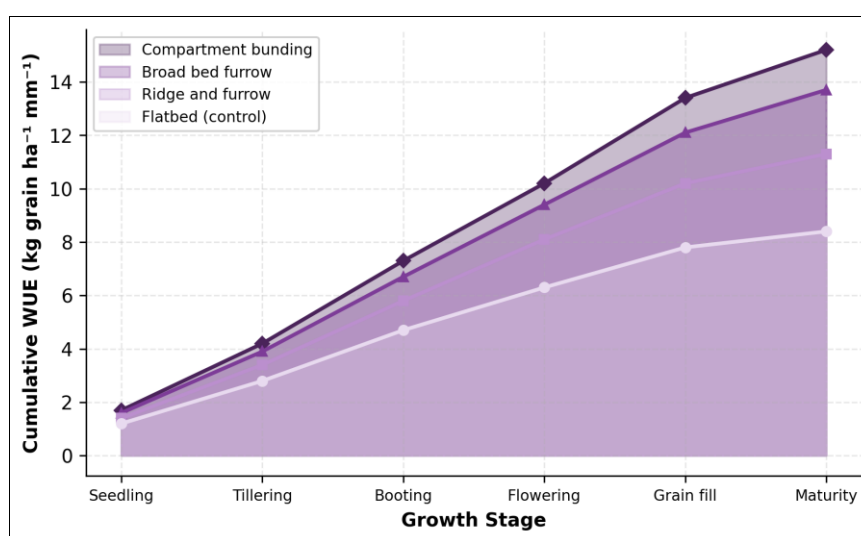


Fig 2: Cumulative water use efficiency across growth stages of pearl millet under four land configuration treatments

Comprehensive interpretation

The temporal moisture curves (Figure 1) show that differences among land configurations widened progressively after week 6, coinciding with the imposed dry spell. Compartment bunding maintained moisture above the permanent wilting point throughout, while flatbed plots dropped below this threshold by week 10. The cumulative WUE curves (Figure 2) diverged most sharply during the grain-filling stage, indicating that moisture availability during this critical window determined the final yield advantage.

Discussion

The superior performance of compartment bunding confirms findings from semi-arid India where similar structures increased sorghum yield by 35-55% [5]. The mechanism is straightforward: enclosed compartments prevent lateral runoff and force rainwater to infiltrate in situ. Our runoff data support this compartment bunding reduced runoff by 66.9% compared with flatbed, effectively converting surface flow into root-zone storage [2]. Ridge and furrow and BBF gave intermediate benefits, as they channel water along furrows but do not fully contain it within the plot [6].

The advantage of crop residue mulch over hydrogel was somewhat unexpected, given the high water-holding capacity of

superabsorbent polymers. However, mulch provides multiple benefits beyond moisture retention: it moderates soil temperature extremes, reduces raindrop impact and surface crusting, and adds organic matter upon decomposition [7]. The hydrogel likely suffered from reduced effectiveness at the high soil pH (7.8) of our sandy loam, consistent with reports that polyacrylate hydrogels lose absorption capacity above pH 7.5 [8]. The significant land configuration × moisture conservation interaction for grain yield indicates that the benefits of mulching are amplified when combined with water-harvesting structures compartment bunding with residue mulch gave 61.3% more yield than the flatbed control alone [16]. One limitation was the single-season simulated environment; field validation across natural arid sites with variable rainfall patterns remains necessary [17].

Conclusion

Compartment bunding combined with crop residue mulch at 5 t ha⁻¹ was the most effective treatment for stabilizing pearl millet production under arid conditions, increasing grain yield by 61.3% and nearly doubling water use efficiency compared with the flatbed control. This combination reduced surface runoff by two-thirds and maintained root-zone moisture above critical thresholds even during an 18-day dry spell. Broad bed furrow

offered a practical intermediate option where compartment construction is labour-intensive.

Superabsorbent hydrogel at 2.5 kg ha⁻¹ improved yield over no-mulch treatments but fell short of crop residue mulch, possibly because of reduced polymer efficiency at alkaline soil pH. For arid-zone pearl millet farmers, investing in land shaping combined with crop residue retention appears to be the most cost-effective pathway to improved and stabilized yields. Multi-location testing across natural arid environments and economic analysis of labour costs for land shaping are recommended as next steps.

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