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Effect of planting density on grain yield and related traits in pearl millet varieties

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Abstract

Pearl millet (*Pennisetum glaucum* [L.] R. Br.) is the principal cereal crop and staple food of Niger, contributing about 73% of national cereal production. Despite its crucial importance, yields on farmers' fields remain well below attainable levels, due to lack of agricultural practice management and limited access to high-yielding cultivars and other stresses. This study evaluated the effects of seven planting densities on grain yield and related agronomic traits in four improved pearl millet varieties (CT6, HKP, Moro, and SOSAT-C88) over three consecutive rainy seasons (2020–2022) at the INRAN experimental field in Maradi, Niger. A split-plot design was used, with planting density as the main plot and variety as the subplot. Planting density significantly affected grain yield, seed weight, stem yield, and downy mildew incidence across all years ($P \leq 0.01$). Grain yield increased progressively from D1 (0.8 m × 0.8 m, 31,250 plants ha^{-1}) to D7 (1.0 m × 0.2 m, 100,000 plants ha^{-1}) in three of the four varieties, with no yield decline at the highest density. SOSAT-C88 at D7 recorded the highest grain yield across the study (2,177 kg ha^{-1} pooled; approximately 3,000 kg ha^{-1} in 2021). Downy mildew incidence peaked at D4 in all varieties, while the highest densities (D6–D7) were associated with the lowest disease levels and the highest yields simultaneously. The absence of significant variety × density interactions for yield traits confirms that density responses were consistent across varieties, simplifying agronomic recommendations. SOSAT-C88 planted at D7 is recommended as the optimal variety–density combination for maximizing pearl millet grain yield under Sahelian conditions in Niger.

1 Introduction

Pearl millet is one of the most important cereal crops in the semi-arid tropical regions of Africa and Asia, where it serves as a primary source of food, feed, and income for millions of smallholder farmers [1]. The Republic of Niger is Africa's largest producer of pearl millet, with an average annual production of approximately 3.3 million tons, contributing nearly 73% of the nation's total cereal production [2]. Pearl millet also serves as the principal staple food for a large share of Niger's population [3]. Its remarkable adaptability to harsh environmental conditions, particularly drought, high temperatures, and low soil fertility, makes it a vital crop for sustaining food security in the arid and semi-arid regions of Niger [4, 5]. In smallholder farming systems, pearl millet is traditionally cultivated at relatively low plant densities [6]. In contrast, crops such as maize have experienced a gradual increase in planting density over the years, which has significantly contributed to yield improvements, even though enhanced density tolerance was not initially a specific breeding objective [7–10]. This was made possible in part by the development of varieties with improved lodging resistance and more compact canopy architecture, allowing plants to tolerate closer spacing without excessive inter-plant competition. Comparable increases in planting density have not been widely adopted in pearl millet production system. However, the growing demand for both grain and fodder, coupled with increasing pressure on global cereal supplies, highlights the need for sustainable intensification of pearl millet production systems. Grain yield in cereal crops generally increases with plant density up to an optimum threshold, beyond which excessive competition among plants can reduce productivity [11]. Nevertheless, improved cultivars often exhibit greater tolerance to higher plant densities, even under limited nitrogen availability [12]. In Niger, pearl millet farmers

commonly plant at densities lower than the nationally recommended rate of 10,000 planting hills per hectare, as a strategy to reduce the risk of moisture stress. Average farmer-managed fields contain approximately 5,200 planting hills per hectare, with significant variation among farms [13–15]. Recent studies have demonstrated that increasing plant density can significantly improve grain yield and total biomass production in pearl millet, suggesting considerable potential for enhancing productivity through optimized planting arrangements [16, 17]. Despite growing evidence for the benefits of increased planting density, information on the optimal plant population for improved pearl millet varieties under the specific agro-ecological conditions of Niger remains limited. Most available studies have been conducted in other regions or under different environmental contexts, making it difficult to directly translate their findings to Nigerien production systems [17, 18]. Furthermore, the interaction between genotype and planting density a critical factor in determining yield response has received relatively little attention in pearl millet research compared to other cereals such as maize and sorghum [19, 20]. Understanding how different pearl millet varieties respond to varying plant densities is therefore essential for developing agronomic recommendations that are both genotype-specific and location-appropriate. Yield improvement in pearl millet is not solely a function of plant density but is also mediated through several related morphological and physiological traits, including panicle length, panicle weight, number of tillers, thousand-grain weight, harvest index, and plant height [21, 22]. At high planting densities, inter-plant competition for light, water, and nutrients can alter the expression of these traits, with consequences for overall productivity [21]. Identifying which yield components are most sensitive to density changes and which varieties are best able to maintain favorable trait expression under higher populations is therefore of both practical and scientific value [23, 24]. Although several improved pearl millet varieties have been released in Niger over the past few decades, adoption remains low, partly due to a lack of site-specific agronomic management recommendations tailored to local Sahelian conditions and soil fertility constraints[3,25] Farmers' reluctance to increase planting density is further compounded by the uncertainty of rainfall patterns and the perception that denser stands are more susceptible to drought-induced crop failure [26]. However, improved varieties are generally characterized by shorter crop cycles, greater yield potential, and enhanced stress tolerance compared to traditional landraces, which may confer greater responsiveness to optimized agronomic practices, including higher plant populations [1, 27]. Evaluating the performance of these varieties across a range of planting densities could therefore provide the empirical basis needed to update and refine national agronomic recommendations. It is therefore hypothesized that current planting densities in Niger are below the agronomic optimum, and that pearl millet varieties may differ in their yield responses to increased plant density, offering opportunities for both agronomic improvement and targeted breeding. Given this context, the present study was conducted to evaluate the effect of planting density on grain yield and related agronomic traits in selected pearl millet varieties under rainfed conditions in the Sahelian zone of Niger. Specifically, the study aimed to: (i) assess the yield and yield-related trait responses of pearl millet varieties to varying planting densities; (ii) identify the optimum planting density for maximum grain yield among the tested varieties; and (iii) determine genotype × planting density interactions to identify varieties with superior performance and density tolerance.

2 Materials and Methods

2.1 Experimental site and design

Field experiments were conducted during three consecutive rainy seasons (2020, 2021, and 2022) at the Regional Center of Agriculture Research (CERRA) Maradi experimental station of the National Institut of Agronomic Research of Niger (INRAN), Maradi (13°27'43" N, 7°06'33" E; 350 m a.s.l.). The site is characterized by a Sudanian–Sahelian climate with a single rainy season extending from June to September. Average annual rainfall is approximately 500 mm, while mean annual temperatures range from 21.4°C to 34.3°C. The soil is classified as sandy loam, representative of the major pearl millet production zones of southern Niger. Rainfall distribution during the 2020, 2021, and 2022 growing seasons is presented in Fig. 1. Four improved pearl millet varieties widely cultivated in Niger were used in this study: HKP, Moro and CT6 (INRAN-released), and SOSAT-C88 (ICRISAT). Their principal agronomic characteristics are summarized **in** Table 1a. The experiment was laid out in a split-plot design with three replications. Planting density was assigned to the main plots, while varieties were allocated to the subplots. Seven planting-density levels were evaluated using different combinations of row and hill spacing **(**Table 1b**).** A 1.6-m alley was maintained between replications to minimize border effects.

Table 1
a. Agronomic characteristics of the four pearl millet varieties used in the study.

Characteristic	HKP	Moro	CT6	SOSAT-C88
Developer / Release year	INRAN (1978)	INRAN (1985)	INRAN (1996)	ICRISAT (1978)
Maturity period (days)	75–90	80–90	80–84	85–90
Tillering ability	Moderate	Good	Moderate	Moderate
Panicle length	Intermediate	Short	Intermediate	Short
Plant height (m)	1.9–2.0	1.5–1.6	1.8–2.0	2
Yield potential (t ha^{-1})	1.5–2.5	2.5	1.0–1.5	2.5
Notable characteristics	Slightly photoperiod-sensitive; susceptible to smut and downy mildew; tolerant to ear head miner.	Excellent panicle compactness; susceptible to smut and downy mildew.	Medium panicle compactness.	Susceptible to Striga, ear head miner and stem borers; resistant to downy mildiou and ergot; tolerant to lodging and drought.

Table 1
b. Planting density treatments applied in the study.

Density	Row spacing (m)	Hill spacing (m)	Area hill^{-1} (m^2)	Hills ha^{-1}	Plants ha^{-1} (2 plants hill^{-1})
D1	0.8	0.8	0.64	15,625	31,250
D2	0.8	0.4	0.32	31,250	62,500
D3	0.8	0.2	0.16	62,500	125,000
D4	1	1	1	10,000	20,000
D5	1	0.5	0.5	20,000	40,000
D6	1	0.25	0.25	40,000	80,000
D7	1	0.2	0.2	50,000	100,000

¹ Hills ha^{-1} = 10,000 ÷ (row spacing × hill spacing); plants ha^{-1} assumes 2 plants hill^{-1} after thinning.

Pearl millet was sown manually using row markers maintaining the prescribed row and hill spacings. Seedlings were thinned at the first weeding operation (approximately two-three weeks after sowing) to two plants per hill. Two manual weedings were carried out per season, the second at stem elongation. Fertilizer was applied using the micro-dosing technique: diammonium phosphate (DAP) at sowing at 2 g hill^{-1}, NPK (15–15–15) at tillering, and urea (46% N) at stem elongation, each at 6 g hill^{-1}.

2.2 Measurements

The following traits were recorded for each plot at the appropriate growth stages: days to 50% flowering (FLO), measured as the number of days from emergence to the date when 50% of plants in the plot had extruded stigmata; seed weight (SW, kg), measured as the total grain weight per plot at harvest after threshing and cleaning; grain yield (GY, kg/ha), calculated from the plot grain weight adjusted to a standard moisture content and converted to per-hectare basis; stem weight (STW, kg/ha), measured as the dry weight of stem and leaf material per plot; stem yield (STY, kg ha^{-1}), representing total above-ground biomass excluding grain; and downy mildew incidence (MI, %), assessed as the percentage of plants in the plot showing visible symptoms of downy mildew (*Sclerospora graminicola*).

2.3 Statistical analysis

All data were subjected to analysis of variance (ANOVA) using a split-plot model. Yearly ANOVA was performed separately for each growing season to partition total variation into variety (V), planting density (D), and V × D interaction effects. A combined ANOVA across all three years was also performed, incorporating year (Yr), variety (V), density (D), and all two-way and three-way interactions as sources of variation. Significance of F-values was assessed at $p < 0.05$ and $p < 0.01$. Mean separation was performed using the Least Significant Difference (LSD) test at $p < 0.05$. Pearson correlation coefficients

were computed between grain yield and all other measured traits. Quadratic regression models of the form $y = ax^2 + bx + c$ were fitted to describe the relationship between planting density (x) and grain yield (y) for each variety × year combination. All statistical analyses were performed using R.

3 Results

3.1 Effects of planting density across growing seasons

The analysis of variance conducted separately for each growing season revealed distinct effects of variety, planting density, and their interaction on the measured traits (Table 2). Planting density was the most influential and consistent source of variation across years. In 2020, density significantly affected FLO, SW, GY, STW, STY, and MI. The strongest responses were observed for GY and SW ($F = 5.96$, $P < 0.01$) and MI ($F = 5.04$, $P < 0.01$). In 2021, density continued to influence GY and SW ($F = 3.22$, $P < 0.01$), STW and STY ($F = 2.55$, $P < 0.05$), and MI ($F = 10.91$, $P < 0.01$). In 2022, density effects were primarily expressed through STW and STY ($F = 4.30$, $P < 0.01$), while its effect on GY was no longer statistically significant. Varietal effects were limited in 2020 to MI ($F = 4.03$, $P < 0.05$) but were highly significant for FLO in 2021 ($F = 28.00$, $P < 0.01$) and 2022 ($F = 14.30$, $P < 0.01$), indicating substantial phenological differences among varieties. The V × D interaction was non-significant for most traits, except FLO in 2021 ($F = 1.86$, $P < 0.05$).

Table 2
Analysis of variance (F-values) of the effects of variety (V), planting density (D), and their interaction (V×D) on measured traits in pearl millet during each growing season. * P < 0.05; ** P < 0.01; ns = not significant.

Trait	Variety (V) (2020)	Density (D) (2020)	V — D (2020)	Variety (V) (2021)	Density (D) (2021)	V — D (2021)	Variety (V) (2022)	Density (D) (2022)	V — D (2022)
FLO	0.82 ns	2.35*	0.39 ns	28**	1.24 ns	1.86*	14.3**	1.7 ns	0.65 ns
SW	0.37 ns	5.96**	0.75 ns	0.48 ns	3.22**	1.4 ns	0.68 ns	0.16 ns	0.73 ns
GY	0.37 ns	5.96**	0.75 ns	0.48 ns	3.22**	1.4 ns	0.68 ns	0.16 ns	0.73 ns
STW	1.56 ns	2.61*	0.77 ns	1.09 ns	2.55*	1.21 ns	1.47 ns	4.3**	0.75 ns
STY	1.56 ns	2.61*	0.77 ns	1.09 ns	2.55*	1.21 ns	1.47 ns	4.3**	0.75 ns
MI	4.03*	5.04**	1.39 ns	1.2 ns	10.91**	0.4 ns	4.99**	1.4 ns	0.99 ns

3.2 Combined ANOVA across seasons

The combined ANOVA confirmed planting density as the most influential factor, significantly affecting all six measured traits at $P \leq 0.01$ (Table 3). Year effects were significant for FLO ($F = 16.18$, $P < 0.01$), MI ($F = 11.61$, $P < 0.01$), SW and GY ($F = 3.57$, $P < 0.05$), reflecting inter-annual environmental variability. Variety had a significant effect only on MI ($F = 5.35$, $P < 0.01$), indicating genetic variability for disease tolerance. The Yr × D interaction was significant for FLO ($F = 2.42$, $P < 0.01$), STW and STY ($F = 2.00$, $P < 0.05$), and MI ($F = 2.98$, $P < 0.01$), indicating that the magnitude of density responses depended on seasonal conditions. The V × D interaction was significant only for MI ($F = 1.85$, $P < 0.05$). The three-way Yr × V × D interaction was non-significant for all traits, confirming the stability of varietal density responses across seasons.

Table 3
Combined analysis of variance (F-values) across 2020–2022 growing seasons. * P < 0.05; ** P < 0.01; ns = not significant.

Trait	Year (Yr)	Variety (V)	Density (D)	Yr — V	Yr — D	V — D	Yr — V — D
FLO	16.18**	1.82 ns	5.18**	1.23 ns	2.42**	0.87 ns	0.52 ns
SW	3.57*	0.19 ns	2.97**	0.36 ns	1.04 ns	0.37 ns	0.79 ns
GY	3.57*	0.19 ns	2.97**	0.36 ns	1.04 ns	0.37 ns	0.79 ns
STW	1.19 ns	2.11 ns	3.52**	0.53 ns	2*	1.04 ns	0.95 ns
STY	1.19 ns	2.11 ns	3.52**	0.53 ns	2*	1.04 ns	0.95 ns
MI	11.61**	5.35**	6.68**	1.54 ns	2.98**	1.85*	0.69 ns

3.3 Correlation between grain yield and other traits

Pearson correlation analysis revealed a significant negative correlation between days to 50% flowering and grain yield ($r = -0.41$, $p < 0.01$), indicating that earlier-flowering combinations tended to produce higher yields (Fig. 2). Seed weight showed a perfect positive correlation with grain yield ($r = 1$, $p < 0.01$), consistent with its direct contribution to yield as a yield component. Both stem weight and stem yield showed significant positive correlations with grain yield ($r = 0.54$, $p < 0.01$ for both), reflecting the role of vegetative biomass in supporting grain filling. Downy mildew incidence showed no significant correlation with grain yield ($r = 0.03$, $p > 0.05$), indicating that disease pressure at the levels observed did not meaningfully reduce grain yield.

3.4 Grain yield response to planting density

Grain yield generally increased with increasing planting density across varieties and growing seasons (Fig. 3). In 2020, all varieties showed progressive yield increases from D1 to D7, with CT6 and SOSAT-C88 reaching their highest yields at D7 (exceeding 1.7 t ha^{-1}). In 2021, the most productive season, SOSAT-C88 achieved the highest grain yield (about 3.0 t ha^{-1}) under D7. CT6 and HKP also responded positively to increasing density in 2021, while Moro exhibited relatively stable yields across density levels with no statistically significant differences among treatments. In 2022, overall yields were intermediate. SOSAT-

C88 again produced the highest yields at the denser planting treatments (D5 and D7), while CT6 maintained relatively stable yields and HKP showed a moderate yield at D4–D6. No yield decline was reported at the highest density (D7) in any variety or season, indicating that the competition threshold was not exceeded within the tested range. Statistical LSD groupings confirmed that D5, D6, and D7 consistently formed the highest-yielding class for CT6, HKP, and SOSAT-C88, while D1 and D2 were consistently the lowest-yielding group.

3.5 Effect of planting density on measured traits

Planting density significantly affects days to flowering, seed weight, stem weight, stem yield, and downy mildew incidence, with responses varying by variety and season (Table 4; Figs. 3a and 3b). Days to flowering showed no significant differences among density levels within any variety when data were pooled (all means sharing letter a), although Moro flowered earliest (52.78–55.44 days) and CT6 and HKP latest (58.22–60.67 days). SW increased significantly with increasing density in CT6, HKP, and SOSAT-C88, with SOSAT-C88 at D7 recording the highest value (3.05 ± 0.35 kg). GY increased progressively from D1 to D7 in CT6, HKP, and SOSAT-C88, with SOSAT-C88 at D7 achieving the highest yield (2,177 ± 247 kg ha^{-1}). Moro showed no significant differences among density levels for any trait. STW and STY increased significantly at higher densities in all varieties. MI consistently peaked at D4 across all varieties in all years and was lowest at D6 and D7. SOSAT-C88 recorded the lowest absolute MI values across all density levels.

Table 4

Means ± SE of measured traits by variety and planting density (pooled over 2020–2022). Within each variety, means followed by the same letter are not significantly different at P ≤ 0.05 (LSD test). FLO = days to 50% flowering; SW = seed weight; GY = grain yield; STW = stem weight; STY = stem yield; MI = downy mildew incidence.

Variety	Density	FLO	SW	GY	STW	STY	MI
CT6	D1	60.67 ± 1.404a	1.64 ± 0.172c	1171.43 ± 123.04c	3.6 ± 0.42c	2573.81 ± 299.915c	20.93 ± 5.314b
CT6	D2	58.89 ± 0.824a	1.74 ± 0.179bc	1242.86 ± 127.592bc	3.52 ± 0.3c	2516.67 ± 214.061c	17.66 ± 3.362b
CT6	D3	58.44 ± 0.944a	2.04 ± 0.281abc	1457.94 ± 200.73abc	3.83 ± 0.627c	2734.92 ± 447.642c	9.82 ± 2.229b
CT6	D4	59.89 ± 1.033a	1.65 ± 0.135c	1175.4 ± 96.496c	4.03 ± 0.342bc	2879.37 ± 243.965bc	42.04 ± 8.724a
CT6	D5	58.89 ± 0.949a	2.28 ± 0.19ab	1627.78 ± 135.581ab	5.37 ± 0.405a	3836.51 ± 289.625a	19.91 ± 5.61b
CT6	D6	59.25 ± 1.146a	2.38 ± 0.273a	1699.21 ± 195.341a	5.22 ± 0.467ab	3725.4 ± 333.368ab	11.99 ± 1.322b
CT6	D7	58.56 ± 0.899a	2.42 ± 0.224a	1726.19 ± 159.67a	5.47 ± 0.531a	3906.35 ± 379.294a	9.1 ± 1.896b
HKP	D1	60.56 ± 1.226a	1.64 ± 0.201d	1172.32 ± 143.477d	3.12 ± 0.37d	2229.37 ± 264.611d	22.77 ± 3.853ab
HKP	D2	59.11 ± 1.124a	1.8 ± 0.209cd	1288.89 ± 149.414cd	3.33 ± 0.238d	2380.16 ± 170.35d	11.6 ± 3.632c
HKP	D3	58.78 ± 1.103a	1.95 ± 0.172cd	1396.03 ± 122.937cd	3.77 ± 0.372cd	2691.27 ± 265.718cd	8.36 ± 2.408c
HKP	D4	60.44 ± 1.132a	1.98 ± 0.19bcd	1412.7 ± 135.53bcd	3.6 ± 0.439cd	2569.84 ± 313.219cd	26.24 ± 6.466a
HKP	D5	59.88 ± 1.368a	2.27 ± 0.163abc	1620.63 ± 116.773abc	4.64 ± 0.406bc	3317.46 ± 289.864bc	14.52 ± 4.663bc
HKP	D6	58.78 ± 1.152a	2.52 ± 0.22ab	1800.79 ± 157.249ab	5.18 ± 0.408ab	3699.21 ± 291.59ab	7.7 ± 2.071c
HKP	D7	58.22 ± 1.14a	2.54 ± 0.212a	1811.11 ± 151.636a	6.04 ± 0.453a	4313.49 ± 323.767a	7.2 ± 2.05c
Moro	D1	55.44 ± 1.725a	1.31 ± 0.195a	938.1 ± 139.636a	1.98 ± 0.32b	1414.29 ± 228.466b	23.74 ± 6.755ab
Moro	D2	54 ± 1.323a	1.41 ± 0.251a	1006.35 ± 178.942a	2.41 ± 0.298b	1718.25 ± 213.145b	12.1 ± 3.372b
Moro	D3	53.44 ± 0.835a	1.61 ± 0.245a	1150.79 ± 174.986a	2.57 ± 0.358b	1838.89 ± 255.446b	10.88 ± 3.066b

Variety	Density	FLO	SW	GY	STW	STY	MI
Moro	D4	55.44 ± 1.334a	2.02 ± 0.497a	1439.68 ± 354.736a	2.52 ± 0.279b	1797.62 ± 199.564b	33.61 ± 7.266a
Moro	D5	53.78 ± 0.997a	1.72 ± 0.17a	1231.75 ± 121.283a	3.84 ± 0.351a	2742.86 ± 250.953a	22.96 ± 5.427ab
Moro	D6	52.78 ± 0.465a	1.93 ± 0.156a	1377.78 ± 111.247a	3.85 ± 0.493a	2752.38 ± 352.437a	13.01 ± 2.164b
Moro	D7	52.89 ± 0.351a	2.07 ± 0.239a	1478.57 ± 170.752a	3.74 ± 0.541a	2670.63 ± 386.488a	10.59 ± 1.76b
SOSAT-C88	D1	58.78 ± 1.46a	1.63 ± 0.236d	1165.87 ± 168.547d	2.88 ± 0.338c	2057.94 ± 241.122c	8.75 ± 5.204ab
SOSAT-C88	D2	58.89 ± 1.328a	2.06 ± 0.33cd	1469.05 ± 235.696cd	4.01 ± 0.519bc	2865.08 ± 370.853bc	5.45 ± 3.127ab
SOSAT-C88	D3	58.44 ± 1.042a	2.15 ± 0.239bcd	1537.3 ± 170.86bcd	3.35 ± 0.369bc	2394.44 ± 263.216bc	4.53 ± 2.329b
SOSAT-C88	D4	60.22 ± 1.681a	1.84 ± 0.235cd	1312.7 ± 168.194cd	3.9 ± 0.469bc	2788.89 ± 334.744bc	17.28 ± 8.117a
SOSAT-C88	D5	59.67 ± 1.247a	2.55 ± 0.321abc	1822.22 ± 229.421abc	4.65 ± 0.435ab	3319.05 ± 311.017ab	7.88 ± 4.629ab
SOSAT-C88	D6	57.67 ± 1.143a	2.92 ± 0.342ab	2084.82 ± 243.978ab	4.41 ± 0.699ab	3153.17 ± 498.987ab	4.14 ± 2.102b
SOSAT-C88	D7	57 ± 1.093a	3.05 ± 0.345a	2176.98 ± 246.689a	5.73 ± 0.518a	4090.18 ± 370.023a	3.36 ± 1.957b

Figure 4a. Effect of planting density on days to 50% flowering, seed weight, and grain yield of four pearl millet varieties over three growing seasons (2020, 2021, 2022). Points represent variety means and error bars indicate ± standard error. Significance of the density effect within each variety is indicated as: * $p < 0.05$; ** $p < 0.01$; ns = not significant

3.6 Quadratic regression of grain yield on planting density

Quadratic regression models were statistically significant for most variety × year combinations (**Table 5;** Fig. 4). In 2020, all four varieties showed highly significant models ($P < 0.01$, $r = 0.731–0.844$). Positive quadratic coefficients for CT6 ($a = 24.24$), Moro ($a = 16.36$), and SOSAT-C88 ($a = 34.61$) indicated accelerating yield responses with increasing density, while HKP showed a concave response ($a = -8.79$). In 2021, significant models were obtained for CT6 ($r = 0.533$, $P < 0.05$), HKP ($r = 0.661$, $P < 0.01$), and SOSAT-C88 ($r = 0.669$, $P < 0.01$), but not for Moro ($r = 0.329$, ns). In 2022, only HKP ($r = 0.570$, $P < 0.05$) and SOSAT-C88 ($r = 0.720$, $P < 0.01$) showed significant models. SOSAT-C88 consistently produced the highest quadratic coefficients and r values across all three seasons ($r = 0.720–0.776$, $P < 0.01$), confirming its strong and predictable density response.

Table 4
Quadratic regression equations describing the relationship between planting density (x) and grain yield (y, kg ha⁻¹) for four pearl millet varieties over three growing seasons (2020, 2021, 2022). r = correlation coefficient; ** significant at p < 0.01; * significant at p < 0.05; ns not significant at p > 0.05.

Year	Variety	Equation	r	p_value
2020	CT6	y = 24.235x² + -44.473x + 876.9	0.844**	0
2020	HKP	y = -8.787x² + 193.254x + 581	0.755**	5.00E-04
2020	Moro	y = 16.355x² + -12.046x + 667.7	0.731**	0.001
2020	SOSAT-C88	y = 34.609x² + -129.507x + 957.8	0.776**	3.00E-04
2021	CT6	y = 3.713x² + 80.754x + 1542.5	0.533*	0.0494
2021	HKP	y = 25.68x² + -79.592x + 1682.7	0.661**	0.0057
2021	Moro	y = -16.44x² + 184.751x + 1285.7	0.329ns	0.3577
2021	SOSAT-C88	y = 48.356x² + -198.243x + 2101.4	0.669**	0.0048
2022	CT6	y = -9.042x² + 106.774x + 959.2	0.391ns	0.2255
2022	HKP	y = -10.337x² + 175.079x + 948.6	0.57*	0.0355
2022	Moro	y = -37.344x² + 374.256x + 283.6	0.309ns	0.4273
2022	SOSAT-C88	y = -33.503x² + 413.453x + 554.7	0.72**	0.002

4 Discussion

As a staple cereal crop in the West African Sahel, particularly in Niger, pearl millet contributes significantly to food security. Nevertheless, its production is constrained by several biotic and abiotic factors that result in consistently low yields [28]. Planting density was the dominant source of variation for all measured traits across all three growing seasons, confirming that plant population management is the primary lever for improving pearl millet productivity under rainfed Sahelian conditions in Niger. The absence of significant variation of main effects on grain yield, combined with non-significant V × D interactions for yield traits, indicates that the density response was consistent across varieties — a practically important result suggesting that a single density recommendation can be applied without variety-specific adjustment. This finding aligns with a broad body of evidence demonstrating that plant density is among the most responsive management factors in cereal crops [7, 29]. Pilloni et al.[30] reported no genotype × density interaction in pearl millet across 50 cultivars in India and Senegal and attributed this to the uniformity of canopy architecture traits among tested varieties. The progressive increase in grain yield from D1 to D7 observed in CT6, HKP, and SOSAT-C88, with no yield decline at the highest density tested, stands in contrast to the classical yield response curve, where productivity peaks at an intermediate density and then declines due to intra-specific competition [31]. In winter wheat,[32] reported that grain number per spikelet, 1000-grain weight, and spike weight all declined with increasing

plant density, indicating that the competition threshold was exceeded at relatively moderate densities. Similarly, in maize, Wang et al.[33] observed that while grain yield increased with density in modern varieties, grain crude fat and protein contents declined. The absence of a yield decline within the tested density range indicates that a supra-optimal density was not reached for the tested varieties. This may be attributed to the open, erect canopy architecture of pearl millet, which reduces mutual shading and maintains adequate light interception per plant even at high densities [34, 35]. Furthermore, the semi-arid growing environment, characterized by high solar radiation and low cloud cover throughout the rainy season, may sustain high canopy photosynthetic rates even at increased plant populations, delaying the onset of light competition relative to more humid environments. Pilloni et al.[30] demonstrated that denser pearl millet canopies reduce within-canopy vapor pressure deficit (VPD), thereby increasing water use efficiency, a mechanism that may also partly explain the sustained yield gains at high density observed in the present study.

The current study extends earlier findings by Iliasso et al.[17] and Bastos et al. [16], who reported positive yield responses to increased density in pearl millet, by showing that the response persists across a wider range of densities and is consistent across multiple growing seasons. The practical implication is that current farmer planting densities in Niger (approximately 5,200 hills ha^{-1}, equivalent to around 10,400 plants ha^{-1}) are far below the agronomic optimum, and that substantial yield gains can be achieved simply by increasing plant populations, without the need for improved inputs or varieties.

The significant year effect on GY, SW, FLO, and MI in the combined ANOVA reflects the inter-annual rainfall variability inherent to rainfed Sahelian agriculture. The 2021 season, which produced the highest yields, was likely characterized by more favorable rainfall during the critical grain-filling period, while early-season moisture deficits in 2020 constrained crop establishment. Critically, the non-significant Yr × D interaction for GY and SW confirms that the positive density–yield relationship was directionally stable across seasons a prerequisite for confident agronomic recommendations in variable rainfall environments. Li et al.[32] reported similar cross-season stability in wheat density responses, suggesting this stability is a general feature of well-adapted crop–environment combinations. Planting density had no consistent effect on days to 50% flowering when pooled over years. Pearl millet flowering in Sahelian environments is primarily regulated by photoperiod [36], which likely overrides the relatively weaker influence of plant density on phenological development. The highly significant variety effects on FLO in 2021 and 2022 ($F = 28.00$ and 14.30 respectively, $P < 0.01$) confirm genetic variability for flowering time, with Moro flowering 5–7 days earlier than CT6 and HKP. The significant negative correlation between FLO and GY ($r = -0.41$, $P < 0.01$) indicates that early flowering confers a yield advantage, likely by extending the effective grain-filling period relative to the end of the rainy season. The consistent peak in downy mildew incidence (MI) at D4 (1.0 m × 1.0 m) across all varieties and seasons is a novel and agronomically significant finding. This non-linear disease–density relationship suggests that D4 creates an intermediate canopy microclimate with sufficient humidity to favour *Sclerospora graminicola* sporangiophore development, but without the air turbulence and transpirational mixing of fully closed canopies at D5–D7 that may suppress sporulation [37, 38]. At low densities (D1–D3), reduced inter-plant proximity limits sporangia dispersal. This hypothesis is consistent with Pilloni et al.[30], who reported

that denser canopies reduced within-canopy VPD in both India and Senegal, thereby modifying the microclimate in ways relevant to pathogen development. The co-occurrence of maximum yield and minimum disease at D6–D7 removes any management trade-off between productivity and disease control, a particularly important consideration for smallholder farmers in Niger who have limited access to fungicides. SOSAT-C88 at D7 produced the highest grain yield across all years (2,177 kg ha^{-1} pooled; ~3,000 kg ha^{-1} in 2021), representing an 87% yield advantage over D1, and was the only variety with consistently significant quadratic regression models across all three seasons ($r = 0.720–0.776$, $P < 0.01$). The increase in seed weight from 1.63 kg at D1 to 3.05 kg at D7 is noteworthy: in wheat, Li et al.[32] reported that individual grain weight declined with increasing density due to intensified competition for assimilates, while Wang et al.[33] noted similar trade-offs in maize. These results are consistent with the known genetic characteristics of SOSAT-C88: its tolerance to lodging and drought, resistance to ergot, and compact panicle architecture make it well-suited to high-density cultivation, where mechanical support from neighbouring plants and efficient light harvesting become increasingly important [1, 5]. In contrast, Moro showed no significant density response for any trait in the pooled analysis, and its quadratic regression models were non-significant in 2021 and 2022. Its consistently low yields, high tillering habit, and short panicles suggest that inter-plant competition at high density constrains rather than stimulates productivity in this variety. Moro appears better suited to low-input, low-density farming systems, while SOSAT-C88, CT6, and HKP are the appropriate targets for density intensification. The shift from predominantly positive quadratic coefficients in 2020 (accelerating yield response) to negative coefficients in 2022 for HKP, Moro, and SOSAT-C88 (saturating response) indicates that the shape of the density–yield curve is modulated by seasonal conditions, with less favorable years producing a more saturating, rather than accelerating, response. Importantly, the theoretical yield maximum (vertex of the parabola) lay beyond the tested density range in all cases, confirming that D7 does not represent an agronomic ceiling for these varieties. Future experiments should evaluate densities beyond 100,000 plants ha^{-1} and include nitrogen management as a co-factor, since Pilloni et al.[30] reported that the positive yield response to density is strongest when other resources are not limiting. Taken together, the regression analysis results confirm that SOSAT-C88 offers the most reliable and strongest density–yield response across diverse seasonal conditions, making it the most appropriate variety for density-based management intensification in the study area. The consistent high r values for SOSAT-C88 (0.720–0.776) across all three seasons indicate that this variety's yield response to density is highly predictable, enabling confident recommendation of high-density planting for this variety without the uncertainty that characterizes less consistent varieties such as Moro.

5 Conclusion

This study provides robust evidence that planting density is the principal agronomic determinant of grain yield, biomass production, and downy mildew incidence in pearl millet under rainfed Sahelian conditions in Niger. Grain yield increased progressively from the lowest density to the highest density in three of the four tested varieties, with no yield decline at D7, suggesting that the density threshold for competition-induced yield loss was not reached within the tested range. SOSAT-C88 planted at D7 produced the

highest grain yield of the entire experiment (2,177 kg ha⁻¹ pooled over three years; approximately 3,000 kg ha⁻¹ in 2021), representing a yield advantage over D1, and exhibited the most consistent and predictable density–yield relationship across seasons ($r = 0.720–0.776$, $P < 0.01$). These results support the following recommendations for pearl millet production in southern Niger: (i) increase plant populations substantially beyond the current farmer practice of approximately 10,400 plants ha⁻¹ toward the range of 80,000–100,000 plants ha⁻¹ (D6–D7); (ii) prioritize SOSAT-C88 for high-density production systems given its superior density tolerance, highest yield potential, and lowest downy mildew susceptibility; and (iii) avoid planting at D4 (20,000 plants ha⁻¹) as this density simultaneously minimizes yield and maximizes disease pressure. Future research should evaluate densities beyond D7 to establish the upper yield threshold, examine the interaction of density with nitrogen fertilization rate, and assess the economic viability of high-density production under diverse soil fertility and rainfall conditions representative of the broader Nigerien pearl millet production zone.

Declarations

Ethics approval and consent to participate

The plant materials used in this study consisted of cultivated pearl millet germplasm obtained through authorized national agricultural research programs. The study did not involve endangered or protected species, and no additional ethical approval was required

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests

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declaration

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Author Contribution

Kassari Ango Issoufou: Lead of activity (conception, analysis and writting), Laouali Ibrahim Hamzatou: (data collection and writing)Mahamane Souley Abdel Kader: (Technical advice and reviewed)Iro Sodo

Abdoul Moumouni: (data analysis and writing)Illiassou Abdou Souley: (Conception and reviewed)Illia Mato Mamane Chapiou: (reviewed)

Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

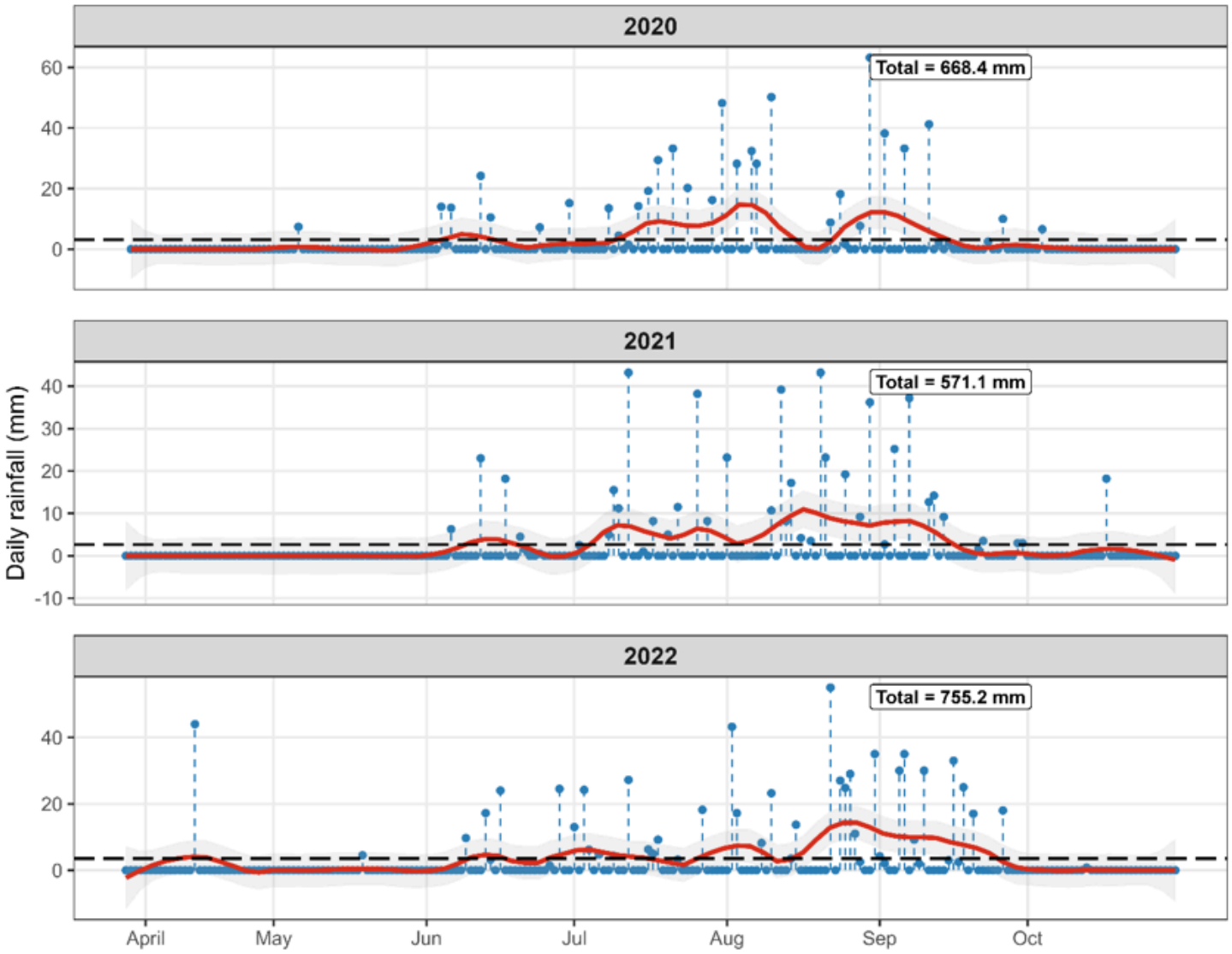

Figure 1

Figure 1. Daily rainfall patterns and seasonal precipitation trends during the 2020–2022 growing seasons at Maradi, Niger. Red line indicates mean daily rainfall for each year.

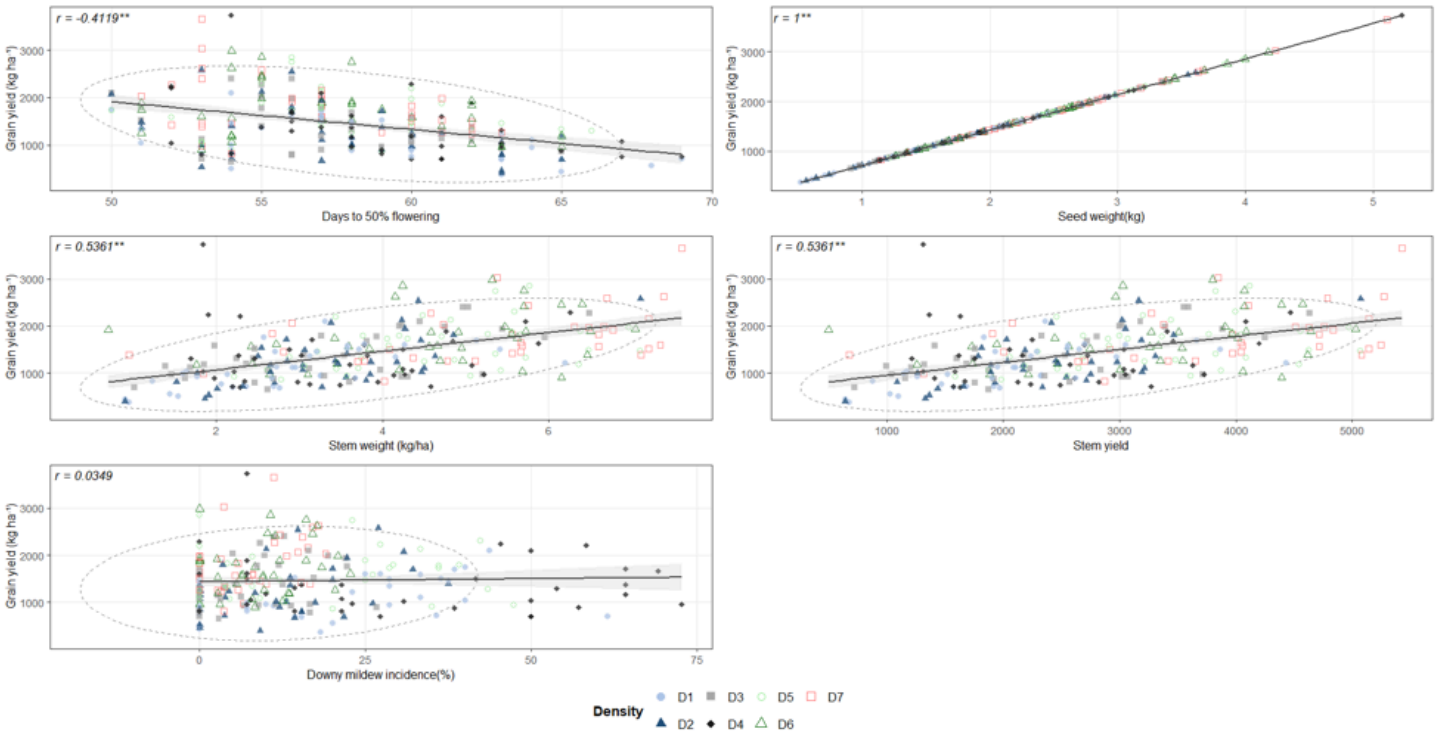

Figure 2

Figure 2. Pearson correlation coefficients between grain yield (kg ha⁻¹) and selected agronomic traits in four pearl millet varieties grown under seven planting densities over three growing seasons. Each point represents one observation coloured by density level (D1–D7). The solid line represents the overall linear regression and the shaded area the 95% confidence band. The dashed ellipse indicates the 95% confidence interval. ** p < 0.01.

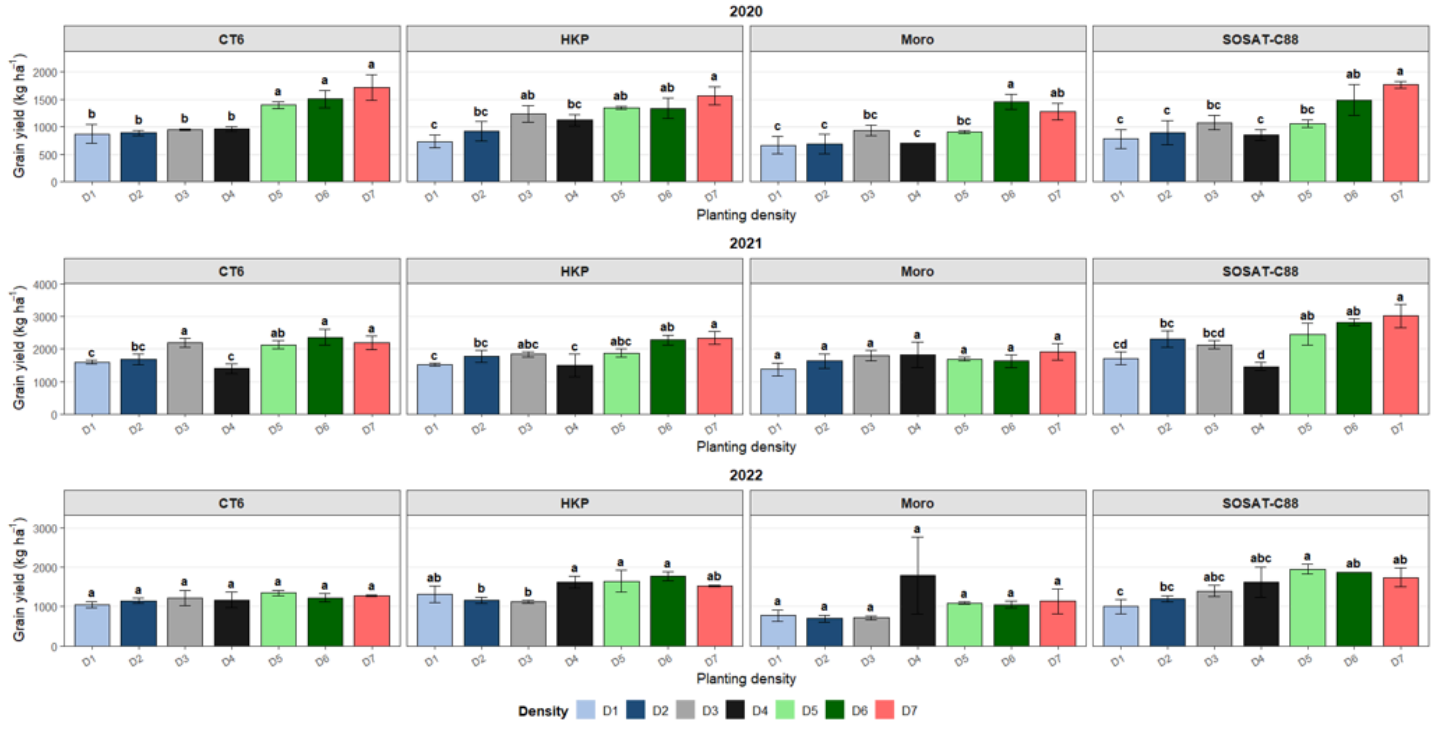

Figure 3

Figure 3. Mean grain yield (kg ha⁻¹) of four pearl millet varieties under seven planting densities during the 2020, 2021, and 2022 growing seasons. Bars = treatment means; error bars = ±SE. Bars within each variety sharing the same letter are not significantly different at P ≤ 0.05 (LSD test).

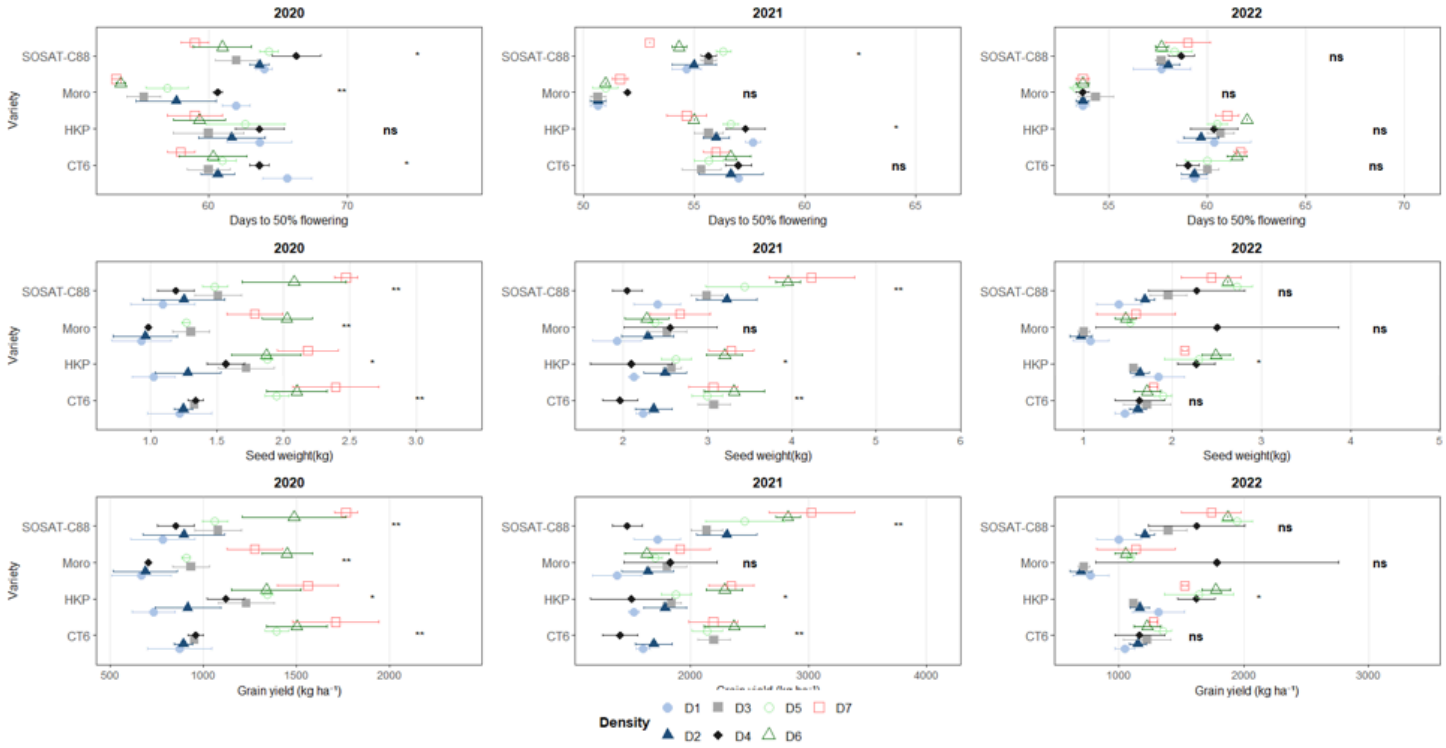

Figure 4

Figure 4a. Effect of planting density on days to 50% flowering, seed weight, and grain yield of four pearl millet varieties over three growing seasons (2020, 2021, 2022). Points represent variety means and error bars indicate ± standard error. Significance of the density effect within each variety is indicated as: * p < 0.05; ** p < 0.01; ns = not significant

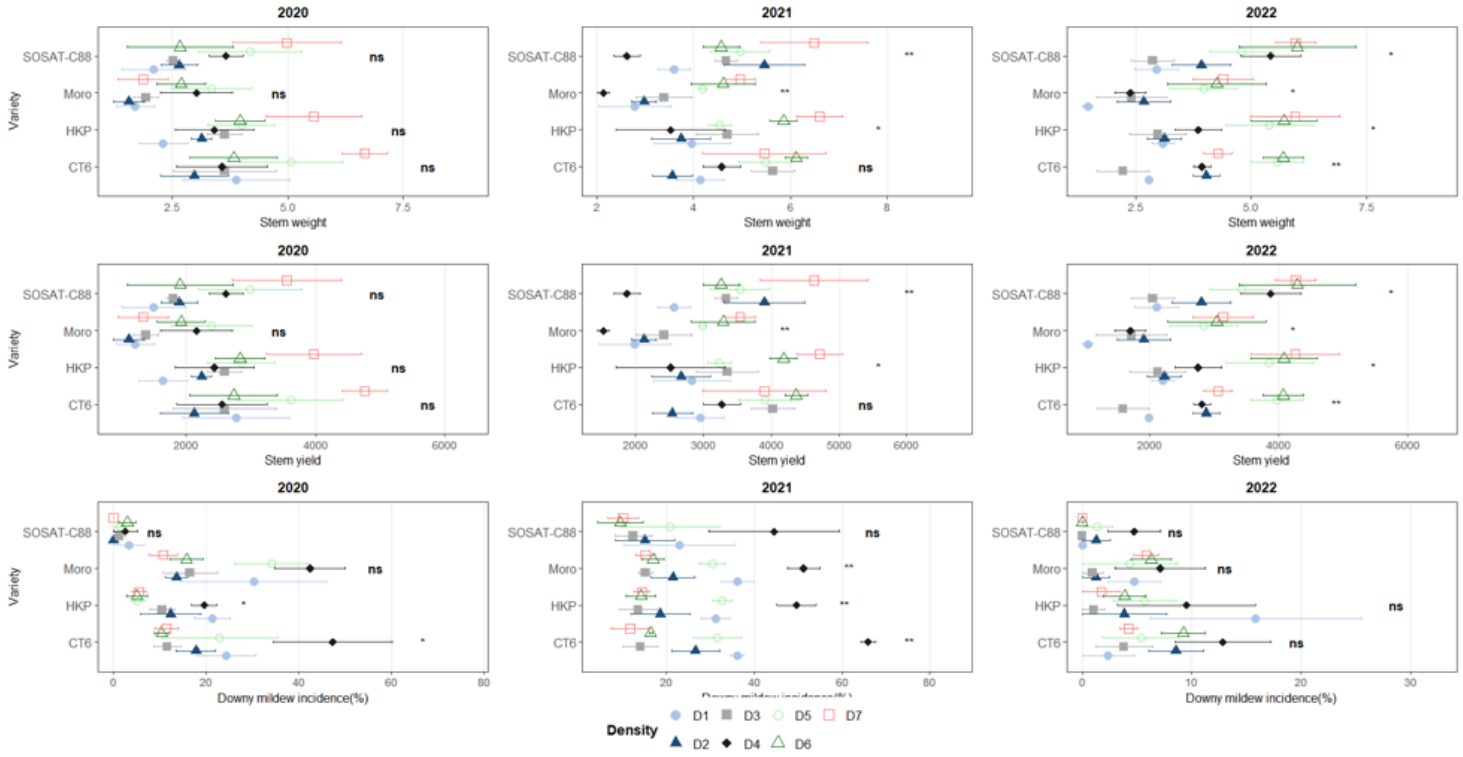

Figure 5

Figure 4b. Effect of planting density on stem weight, stem yield, and downy mildew incidence of four pearl millet varieties over three growing seasons (2020, 2021, 2022). Points represent variety means and error bars indicate ± standard error. Significance of the density effect within each variety is indicated as: * p < 0.05; ** p < 0.01; ns = not significant

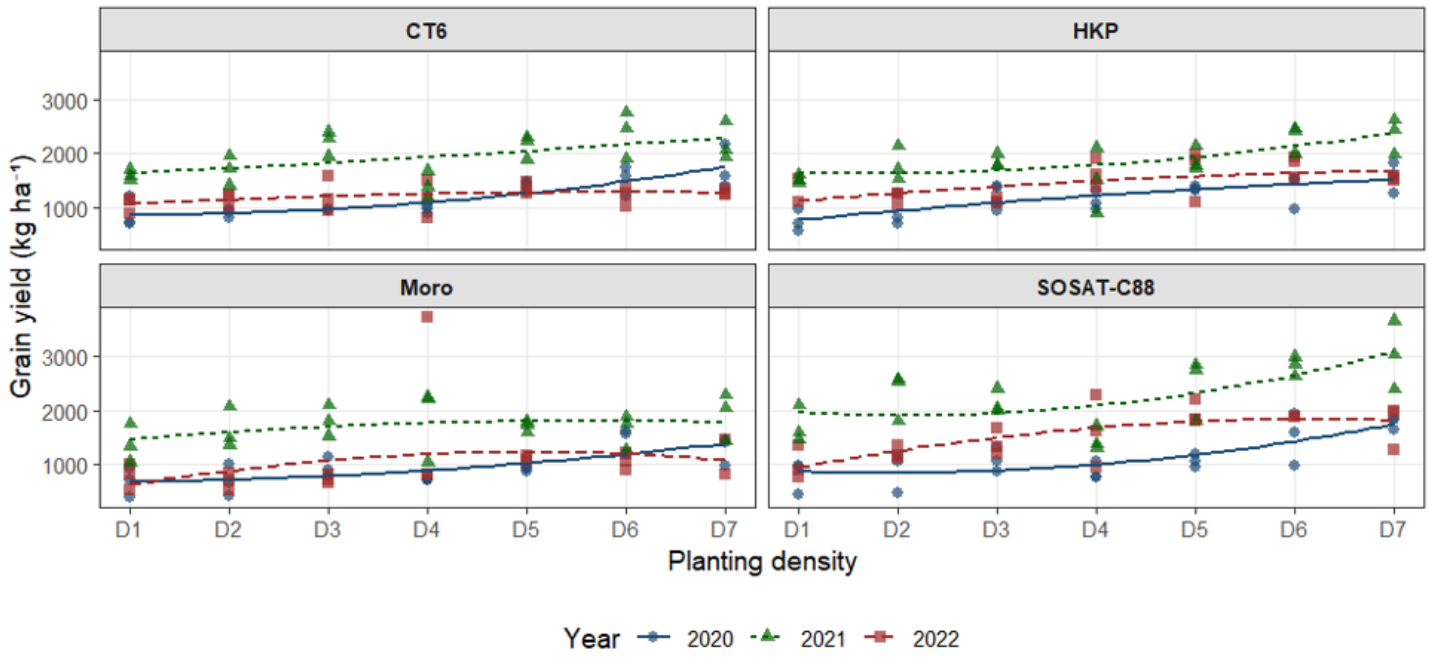

Figure 6

Figure 4: Quadratic relationship between planting density and grain yield for four pearl millet varieties over three growing seasons (2020, 2021, 2022). Points are observed values coloured by year; lines are fitted quadratic regression curves.