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Comparative performance of summer cereals under limited water and fertilizer inputs

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Abstract
Optimizing cereal production under limited water and nitrogen availability is crucial for sustainable agriculture. This study evaluates the effects of three planting densities (D1: low, D2: medium, D3: high) and input levels on the yield, resource use efficiency, and economic performance of three summer cereals: maize, pearl millet, and sorghum. A split-split plot design with three replications was used. Statistical analysis revealed that pearl millet exhibited the highest leaf area under D1 (low planting density) with optimum inputs. It also had the maximum ear/panicle number (35 m^{-2}), while D2 (medium density) and D3 (high density) resulted in a higher ear/panicle count. Maize produced the longest (17.1 cm) and heaviest (91 g) ears under D2 planting density. Among the three cereals, maize had the highest grain yield (2695 kg ha^{-1}). Across all planting densities, D2 (medium density) resulted in the highest yield (2434 kg ha^{-1}). Additionally, optimum input levels significantly improved grain yield, reaching 2467 kg ha^{-1}. Water use efficiency (WUE) and nitrogen use efficiency (NUE) varied significantly, with sorghum showing the highest WUE (5.93 kg m^{-2}) and maize showing the highest NUE (19.4 kg kg^{-1}). Constrained inputs led to higher NUE (20.1 kg kg^{-1}) and WUE (5.77 kg m^{-2}). Quality analysis indicated sorghum had the highest grain protein content (9.4%), while pearl millet showed the highest root and shoot dry weights. Principal component analysis revealed strong associations between specific yield attributes and each cereal, with D2 planting density showing the strongest overall associations. Economic analysis highlighted that sorghum under D2 density with optimum inputs yielded the highest gross return (858.0 USD ha^{-1}), while sorghum at D3 density with constrained inputs achieved the highest net benefit (711.6 USD ha^{-1}) and benefit–cost ratio (5.9). To maximize production, D2 planting density is recommended. Optimizing input management can enhance productivity, while sorghum cultivation under constrained input offers the highest economic returns.

Keywords Planting density · Yield · Economic viability · Net benefits · Yield related traits

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1 Introduction

Maize, sorghum, and pearl millet are the main cereals grown in tropical and subtropical regions. Maize is an important grain cereal in Pakistan. It is used for human food, poultry feed, animal fodder, and as a raw material in the paper industry [55]. Maize is one of the most highly regarded cereals in terms of yield and productivity. It is Pakistan's third-most important cereal after wheat and rice [24]. Maize plays a vital role in Pakistan's food system, particularly due to the rising demand for food and fodder amid a growing population. This is because maize has a higher energy content than other cereal grains [6]. Additionally, maize rotation with legumes enhances soil fertility, improves nitrogen availability through biological nitrogen fixation, and reduces the dependency on synthetic fertilizers, contributing to sustainable agriculture [60]. Crop rotation with legumes enhances soil structure, increases organic matter content, and reduces pest and disease pressure, ultimately improving maize yield stability under varying environmental conditions [29]. Furthermore, maize as a preceding crop for legumes can help reduce soil-borne diseases such as Fusarium wilt, thereby improving subsequent legume yields and overall crop health [41]. Another advantage of maize as a preceding crop for legumes is the suppression of root rot pathogens, as crop rotation with maize has been found to restrict soil populations of these pathogens [40]. Because of its various applications and relatively greater moisture requirements for growth and its cultivation in drier places and on marginal lands due to higher demand, its output may be limited. A recent survey of maize production in Pakistan, specifically in the province of Khyber Pakhtun Khwa, shows that although maize production is increasing annually, it is not keeping pace with the rising demand, which may lead to a decline in both annual production and the area under cultivation will be minus. However, choosing crops with low water requirements and high biomass yields, such as sorghum and pearl millet [67], which are also staple foods that provide a significant portion of calories to a large segment of the population [47].

Sorghum (*Sorghum bicolor Moench* L.) and pearl millet (*Pennisetum glaucum* L.) are the staple crops of a large population in semi-arid regions of Asia. These two cereals were ranked fourth and fifth in Pakistan, respectively. Sorghum is a drought-resistant crop, while pearl millet is a climate-hardy crop that can be grown in various climates [1, 34]. Sorghum is grown in areas where it is too hot or dry to grow maize, while pearl millet is grown in areas where it is too hot, sandy, and dry to grow sorghum [7]. These are also regarded as crops that can supply adequate nutrition [48]. As a result, it adds to livelihoods and food availability. These two crops are also valued for their plant residue that can be used to feed animals, and crop stover is sometimes considered as important as grains, especially in the country's hot and dry regions. Small grains like sorghum and pearl millet could replace maize in people's diets as a nutritional energy source [50]. Many past studies have highlighted the drought resilience of sorghum and pearl millet but do not explicitly consider how future climate scenarios might alter their performance and contribution to food security. Despite their importance and significance, sorghum and pearl millet are not considered crops critical to food security.

The sowing rate and germination percentage govern plant density, influencing establishment success, yield, and crop profitability. In various producing zones worldwide, inadequate plant stand is one of the most common yield retardants. The major technique for enhancing yield is to optimise plant density. On the other hand, high plant density may yield more if the plant is tolerant to intense competition for light, nutrients, and water, such as sorghum and millet [8, 9]. High plant density may increase root rot diseases, as dense plantings create favorable conditions for pathogen proliferation [40, 42]. Increased plant density without proper spacing can exacerbate these issues, leading to significant yield losses. Increasing plant density is an effective strategy to increase crop yield. In maize, this agronomic approach has been extensively studied. Research also indicates that increased plant population density has led to higher yields in sorghum and millet [43, 56]. However, resistance to root rot diseases becomes crucial under high-density planting conditions and can be improved by selecting an optimum planting date [65].

Constrained inputs, particularly limited water and nutrient availability, profoundly affect crop yields by triggering different physiological and biochemical stress responses. When water is scarce, plants undergo reduced cell turgor and stomatal closure, which limits carbon dioxide uptake and decreases photosynthetic efficiency [51], this results in lower biomass accumulation as resources are diverted from growth to stress tolerance mechanisms. Concurrently, nutrient limitations, especially nitrogen, phosphorus, and potassium—disrupt essential metabolic processes, including protein synthesis, enzyme activation, and energy production, thereby impeding cell division and development [16]. In maize, which is widely cultivated in Pakistan on marginal lands, these constraints force the crop to allocate energy to survival rather than yield formation, with even drought-tolerant varieties exhibiting compromised performance under severe deficits [19, 54]. Similarly, although pearl millet and sorghum are generally more resilient, they still experience significant yield reductions when water and nutrient supplies are restricted, particularly during critical growth phases at the end of the rainy season and in regions with short cropping windows [12]. Furthermore, continuous nutrient depletion without proper replenishment leads to declining soil fertility and disrupted ecosystem processes, undermining long-term agricultural sustainability [58].

The main goal of this study was to evaluate the impact of different planting densities and input levels (water and fertilizers) on the yield and efficiency of maize, pearl millet, and sorghum. Specifically, we aimed to determine whether sorghum or millet could serve as viable alternatives to maize in resource-limited conditions. The constrained input treatment in this study involved a reduction in both irrigation and nitrogen application, simulating conditions where water and fertilizer availability are limited, as commonly experienced in semi-arid agricultural regions.

2 Materials and methods

2.1 Plant material

The seeds of maize (*Zea mays*), sorghum (*Sorghum bicolor*), and millet (*Pennisetum glaucum*) used in this study were obtained from the Cereal Crop Research Institute (CCRI), Pirsabak, Nowshera, Pakistan.

2.2 Experimental site and design

The three summer cereals, Maize, Sorghum, and Millet, were assessed in 2022 at the Cereal Crop Research Institute (CCRI) in Nowshera, Pakistan situated at 288 m (945 ft) AMSL at the left bank of Kabul River, 3 km east of Nowshera, at 32°N latitude and 74°E longitude. Nowshera has a warm to hot, semi-arid, and sub-tropical climate with a mean annual rainfall of about 364 mm. The soil was classified as Calcaric Luvisols according to the World Reference Base (WRB) system and exhibited a sandy clay loam texture, consisting of 38.5% sand, 30.1% silt, and 30.0% clay. It had an alkaline pH of 7.69 and was non-saline, with an electrical conductivity of 0.85 dS m^{-1}. The organic matter content was low at 1.53 g kg^{-1}, and the organic carbon content was 11.21 g kg^{-1}. Additionally, the soil moisture was measured at 9.01%, with a bulk density of 1.63 g cm^{-1}. The nutrient analysis further revealed that the available nitrogen content was 3.11 mg kg^{-1}, the AB-DTPA extractable phosphorus was 4.49 mg kg^{-1} and the potassium content was 81.21 mg kg^{-1}. This research was performed with a factorial design employing a split-split-plot design, and three replications were utilised for each treatment. Each plot was randomly assigned to specific treatments, and the plot size was standardised at four meters in width and three meters in length (12 m^2). Within each plot, four rows of cereals were sown and a row spacing of 70 cm and plant spacing of 25 cm was maintained. The experimental factors were three cereal crops, Maize, Sorghum, and pearl millet and planting densities encompassed three levels: D1, D2 and D3 that were assigned to subplots whereas the inputs, involved two treatments: I1, which represented the application of optimum fertilizer and irrigation levels and I2, which simulated constrained fertilizer and irrigation conditions were allotted to main plots. Half the dose of the fertilizer as calculated per treatment was broadcasted during sowing while the rest was applied at the late vegetative stage. Similarly, four canal irrigations were applied during the whole season at emergence, early vegetative stage, silking stage and grain filling stage. The details of these factors are given in Table 1. The planting densities (D1: 60,000 plants ha^{-1}, D2: 80,000 plants ha^{-1}, and D3: 100,000 plants ha^{-1}) refer to actual plant stands per hectare after seedling establishment, ensuring a uniform population across treatments. The experiment was executed in the first week of June. Azam, PARC MS-2 and DS-97 varieties of maize, pearl millet and sorghum were planted, respectively. Management practices, including weeding, irrigation, and thinning, were consistently applied to all plots according to recommended guidelines.

Table 1 Factors and their levels applied in the trial

Factor	Levels
Summer cereals	Maize, Pearl millet, Sorghum
Planting densities (plants ha^{-1})	Maize: 60,000 (D1), 80,000 (D2), 100,000 (D3) Pearl millet: 60,000 (D1), 80,000 (D2), 100,000 (D3) Sorghum: 60,000 (D1), 80,000 (D2), 100,000 (D3)
Supplied inputs	
Irrigation (mm)	550 mm (I1), 250 mm (I2)
Fertilizer (kg ha^{-1}, N:P: K)	120:90:60 (I1), 60:45:30 (I2)

2.3 Yield and yield attributes

To measure the leaf area, the length and width of central leaves from five plants within each sub-plot were measured using a measuring tape. The average leaf area (LA) was calculated using the given equation.

$$LA = (Leaf\ Length \times Leaf\ width) \times 0.75 \tag{1}$$

The coefficient 0.75 was used for all three cereals based on standard empirical estimations [2].

Ear/panicle per m^2 was determined by counting the ear/panicles in each plot within the selected area of 1 m^2. In contrast, ear/panicle length (cm), and ear/panicle weight (g), were estimated based on five randomly selected ears/panicles. A SPAD meter was used to determine SPAD values by placing it on the flag leaf of pearl millet and sorghum and the uppermost fully expanded leaf (ear leaf) of maize. Readings were taken from five plants per plot, and the average SPAD value was recorded. Days to harvest maturity were determined by counting the days from sowing till all the ears/panicles in each plot were fully matured.

To determine crop water use efficiency (WUE), following the formula presented by Zhang et al. [67],

$$\mathrm{WUE}\ (\mathrm{kg\ m^{-2}}) = \mathrm{GY/Etc} \tag{2}$$

where GY is the grain yield produced, ETc is the evapotranspiration in the growing season.

Total seed weight was calculated by separating 1000 seeds from the seed lot of individual plots and weighing them on a precise digital scale. Grain yield, initially measured in kg m^{-2} was estimated from the two central rows and later converted to kg ha^{-1}. Additionally, nitrogen use efficiency (NUE) was computed by dividing the grain yield by the rate of nitrogen application, drawing upon established methodologies referenced in previous studies [13, 21, 39].

$$\mathrm{NUE}\ (\mathrm{kg\ kg^{-1}}) = \mathrm{GY/\ Total\ N\ supplied} \tag{3}$$

Nitrogen content (%) was determined using the Kjeldahl method [27]. The obtained nitrogen % was further multiplied by a protein factor of 6.25 to obtain grain protein.

Shoot dry weight (g) was determined by collecting above-ground plant biomass, cleaning them, and oven-drying until a constant weight. Root dry weight (g) was assessed by excavating and cleaning below-ground roots, followed by the same drying process. The root-to-shoot ratio (%) was calculated by dividing root dry weight by shoot dry weight and multiplying by 100.

2.4 Economic analysis

Economic analysis in terms of net return and benefit–cost ratio calculations was done according to procedures defined by Fawad et al. [17], where:

$$Net\ return = Gross\ return - Total\ production\ cost \tag{4}$$

$$Benefit\ cost\ ratio = \frac{Net\ return}{Total\ production\ cost} \tag{5}$$

2.5 Soil analysis

Before planting, soil samples were collected from a 5–15 cm depth using a soil auger to analyze various physiochemical properties. Once gathered, these samples were oven-dried and finely ground to assess factors such as soil texture, pH, moisture, bulk density, electrical conductivity, organic matter, organic carbon, and the concentrations of nitrogen, phosphorus, and potassium. The soil texture was determined using Foth's method [18], while pH and electrical conductivity were measured according to NMSU procedures [22]. Additionally, the proportions of sand, silt, and clay were estimated by employing different sieves and using a hydrometer to track settling rates, as described in Alexander [3]. The wet oxidation method of Walkley and Black [62] was used for analyzing organic matter and carbon, and the Olsen extractant $NaHCO_3$ procedure [46] was applied to quantify the available N, P, and K contents.

2.6 Statistical data analysis

The data were analysed using analysis of variance (ANOVA) appropriate for a split-split plot design using Statistix version 9.0. When significance was achieved, mean differences were assessed using the Least Significant Difference (LSD) test at a 5% probability level. Moreover, principal component analysis (PCA) of the measured attributes was performed using OriginPro 2024 (Origin Lab Corporation, Northampton, MA, USA).

3 Results

3.1 Yield and yield attributes

Statistical data analysis revealed significant effects of planting densities and inputs on the yield and yield attributes of maize, pearl millet and sorghum (Table 2). Among the cereals, pearl millet exhibited the highest leaf area (631 cm^2) compared to maize (573 cm^2) and sorghum (517 cm^2). Planting densities also had a notable effect, with the highest leaf area (589 cm^2 each) recorded under D1 and D2 densities, while D3 had the lowest (548 cm^2). Optimal inputs resulted in higher leaf areas (609 cm^2), whereas constrained inputs led to a decrease (538 cm^2) (Table 2).

Ear/panicle per m^2 was highest for pearl millet (35), followed by sorghum (26) and maize (14). Across planting densities, D2 and D3 recorded the highest ear/panicle count (26 each), whereas D1 had the lowest (21). Similarly, optimal inputs resulted in a higher ear/panicle count (26), while constrained inputs led to a lower count (23).

For ear/panicle length, pearl millet recorded the highest value (19.6 cm), followed by sorghum (17.2 cm) and maize (12.2 cm). Among planting densities, D2 and D3 showed longer ear/panicle lengths (17.1 and 16.5 cm, respectively), while the shortest length was observed at D1 (15.3 cm). No significant effect of input levels was found for ear/panicle length (Table 2).

Cereal types also significantly differed in ear/panicle weight, with maize producing the heaviest ears (121 g), followed by sorghum (98 g) and pearl millet (41 g). Among planting densities, D2 resulted in the highest weight (91 g), followed by D1 (86 g) and D3 (83 g), with the latter two being statistically similar. Optimum inputs increased ear/panicle weight (88 g) compared to constrained inputs (85 g) (Table 2).

Table 2 Effect of planting densities and inputs on growth and yield attributes of summer cereals

Treatments	Leaf area (cm^2)	Ear/panicle m^{-2}	Ear/panicle length (cm)	Ear/panicle weight (g)	SPAD value
Summer cereals (C)					
Maize	573^b	14^c	12.2^c	121^a	36
Pearl millet	631^a	35^a	19.6^a	41^c	36
Sorghum	517^c	26^b	17.2^b	98^b	36
$LSD_{(0.05)}$	9	1	0.9	4	ns
Planting densities (P)					
D1	589^a	21^b	15.3^b	86^b	35^b
D2	585^a	26^a	17.1^a	91^a	38^a
D3	548^b	26^a	16.5^{ab}	83^b	35^b
$LSD_{(0.05)}$	5	1	1.3	3	1.2
Inputs (I)					
Optimum	609^a	26^a	16.8	88^a	40^a
Constrained	538^b	23^b	15.9	85^b	32^b
$LSD_{(0.05)}$	3	2	ns	2	2
C × P × I	***	**	ns	***	**

Means followed by different letters are significantly different and ns represent non-significant data at $p \leq 0.05$

SPAD values were not significantly different among the cereals. However, planting densities influenced SPAD values, with the highest observed at D2 (38), followed by D1 and D3 (35 each). Optimal inputs produced the highest SPAD value (40), whereas constrained inputs resulted in the lowest (32) (Table 2).

Interaction effects between planting densities and input levels revealed notable differences in leaf area, ear/panicle count, and ear/panicle weight (Fig. 1a–c). Pearl millet exhibited the highest leaf area when planted at D1 under optimal input conditions, which was statistically similar to maize grown at D2 with optimal inputs (Fig. 1a).

For ear/panicle count, pearl millet achieved the highest values at D2 and D3 under optimal input conditions (Fig. 1b). Similarly, maize at D2 with optimal inputs resulted in the heaviest ears/panicles (Fig. 1c). Regarding SPAD values, no significant interaction effects were observed across different planting densities when optimal inputs were supplied (Fig. 2a).

3.2 Yield and yield-related traits

Statistical analysis showed a significant effect of planting densities and input levels on the yield and yield-related traits of three summer cereals (Table 3). Maize and sorghum required more days to reach maturity (110 days) compared

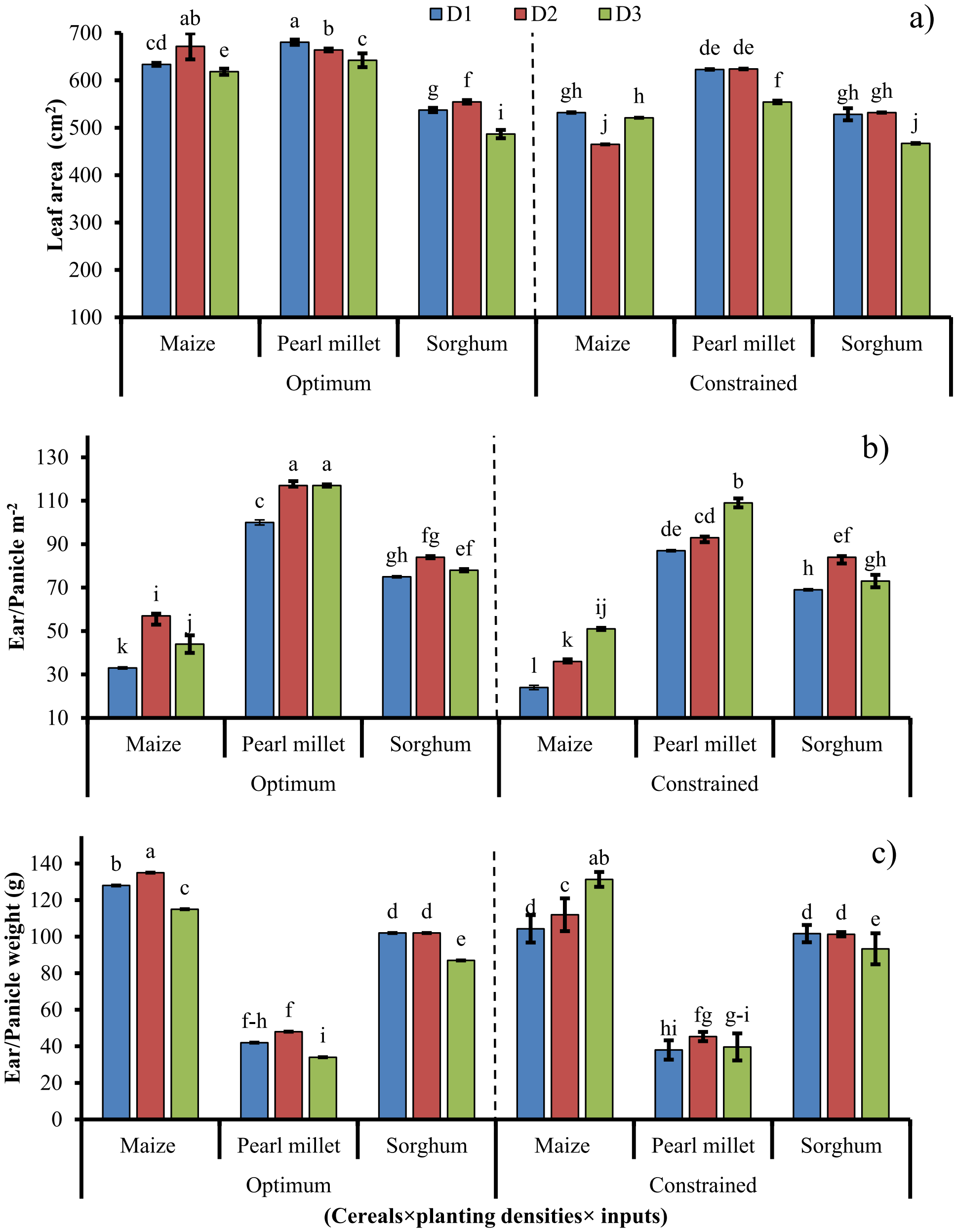

Fig. 1 Planned mean comparison of the applied factors on **a** leaf area, **b** ear/panicle m^{-2} and **c** ear/panicle weight of summer cereals. Data are presented as mean ± standard deviation. *Different small letters* on the bars indicate significant differences at $p \leq 0.05$

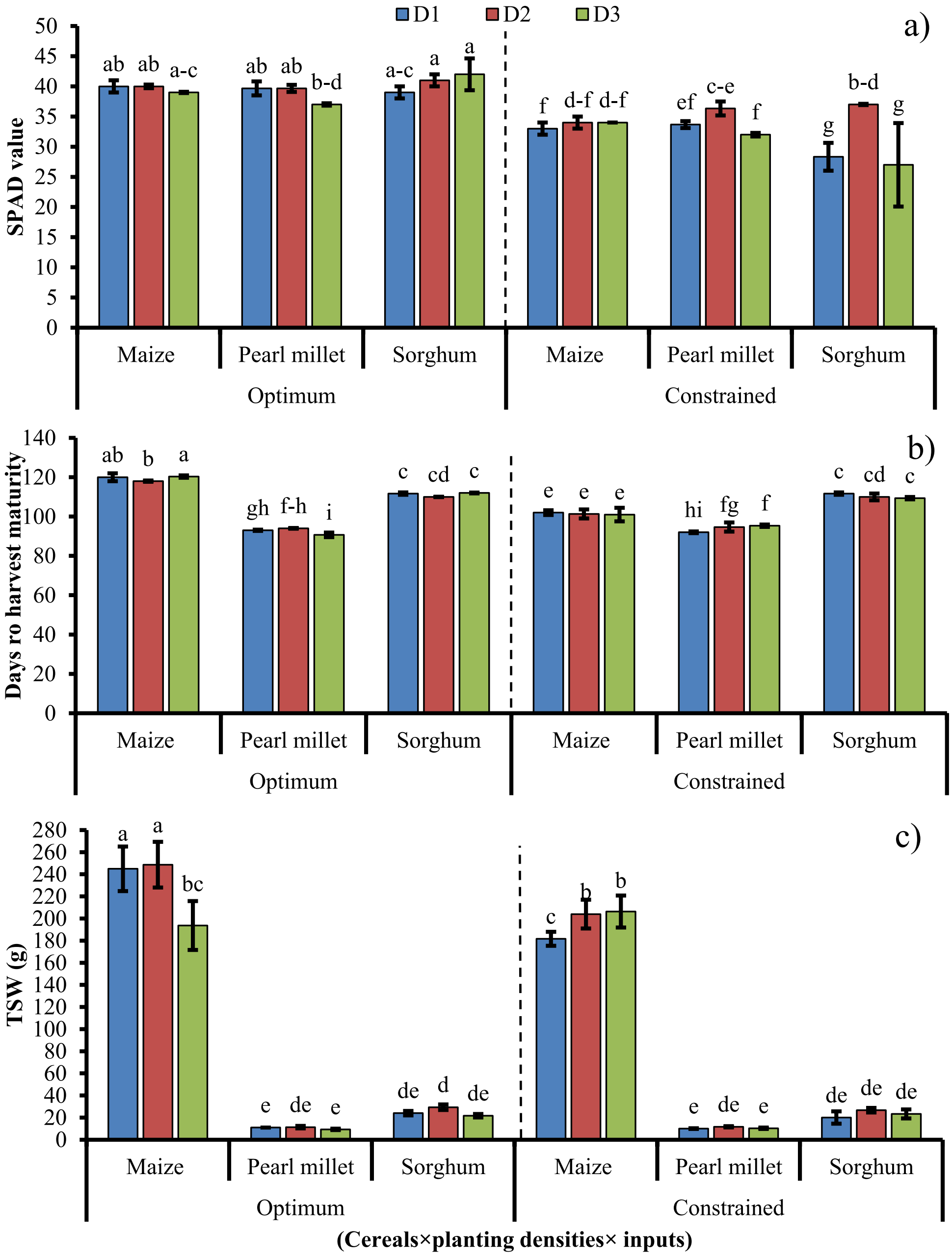

Fig. 2 Planned mean comparison of the applied factors on **a** SPAD values, **b** days to harvest maturity and **c** TSW of summer cereals. TSW is a thousand seed weight. Data are presented as mean ± standard deviation. *Different small letters* on the bars indicate significant differences at $p \leq 0.05$

to pearl millet (93 days). However, planting density had no significant effect on maturity duration. Inputs influenced harvest maturity, with crops maturing later under optimal input conditions (107 days) compared to constrained inputs (105 days) (Table 3).

Thousand seed weight (TSW) was highest for maize (213 g), followed by sorghum (24 g) and pearl millet (11 g). Among planting densities, D1 and D2 recorded the highest and statistically similar TSW values (82 and 89 g, respectively), while D3 resulted in the lowest (77 g). Optimum inputs led to a higher TSW (88 g) compared to constrained inputs (77 g), but this difference was not statistically significant (Table 3).

Grain yield varied significantly among the cereals, with maize producing the highest yield (2695 kg ha^{-1}), followed by sorghum (2195 kg ha^{-1}) and pearl millet (2023 kg ha^{-1}). Among planting densities, D2 resulted in the highest yield (2434 kg ha^{-1}), while D1 recorded the lowest (2167 kg ha^{-1}). Grain yield was also influenced by input levels, with optimal input application yielding 2467 kg ha^{-1} compared to 2142 kg ha^{-1} under constrained inputs (Table 3).

Table 3 Effect of planting densities and inputs on yield attributes of summer cereals

Treatments	DHM	TSW (g)	GY (kg ha^{-1})	WUE (kg m^{-2})	NUE (kg kg^{-1})
Summer cereals (C)					
Maize	110^{a}	213^{a}	2695^{a}	5.01^{a}	19.4^{b}
Pearl millet	93^{b}	11^{c}	2023^{c}	5.60^{b}	15.7^{c}
Sorghum	110^{a}	24^{b}	2195^{b}	5.93^{a}	17.2^{a}
LSD$_{(0.05)}$	1	12	116	0.24	0.8
Planting densities (P)					
D1	105	82^{ab}	2167^{c}	5.07^{c}	16.2^{b}
D2	105	89^{a}	2434^{a}	5.86^{a}	18.4^{a}
D3	105	77^{b}	2312^{c}	5.61^{b}	17.6^{a}
LSD$_{(0.05)}$	ns	7	116	0.24	0.8
Inputs (I)					
Optimum	107^{a}	88^{a}	2467^{a}	5.27^{b}	14.8^{b}
Constrained	105^{b}	77^{b}	2142^{b}	5.77^{a}	20.1^{a}
LSD$_{(0.05)}$	1	15	94	0.21	0.7
C×P×I	*	**	*	ns	***

Means followed by different letters are significantly different, and **ns** represent non-significant data at $p \le 0.05$. Days to harvest maturity presented as DHM, thousand seed weight is TSW, grain yield is GY, water use efficiency is WUE, and nitrogen use efficiency is NUE

Water use efficiency (WUE) varied among cereals, with sorghum exhibiting the highest WUE (5.93 kg m^{-2}). Planting densities significantly affected WUE, with D2 recording the highest efficiency (5.86 kg m^{-2}) compared to D1 (5.07 kg m^{-2}). Interestingly, constrained inputs led to higher WUE (5.77 kg m^{-2}) than optimal inputs (5.27 kg m^{-2}) (Table 3).

Nitrogen use efficiency (NUE) was highest in maize (19.4 kg kg^{-1}), followed by sorghum and pearl millet. NUE was influenced by planting densities, with D2 and D3 showing the highest values (18.4 and 17.6 kg kg^{-1}, respectively). Contrary to expectations, constrained inputs resulted in higher NUE (20.1 kg kg^{-1}), whereas optimal inputs led to a lower NUE (14.8 kg kg^{-1}) (Table 3).

Interaction effects between planting densities and input levels highlighted key trends in yield and efficiency parameters (Figs. 2b, 3c). Delayed maturity was observed in maize under optimal input conditions (Fig. 2b).

For thousand seed weight, maize exhibited heavier grains at D1 and D2 when inputs were supplied optimally (Fig. 2c). Similarly, maize at D2 with optimum inputs achieved the highest grain yield (Fig. 3a).

In terms of NUE, maize and sorghum had higher NUE values compared to millet when planting density was maintained at D3 under constrained input supply (Fig. 3b). Additionally, a significant correlation was observed between NUE and grain yield, indicating that an increase in NUE resulted in a proportional increase in grain yield. Conversely, the relationship between WUE and grain yield appeared weaker (Fig. 3c).

3.3 Grain quality

Planting densities and inputs significantly influenced the grain protein and carbohydrate content of the three summer cereals (Table 4). Among cereals, sorghum had the highest grain protein content (9.4%), followed by pearl millet (9.1%) and maize (7.9%). Higher protein content was observed at D2 planting density (9.4%), whereas the lowest was recorded for D3 (8.1%). Regarding inputs, optimal input application resulted in a higher protein content (9.1%) compared to constrained conditions (8.5%). The interaction effects showed that sorghum maintained the highest protein content regardless of input levels and planting densities (Fig. 4a).

For grain carbohydrate content, sorghum and pearl millet exhibited statistically similar values (72.4 and 72.8%, respectively), which were significantly higher than maize (7.9 g). D1 and D2 planting densities resulted in the highest carbohydrate content (72.8 and 72.1%, respectively), whereas D3 recorded the lowest (68.2%). Optimal input application resulted in a higher carbohydrate content (74.0%), while constrained inputs led to a lower carbohydrate content (68.1%). Notably, sorghum maintained the highest carbohydrate content even under constrained input conditions, while maize and pearl millet exhibited declines (Fig. 4b).

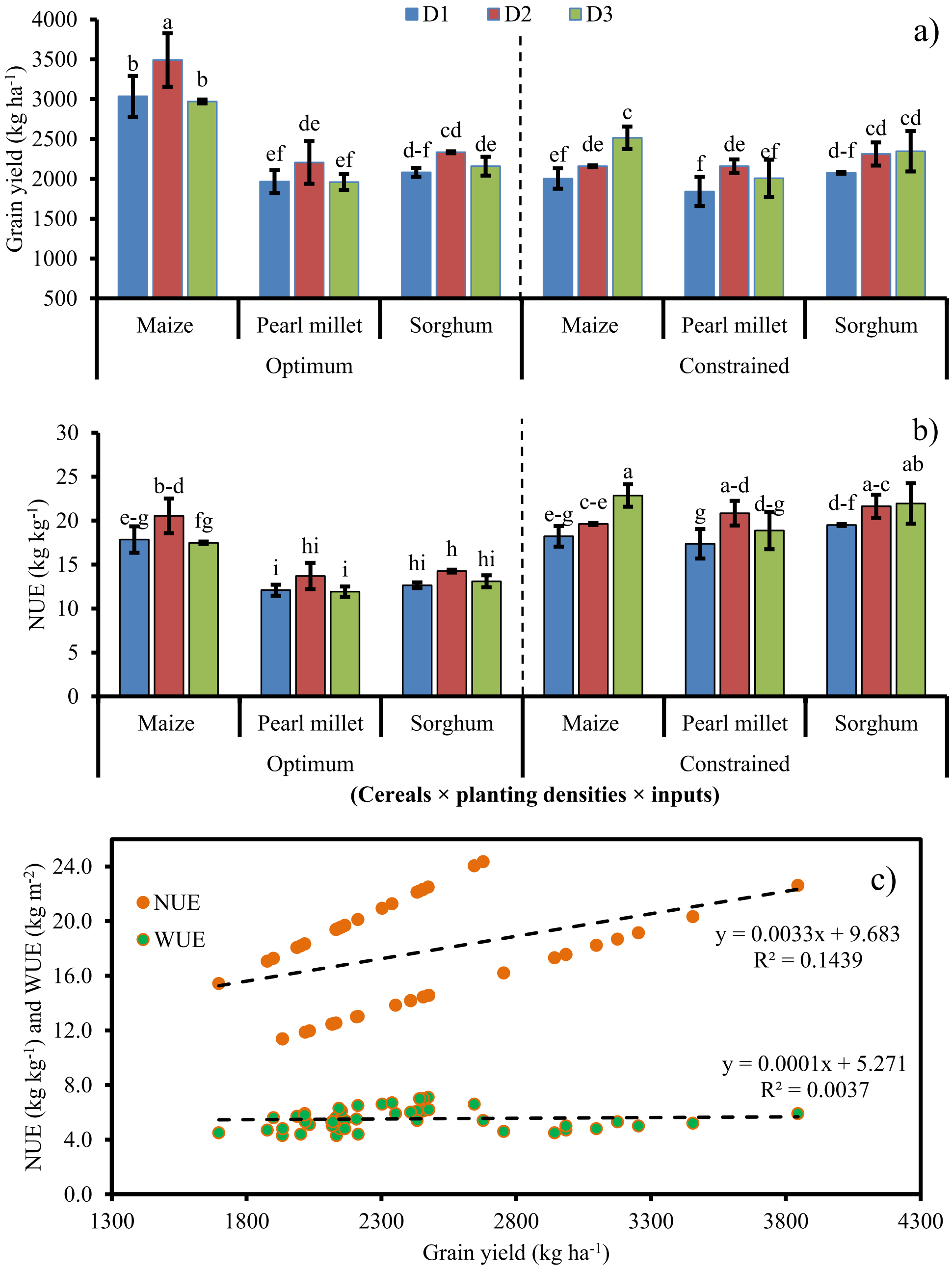

Fig. 3 Planned mean comparison of the applied factors on grain yield and nitrogen use efficiency (NUE) of summer cereals (**a**, **b**). Relationship of grain yield with WUE and NUE (**c**). Data are presented as mean ± standard deviation. *Different small letters* on the bars indicate significant differences at $p \leq 0.05$

3.4 Dry matter partitioning

Planting densities and inputs significantly influenced the dry weights of three summer cereals (Table 4). Pearl millet produced the highest (9.8 g) root dry weight (RDW) among cereals, surpassing RDW produced by maize (4.8 g) and sorghum (8.5 g). The effect of planting densities was also prominent, with D1 producing higher RDW (8.2 g) as compared to D2 (7.8 g) and D3 (7.2 g). The application of inputs showed that a limited supply of resources resulted in higher RDW (8.7 g) compared to optimal input supply (6.7 g).

Shoot dry weight (SDW) varied significantly, with pearl millet producing the highest value (145.9 g), followed by sorghum (116.8 g) and maize (114.4 g). Maximum SDW was obtained at D1 (132 g), whereas lower values were recorded at D3 (117.6 g). A significant disparity in SDW was observed with different input levels, as optimal input application resulted in higher SDW (134.1 g), whereas constrained inputs led to lower SDW (117.3 g). Pearl millet had the highest SDW under optimal input supply, while its RDW was highest under constrained conditions (Fig. 5a, b).

Table 4 Effect of planting densities and inputs on quality and dry weight of summer cereals

Treatments	GPC (%)	GCC (%)	RDW (g)	SDW (g)	R/S ratio
Summer cereals (C)					
Maize	7.9^{c}	69.0^{b}	4.8^{c}	114.4^{c}	4.5^{c}
Pearl millet	9.1^{b}	72.8^{a}	9.8^{a}	145.9^{a}	6.7^{b}
Sorghum	9.4^{a}	72.4^{a}	8.5^{b}	116.8^{b}	7.3^{a}
$LSD_{(0.05)}$	0.3	1.9	0.04	1.3	0.09
Planting densities (P)					
D1	8.9^{b}	72.8^{a}	8.2^{a}	132.0^{a}	6.2^{a}
D2	9.4^{a}	72.1^{a}	7.8^{b}	127.6^{b}	6.2^{a}
D3	8.1^{c}	68.2^{b}	7.2^{c}	117.6^{c}	6.1^{b}
$LSD_{(0.05)}$	0.3	1.1	0.02	0.6	0.04
Inputs (I)					
Optimum	9.1^{a}	74.0^{a}	6.7^{b}	134.1^{a}	5.0^{b}
Constrained	8.5^{b}	68.1^{b}	8.7^{a}	117.3^{b}	7.3^{a}
$LSD_{(0.05)}$	0.4	1.7	0.02	0.10	0.08
C × P × I	*	*	**	***	***

Means followed by different letters are significantly different, and ns represent non-significant data at $p \leq 0.05$. The grain protein content is presented as GPC, grain carbohydrate content as GCC, root dry weight as RDW, shoot dry weight as SDW, and the root-to-shoot ratio as R/S ratio

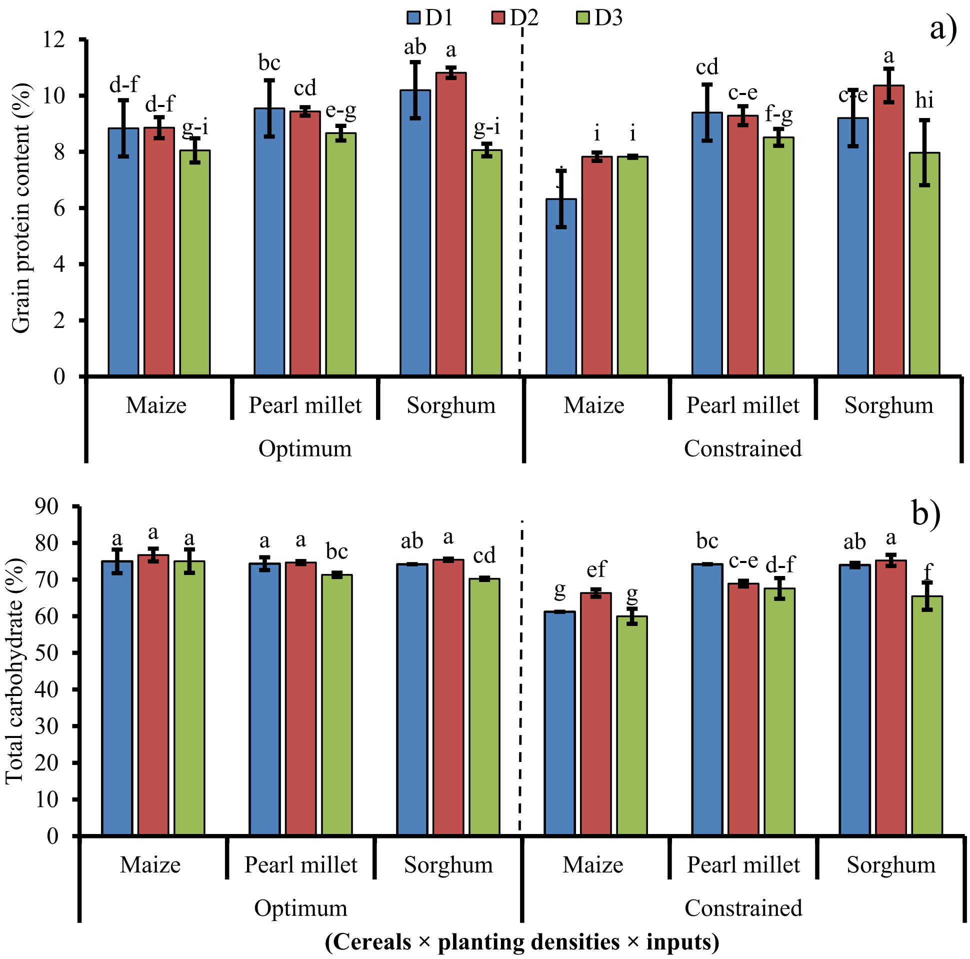

Fig. 4 Planned mean comparison of the applied factors on quality of summer cereals, **a** grain protein content and **b** total carbohydrate. Data are presented as mean ± standard deviation. *Different small letters* on the bars indicate significant differences at $p \leq 0.05$

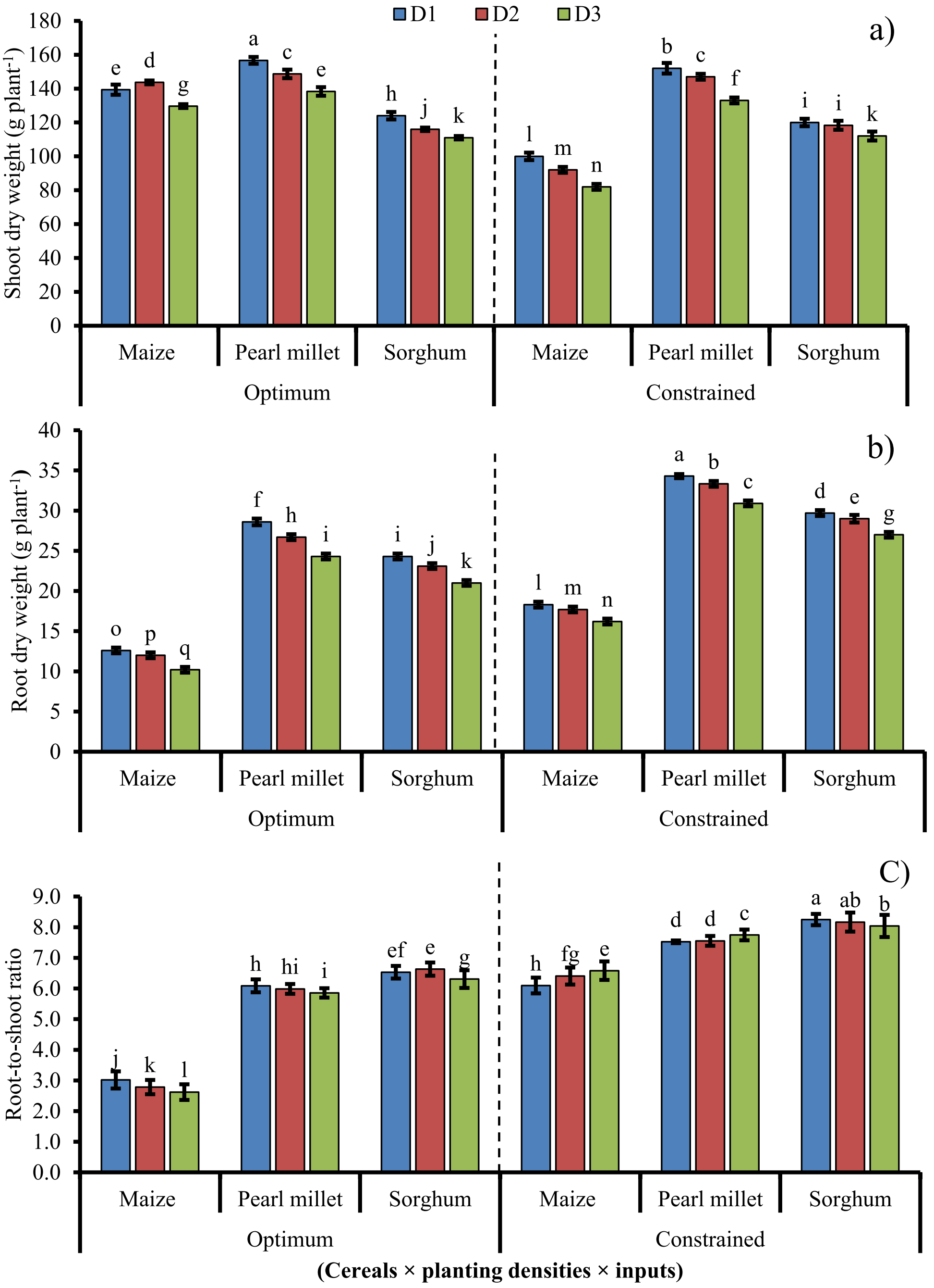

Fig. 5 Planned mean comparison of the applied factors on shoot and root dry weights (**a**, **b**) and the root-to-shoot ratio of summer cereals (**c**). Data are presented as mean ± standard deviation. *Different small letters* on the bars indicate significant differences at $p \leq 0.05$

Summer cereals differed significantly in the root-to-shoot ratio (R/S ratio), with sorghum recording the highest value (7). The R/S ratio was higher at D2 (5.86), while D1 (5.07) recorded the lowest value. Finally, the highest R/S ratio (7.3) was obtained under constrained input conditions, whereas a lower ratio (5.0) was observed under optimal inputs. Sorghum consistently maintained the highest R/S ratio under constrained input conditions (Fig. 5c).

3.5 Principal component analysis

Principal component analysis was performed for all the applied factors of the experiment to check the individual effects and relationships between the attributes studied (Fig. 6). It was revealed that thousand-grain weight, SPAD value and grain yield were more associated with maize crops while WUE, grain protein, and carbohydrate content were more related to sorghum crops. Lastly, pearl millet showed a closer association with shoot dry weight, leaf area,

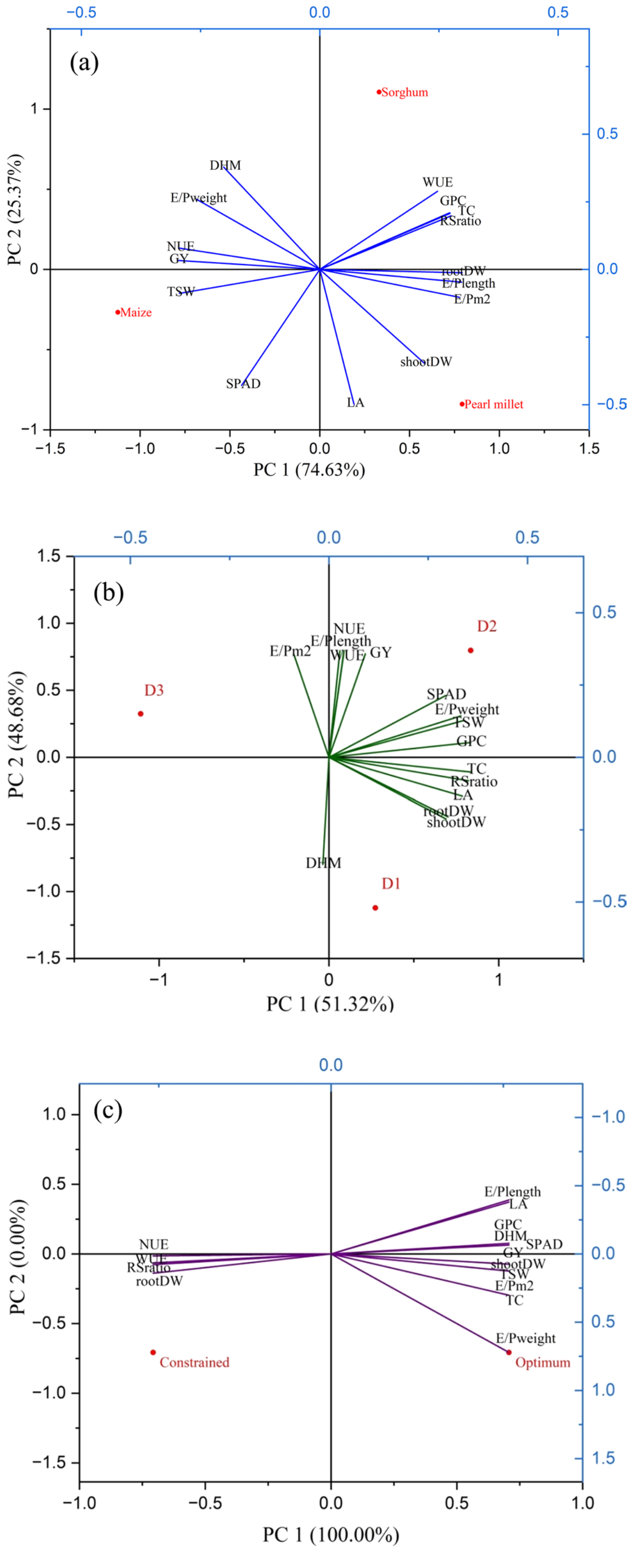

Fig. 6 Principal component analysis showing association of evaluated parameters with three cereals (**a**), planting densities (**b**) and inputs applied (**c**). E/P is ear/panicle length, LA is Leaf area, GPC is Grain protein content, DHM is Days to harvest maturity, GY is Grain yield, ShootDW is shoot dry weight, TSW is Thousand seed weight, E/Pm^2 is Ear/panicle m^2, E/Pweight is Ear/panicle weight, NUE is Nitrogen use efficiency, WUE is water use efficiency, RSratio is Root-to-shoot ratio and rootDW is root dry weight

ear/panicle weight, ear/panicle length and root dry weight, which was more related to pearl millet crop. Among planting densities, all the attributes studied were more associated with D2 except ear/panicle m^{-2} and days to harvest maturity which showed more association with D3 and D1, respectively. The inputs applied significantly affected various attributes with NUE, WUE, root dry weight and root shoot ratio showing more association with constrained inputs. On the other hand, attributes such as ear/panicle weight, ear/panicle m^{-2}, thousand-grain weight, grain yield, protein and carbohydrate content showed more association with the optimum application of inputs.

3.6 Economic analysis

Economic analysis was conducted to determine the best treatment combination economically feasible for farmers to adapt to changing climatic and financial orders. It was revealed that gross return was the highest (858.0) for sorghum crops when planting density was kept at D2, and the supplied inputs were optimum while the net benefit was highest when the density of sorghum crops was kept at D3, and the inputs were constrained (711.6). Similarly, this combination recorded the highest benefit–cost ratio among all the combinations (5.9) as stated in Table 5.

4 Discussion

A comparative assessment of crops is crucial for resource allocation in the face of climate change [32, 35, 57, 61, 63]. With global cereal production set to rise to meet increasing food demands, evaluating environmental impacts, i.e. water footprint and greenhouse gas emissions, is critical. Maize production is more vulnerable to resource changes than sorghum and millet [28]. Projections indicate that maize yields could decline by around 30% by 2030 in southern Africa, whereas sorghum yields are expected to decrease by only about 2% [33]. Research shows that sorghum is the fifth most important cereal worldwide, thriving in arid and semi-arid regions due to its drought and heat resilience [59].This study compared maize, pearl millet, and sorghum under varying planting densities and inputs (water and fertilizer) and found significant effects on yield and related traits. Notably, pearl millet exhibited the highest leaf area and ear/panicle per square meter, with D1 and D2 densities producing higher leaf area and D2 and D3 densities yielding greater ear/panicle numbers. The differences in physiological parameters are due to crop differences and adaptation to environmental conditions [5, 36].

Optimum inputs increased leaf area and ear/panicle density, with pearl millet having the longest ears and maize the heaviest. D2 planting and optimal conditions resulted in higher ear weights and improved thousand seed weight. Under limited input conditions, pearl millet and sorghum matured earlier, enabling farmers to prepare the land sooner for the next crop. In contrast, optimal input levels combined with D2 planting significantly enhanced overall yields. As per our findings, maize produced the highest yield, but it did not stay stable under constrained inputs compared to pearl millet and sorghum. Sorghum and millets tend to perform better in arid conditions compared to maize because their root systems are deeper and more fibrous, allowing them to access moisture from deeper soil layers, while their smaller leaf area and thicker, waxy cuticles reduce water loss through transpiration [14, 15]. Maman et al. [38] also reported that sorghum produced stable yield under drought stress. Similarly, Matsuura et al. [37] reported that pearl millet and sorghum showed less reduction in relative growth rate and net assimilation rate under drought conditions compared to maize. Liben et al. [31] also stated that sorghum is more economical in terms of nitrogen requirement than maize. Therefore, substituting maize with small grains has been suggested as a viable adaptation strategy in response to climate variability [33].

Sorghum exhibited the highest WUE, while maize had the highest NUE. These efficiencies of the cereals were improved when the inputs supplied were limited. Hasan et al. [20] concluded that PIP1,5 and PIP2;3 genes are highly responsive in sorghum compared to maize during water stress that maintains higher WUE in sorghum plants than maize. The increased root surface area and length density facilitate higher uptake rates by reducing the distance water must travel from the soil to the plant's vascular system. Upregulation of water channel proteins (aquaporins) further supports efficient water transport across cell membranes in sorghum [26]. The higher NUE of maize is due to its ability to recover applied fertiliser N efficiently in its aboveground biomass [4]. Maize also expresses a suite of high-affinity nitrate and ammonium transporters that enable efficient acquisition of nitrogen from the soil [10]. Once absorbed, enzymes such as nitrate reductase and glutamine synthetase operate at high activity levels in maize leaves, rapidly converting inorganic nitrogen into amino acids and proteins essential for growth and grain filling [44]. Optimal planting densities have been identified for each crop, with specific densities leading to maximum yield and growth parameters. For example, planting densities of 50,000 to 70,000 plants ha^{-1} in maize have been shown to produce the best cob length, grain weight, and overall yield [30]. Similarly, in sorghum, higher crop densities of over 7.5 plants m^{-2} have been found to suppress weed growth effectively and minimise yield losses in the study of Wang et al. [64].

Sorghum exhibited the highest grain protein content, while D2 resulted in the highest grain protein content among planting densities. Optimal inputs led to higher protein content compared to constrained inputs. Carbohydrate content was similar for sorghum and pearl millet, surpassing that of maize. D1 and D2 planting densities yielded higher

Table 5 Economic outcomes of maize cultivation under different planting densities and input conditions

Crops	Planting densities	Supplied inputs	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain yield cost	Straw yield cost	Gross return	Seed cost	Irrigation cost	Urea cost	P cost	K cost	Labor cost	Total cost	Net return	B:C
Maize	D1	Optimum	3035	4189	621.2	75.3	696.5	10.8	2.9	28.8	71.9	86.3	21.6	222.3	474.2	2.1
		Constrained	2004	3783	428.5	68.0	496.5	10.8	1.4	14.4	36.0	43.2	21.6	127.3	369.2	2.9
	D2	Optimum	3492	4362	706.5	78.5	785.0	13.5	2.9	28.8	71.9	86.3	21.6	225.0	560.0	2.5
		Constrained	2158	4088	461.7	73.5	535.2	13.5	1.4	14.4	36.0	43.2	21.6	130.0	405.1	3.1
	D3	Optimum	2971	4131	608.7	74.3	682.9	16.2	2.9	28.8	71.9	86.3	21.6	227.7	455.3	2.0
		Constrained	2515	4007	524.4	72.1	596.5	16.2	1.4	14.4	36.0	43.2	21.6	132.7	463.7	3.5
Pearl millet	D1	Optimum	1966	4123	565.8	74.2	639.9	2.3	2.9	28.8	71.9	86.3	21.6	213.8	426.1	2.0
		Constrained	1842	4128	530.1	74.2	604.3	2.3	1.4	14.4	36.0	43.2	21.6	118.8	485.5	4.1
	D2	Optimum	2206	4272	634.8	76.8	711.7	3.5	2.9	28.8	71.9	86.3	21.6	215.0	496.7	2.3
		Constrained	2158	4177	621.0	75.1	696.1	3.5	1.4	14.4	36.0	43.2	21.6	120.0	576.1	4.8
	D3	Optimum	1960	4352	564.0	78.3	642.3	4.6	2.9	28.8	71.9	86.3	21.6	216.1	426.2	2.0
		Constrained	2008	4161	577.8	74.8	652.7	4.6	1.4	14.4	36.0	43.2	21.6	121.2	531.5	4.4
Sorghum	D1	Optimum	2082	4067	674.0	73.1	747.2	3.2	2.9	28.8	71.9	86.3	21.6	214.7	532.5	2.5
		Constrained	2077	4044	672.4	72.7	745.1	3.2	1.4	14.4	36.0	43.2	21.6	119.7	625.4	5.2
	D2	Optimum	2425	4055	785.1	72.9	858.0	4.0	2.9	28.8	71.9	86.3	21.6	215.5	642.5	3.0
		Constrained	2312	4119	748.5	74.1	822.6	4.0	1.4	14.4	36.0	43.2	21.6	120.5	702.1	5.8
	D3	Optimum	2159	4052	699.0	72.9	771.8	4.7	2.9	28.8	71.9	86.3	21.6	216.3	555.6	2.6
		Constrained	2347	4061	759.8	73.0	832.9	4.7	1.4	14.4	36.0	43.2	21.6	121.3	711.6	5.9

Whereas, Grain cost (USD) (maize = 0.17, pearl millet = 0.28 and sorghum = 0.32) Straw cost = (0.02)

Seed rate (kg ha^{-1}) (maize = 0.25, pearl millet = 0.05 and sorghum = 0.03)

Fertilizer price (rupee/bag) = (urea = 14.38, DAP = 35.97 and SoP = 43.16)

Labor cost = 2.51 per day, Electricity cost = 0.16 per unit

Values presented are in United States Dollars (USD) carbohydrate content. Rajalakshmi et al. [52] reported that the nutritional value of pearl millet and sorghum is higher than maize, which their proximate analysis can justify. Pearl millet exhibited the highest RDW and SDW. Compared to maize, pearl millet has a greater capacity for dry matter accumulation, especially under drought conditions [23]. Pearl millet can extend its roots during periods of limited resources, allowing it to access further away resources, which results in higher root length and biomass. Limited resource availability led to a higher RDW compared to optimal resource supply. When resources, i.e. water and nutrients, are scarce, plants invest more in root growth to explore a larger soil volume [11], enhancing their ability to capture these limited inputs. Hormonal signals, including increased levels of abscisic acid under stress, further promote root elongation and branching [25]. Sorghum demonstrated the highest root-to-shoot ratio (R/S ratio), with D2 showing the highest ratio. Constrained inputs resulted in a higher R/S ratio compared to optimal inputs. Under constrained inputs, shoot growth is reduced while root growth expands, enhancing the plant's ability to absorb water and nutrients. Consequently, a higher R/S ratio is observed in plants experiencing severe drought conditions [45].

Economic analysis revealed the performance of all crops under various treatment combinations to explore the most economically viable option for adaptation. Sorghum under normal planting density and limited inputs reported higher net returns and benefit–cost ratios than other combinations. In India, sorghum is a major coarse cereal crop with a strong history of high production and yields, making it a financially appealing choice for farmers [53]. Genetic enhancement studies on sorghum and millet have revealed high rates of return on research investments, ranging from 54 to 76% annually, underscoring the economic advantages of these crops [49]. Furthermore, improvements in sorghum processing and market connections have boosted farm incomes and established sustainable value chain models, demonstrating the economic viability of sorghum cultivation [66]. These findings are significant for climate change adaptation, especially in areas facing increased aridity, erratic rainfall, and higher temperatures. Sorghum and pearl millet maintain stable yields under water stress and efficient water uptake, unlike maize, which is more vulnerable to drought. Keeping in view the recent development and findings of our research, the cultivation of small grain crops like pearl millet and sorghum is encouraged.

5 Conclusions

This study provides a comparative assessment of maize, pearl millet, and sorghum under different planting densities and input conditions, highlighting the adaptability and performance of these cereals in resource-constrained environments. The results showed significant differences in yield characteristics, water use efficiency (WUE), and nitrogen use efficiency (NUE) among the studied cereals. While maize had the highest yield and NUE under optimal conditions, sorghum emerged as the most water-efficient crop, offering resilience in drought-prone regions. Pearl millet showed remarkable adaptability by maintaining robust dry matter accumulation and shoot–root ratios under constrained inputs. The economic analysis highlighted the superior cost-effectiveness of sorghum at high planting densities and limited inputs, achieving the highest benefit–cost ratio. These results highlight the potential of sorghum and pearl millet as sustainable alternatives to maize in regions facing climate variability and resource constraints. Future research should investigate the long-term effects of input constraints on soil health and productivity while integrating genetic advances to improve the resilience and nutritional profiles of these cereals. Policymakers and farmers should consider adopting cropping strategies and input management adapted to local climatic and economic conditions to ensure sustainable agricultural practices.

Author contributions Uzair Ahmed: Conceptualization, Data Curation, Investigation, Writing—Original Draft Preparation. Waleed Iqbal: Methodology, Formal Analysis, Visualization, Writing—Review & Editing. Hazrat Amin: Software, Validation, Resources. Emaan Noor: Data Curation, Writing—Review & Editing, Project Administration. Aftab Jamal: Conceptualization, Supervision, Funding Acquisition, Writing—Review & Editing. Muhammad Farhan Saeed: Methodology, Validation, Writing—Original Draft Preparation. Jakub Černý: Conceptualization, Supervision, Resources, Writing—Review & Editing.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate The collection of crop seeds used in this study complies with local and national guidelines, and no further affirmation is required.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Afzal M, Ahmad A, Ahmad AUH. Effect of nitrogen on growth and yield of sorghum forage (*Sorghum bicolor* (L.) Moench cv.) under three cuttings system. Cerc Agron Mol. 2012;45:57–64.
2. Agapie AL, Florin SALA. Leaf area in grass cereals in relation to leaf parameters; case study in wheat. Life Sci Sustainable Dev. 2023;4(1):41–50. https://doi.org/10.58509/lssd.v4i1.234.
3. Alexander. Introduction to soil microbiology. Soil Sci. 1978;5:331.
4. Aliyu ML, Tijjani SA, Ameh DA, Babagana A. Glycemic index of traditional meal (Dambu) from pearl millet and maize. Sci J Anal Chem. 2020;8:29–32.
5. Assefa Y, Roozeboom K, Thompson C, Schlegel A, Stone L, Lingenfelser JE. Corn and grain sorghum morphology, physiology and phenology. In: Corn and grain sorghum comparison. 2014; p. 3–14.
6. Atteh JO. Principles and practice of livestock feed manufacturing. Ilorin: Adlek Printers; 2002. p. 52–8.
7. Ben Mohamed A, Van Duivenbooden N, Abdoussallam S. Impact of climate change on agricultural production in the Sahel-Part 1. Methodological approach and case study for millet in Niger. Clim Change. 2002;54(3):327–48. https://doi.org/10.1023/A:1016189605188.
8. Berzsenyi Z, Tokatlidis IS. Density dependence rather than maturity determines hybrid selection in dryland maize production. Agron J. 2012;104(2):331–6. https://doi.org/10.2134/agronj2011.0205.
9. Brekke B, Edwards J, Knapp A. Selection and adaptation to high plant density in the Iowa stiff stalk synthetic maize (*Zea mays* L.) population. Crop Sci. 2011;51(5):1965–72. https://doi.org/10.2135/cropsci2010.09.0563.
10. Cao H, Liu Z, Guo J, Jia Z, Shi Y, Kang K, Yuan L. ZmNRT1. 1B (ZmNPF6.6) determines nitrogen use efficiency via regulation of nitrate transport and signalling in maize. Plant Biotechnol J. 2024;22(2):316–29. https://doi.org/10.1111/pbi.14185.
11. Comas LH, Becker SR, Cruz VMV, Byrne PF, Dierig DA. Root traits contributing to plant productivity under drought. Front Plant Sci. 2013;4:442. https://doi.org/10.3389/fpls.2013.00442.
12. Choudhary S, Guha A, Kholova J, Pandravada A, Messina CD, Cooper M, Vadez V. Maize, sorghum, and pearl millet have highly contrasting species strategies to adapt to water stress and climate change-like conditions. Plant Sci. 2020;295: 110297. https://doi.org/10.1016/j.plantsci.2019.110297.
13. Dobermann AR. Nitrogen use efficiency-state of the art. Frankfurt: Agronomy Faculty Publications; 2005. p. 316.
14. Djanaguiraman M, Priyanka AS, Vaishnavi SJ, Perumal R, Ciampitti IA, Prasad PV. Impact of drought and high-temperature stresses on growth and development stages, physiological, reproductive, and yield traits on pearl millet. In: Pearl millet: a resilient cereal crop for food, nutrition, and climate security. 2024. 249–276. https://doi.org/10.1002/9780891184034.ch9
15. Djanaguiraman M, Prasad PVV, Ciampitti IA. Growth, development and physiology of grain sorghum. In: Rooney B, editor. Achieving sustainable cultivation of sorghum volume 2. London: Burleigh Dodds Science Publishing; 2018. p. 81–102.
16. Farhan M, Sathish M, Kiran R, Mushtaq A, Baazeem A, Hasnain A, Hakim F, Naqvi SAH, Mubeen M, Iftikhar Y, Abbas A, Hassan MZ, Moustafa M. Plant nitrogen metabolism: balancing resilience to nutritional stress and abiotic challenges. Phyton. 2024;93(3):581–609.
17. Fawad M, Khan MA, Wahid F, Khan H, Gul B, Khattak AM, et al. Irrigation scheduling and weed management: a sustainable approach for managing Broomrape and other weeds in tomato crop. Horticulturae. 2022;8(8):676. https://doi.org/10.3390/horticulturae8080676.
18. Foth HD. Fundamentals of soil science. 6th ed. Hoboken, NJ: Wiley; 1982.
19. Garoma B. Conventional and molecular improvement of maize for drought tolerance: research review. J Environ Sci Agric Res. 2024. https://doi.org/10.60105/josaet.2024.2.3.87-92.
20. Hasan SA, Rabei SH, Nada RM, Abogadallah GM. Water use efficiency in the drought-stressed sorghum and maize in relation to expression of aquaporin genes. Biol Plant. 2017;61:127–37. https://doi.org/10.1007/s10535-016-0656-9.
21. Hermanson R, Pan W, Perillo C, Stevens R, Stockle C. Nitrogen use by crops and the fate of nitrogen in the soil and vadose zone. Washington State University and Washington Department of Ecology Interagency Agreement; 2000 (C9600177).
22. Herrera E. Soil Test Interpretations Guide A-122. New Mexico State University Board of Regents. 2000. http://www.nmsu.edu/pubs/_a/A122/. Accessed 21 Aug 2024.
23. Igbetar BD, Bosch C, Orfila C. Pearl millet: a sustainable cereal with low glycemic potential. Proc Nutr Soc. 2018;77(OCE4):E136.

24. Iqbal W, Khan A, Jamal A, Radicetti E, Elsadek MF, Ali MA, Mancinelli R. Optimizing maize productivity and soil fertility: insights from tillage, nitrogen management, and hydrochar applications. Land. 2024;13(8):1329. https://doi.org/10.3390/land13081329.
25. Jia Z, Giehl RF, von Wirén N. Nutrient–hormone relations: driving root plasticity in plants. Mol Plant. 2022;15(1):86–103. https://doi.org/10.1016/j.molp.2021.12.004.
26. Kadam S, Abril A, Dhanapal AP, Koester RP, Vermerris W, Jose S, Fritschi FB. Characterization and regulation of aquaporin genes of sorghum [*Sorghum bicolor* (L.) Moench] in response to waterlogging stress. Front Plant Sci. 2017;8:862. https://doi.org/10.3389/fpls.2017.00862.
27. Kirk PL. Kjeldahl method for total nitrogen. Anal Chem. 1950;22(2):354–8. https://doi.org/10.1021/ac60038a038.
28. Knox J, Hess T, Daccache A, Wheeler T. Climate change impacts on crop productivity in Africa and South Asia. Environ Res Lett. 2012;7(3):34032.
29. Lengwati DM, Mathews C, Dakora FD. Rotation benefits from N2-fixing grain legumes to cereals: from increases in seed yield and quality to greater household cash-income by a following maize crop. Front Sustainable Food Syst. 2020;4:94. https://doi.org/10.3389/fsufs.2020.00094.
30. Li H-Q, Pei R-J, Lin H-M, Yuan L-G, Hu W-W, Zhao H-J, Wang J-Z. Effects of planting density and mode on summer maize chloroplastD1 protein and photo-system II. Chin J Eco-Agric. 2012;20(9):1142–8. https://doi.org/10.3724/SP.J.1011.2012.01142.
31. Liben FM, Adisu T, Atnafu O, Bekele I, Berhe H, Wortmann CS. Maize and sorghum nutrient response functions for Ethiopia. Nutr Cycl Agroecosyst. 2020;117:401–10. https://doi.org/10.1007/s10705-020-10077-7.
32. Liu Y, Tao F. Impacts and uncertainty analysis of elevated temperature and CO_2 concentration on wheat biomass. J Geog Sci. 2012;22:1002–12. https://doi.org/10.1007/s11442-012-0979-1.
33. Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, Naylor RL. Prioritizing climate change adaptation needs for food security in 2030. Science. 2008;319(5863):607–10. https://doi.org/10.1126/science.1152339.
34. Macauley H, Ramadjita T. Cereal crops: Rice, maize, millet, sorghum, wheat. 2015. http://hdl.handle.net/123456789/4510.
35. Mali SS, Shirsath PB, Islam A. A high-resolution assessment of climate change impact on water footprints of cereal production in India. Sci Rep. 2021;11(1):8715. https://doi.org/10.1038/s41598-021-88223-6.
36. Masenya TI, Mlambo V, Mnisi CM. Complete replacement of maize grain with sorghum and pearl millet grains in Jumbo quail diets: Feed intake, physiological parameters, and meat quality traits. PLoS ONE. 2021;16(3): e0249371. https://doi.org/10.1371/journal.pone.0249371.
37. Matsuura A, Inanaga S, Sugimoto Y. Mechanism of interspecific differences among four gramineous crops in growth response to soil drying. Jap J Crop Sci. 1996;65(2):352–60.
38. Maman N, Lyon DJ, Mason SC, Galusha TD, Higgins R. Pearl millet and grain sorghum yield response to water supply in Nebraska. Agron J. 2003;95(6):1618–24. https://doi.org/10.2134/agronj2003.1618.
39. Moll RH, Kamprath EJ, Jackson WA. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization 1. Agron J. 1982;74(3):562–4. https://doi.org/10.2134/agronj1982.00021962007400030037x.
40. Naseri B, Hamadani SA. Characteristic agro-ecological features of soil populations of bean root rot pathogens. Rhizosphere. 2017;3:203–8. https://doi.org/10.1016/j.rhisph.2017.05.005.
41. Naseri B, Tabande L. Patterns of Fusarium wilt epidemics and bean production determined according to a large-scale dataset from agro-ecosystems. Rhizosphere. 2017;3:100–4. https://doi.org/10.1016/j.rhisph.2017.02.002.
42. Naseri B. The potential of agroecological properties in fulfilling the promise of organic farming: a case study of bean root rots and yields in Iran. In: Organic farming. 2023; p. 203–236. https://doi.org/10.1016/B978-0-323-99145-2.00011-2.
43. Nandini KM, Sridhara S. Response of growth, yield and quality parameters of foxtail millet genotypes to different planting density. Int J Curr Microbiol App Sci. 2019;8(2):1765–73. https://doi.org/10.20546/ijcmas.2019.802.208.
44. Nunes EN, de Araujo Montenegro IN, Fernandes YTD, do Nascimento DAM, do Nascimento R, Alves CAB, Souto JS. Biochemical responses of maize (*Zea mays* L.) cultivars subjected to nitrate and glutamine fertilizers. Afr J Agric Res. 2014;9(50):3663–71. https://doi.org/10.5897/AJAR2014.8716.
45. Nejad TS. Effect of drought stress on shoot/root ratio. World Acad Sci Eng Technol. 2011;81:598–600.
46. Olsen S. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. 939th edition. US Department of Agriculture; 1954.
47. O'Kennedy MM, Grootboom A, Shewry PR. Harnessing sorghum and millet biotechnology for food and health. J Cereal Sci. 2006;44(3):224–35. https://doi.org/10.1016/j.jcs.2006.08.001.
48. Patel K, Gartaula H, Johnson D, Karthikeyan M. The interplay between household food security and wellbeing among small-scale farmers in the context of rapid agrarian change in India. Agric Food Secur. 2015;4:1–16. https://doi.org/10.1186/s40066-015-0036-2.
49. Prabhakar MR, Aruna C. Sorghum breeding. In: Fundamentals of field crop breeding, p. 367–447. Cham: Springer; 2022. https://doi.org/10.1007/978-981-16-9257-4_7
50. Qaisrani SN, Murtaza S, Khan AH, Bibi F, Iqbal SMJ, Azam F, et al. Variability in millet: factors influencing its nutritional profile and zootechnical performance in poultry. J Appl Poultry Res. 2019;28(2):242–52. https://doi.org/10.3382/japr/pfy073.
51. Qiao M, Hong C, Jiao Y, Hou S, Gao H. Impacts of drought on photosynthesis in major food crops and the related mechanisms of plant responses to drought. Plants. 2024;13(13):1808. https://doi.org/10.3390/plants13131808.
52. Rajalakshmi G, Gnanalaksshmi KS, Baskaran D, Reiyaz MA. Proximate composition of sorghum grain and pearl millet. Int J Agric Sci Res. 2021;11(1):97–102.
53. Rao BD. Sorghum value chain for food and fodder security. In: Breeding sorghum for diverse end uses, p. 409–419. Amsterdam: Elsevier; 2019. https://doi.org/10.1016/B978-0-08-101879-8.00023-1
54. Reddy PP, Reddy PP. Climate change adaptation. Climate resilient agriculture for ensuring food security, 2015; p. 223–272.
55. Riaz B, Ali S, Jan D. Acreage response analysis of maize growers in Khyber Pakhtunkhwa, Pakistan. Int J Food Agric Econ. 2014;2(3):33–44.
56. Sahu H, Tomar GS, Nandeha N. Effect of planting density and levels of nitrogen on yield and yield attributes of sweet sorghum (*Sorghum bicolor* [L.] Moench) varieties. Int J Chem Stud. 2018;6(1):2098–101.
57. Singh M, Mishra GC, Mall RK. Assessment of climate change on wheat (*Triticum aestivum*) production using crop simulation under Indo-Gangetic Plains. Indian J Agric Sci. 2022;92(3):413–5.

58. Sultan B, Roudier P, Quirion P, Alhassane A, Muller B, Dingkuhn M, et al. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ Res Lett. 2013;8(1):14040.
59. Taylor JRN, Taylor J. Chapter 17 - Sorghum and millets. In: Shewry PR, Koksel H, Taylor JRN (eds) ICC handbook of 21st century cereal science and technology. Academic Press; 2023. p. 161–171. https://doi.org/10.1016/B978-0-323-95295-8.00039-3
60. Uzoh IM, Igwe CA, Okebalama CB, Babalola OO. Legume-maize rotation effect on maize productivity and soil fertility parameters under selected agronomic practices in a sandy loam soil. Sci Rep. 2019;9(1):8539. https://doi.org/10.1038/s41598-019-43679-5.
61. Vinci G, Ruggieri R, Ruggeri M, Zaki MG. Application of Life Cycle Assessment (LCA) to cereal production: an overview. IOP Conf Ser. 2022;1077:12004.
62. Walkley A, Black IA. An examination of the Degtjarett method for determination of soil organic matter and a proposed modification of chromic acid titration method. Soil Sci. 1934;37:29–38.
63. Wang J, Vanga SK, Saxena R, Orsat V, Raghavan V. Effect of climate change on the yield of cereal crops: a review. Climate. 2018;6(2):41. https://doi.org/10.3390/cli6020041.
64. Wang Y, Wang EJ, Wang Y, Yang LG. Effects of planting density on growth and yield of a edible sorghum hybrid PLiaoza 13R. Liaoning Agric Sci. 2010;6:24–7.
65. Younesi H, Chehri K, Sheikholeslami M, Safaee D, Naseri B. Effects of sowing date and depth on Fusarium wilt development in chick pea cultivars. J Plant Pathol. 2020;102(2):343–50. https://doi.org/10.1007/s42161-019-00423-2.
66. Zereyesus YA, Dalton TJ. Rates of return to sorghum and millet research investments: a meta-analysis. PLoS ONE. 2017;12(7): e0180414. https://doi.org/10.1371/journal.pone.0180414.
67. Zhang G, Liu C, Xiao C, Xie R, Ming B, Hou P, et al. Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. Field Crop Res. 2017;211:137–46. https://doi.org/10.1016/j.fcr.2017.05.026.