



RESEARCH ARTICLE

Influence of real time nitrogen management and optimisation of phosphorus and potassium on productivity of grain sorghum in South Odisha

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Abstract

Sorghum is emerging as a climate-resilient cereal due to its adaptability to heat and soil moisture stress; however, its high nutrient demand necessitates efficient nutrient management for sustaining productivity under changing climatic conditions. Conventional blanket fertiliser application often leads to nutrient imbalance, low use efficiency and environmental concerns. In this context, the present study was conducted to evaluate the effect of precision nitrogen management integrated with different levels of phosphorus and potassium on growth, yield attributes and yield of grain sorghum. The experiment was laid out in a factorial randomised block design with four nitrogen management practices, namely recommended dose of nitrogen, Soil Plant Analysis Development (SPAD)-based sufficiency index < 90 %, SPAD-based sufficiency index < 95 % and Normalised Difference Vegetation Index (NDVI)-based relative index > 1.15 and 3 levels of phosphorus and potassium (75 %, 100 % and 125 % of recommended dose), replicated thrice. The results revealed that precision nitrogen management significantly influenced growth attributes, yield attributes and yield of sorghum. Among the nitrogen management practices, SPAD-based sufficiency index < 95 % recorded the maximum plant height, dry matter accumulation, leaf area index, yield attributes, grain yield (3274 kg/ha), stover yield (11230 kg/ha) and biological yield (14503 kg/ha) and remained superior to the conventional recommended dose of nitrogen. Similarly, the application of 125 % recommended dose of phosphorus and potassium resulted in significantly higher growth and yield parameters compared to lower levels. The interaction effect showed that SPAD-based sufficiency index < 95 % in combination with higher levels of phosphorus and potassium produced the highest yields. Regression analysis further confirmed a strong positive relationship between growth and yield attributes with grain yield. The study concluded that precision nitrogen management and SPAD-based sufficiency index, along with adequate phosphorus and potassium fertilisation, can be effectively adopted to enhance the productivity of grain sorghum.

Keywords: normalised difference vegetation index; P and K dose optimisation; precision nitrogen management; soil plant analysis development; yield

Introduction

The green revolution scenario driven by fossil fuel created emphasis for enhancing productivity through higher resource use. However, this approach fostered many inefficiencies in agricultural input optimisation and nutrient management that now undermine the long-term sustainability. Excessive and indiscriminate use of synthetic fertilisers, agro-chemicals and irrigation water driven by a productivity first paradigm has disrupted various factors like soil nutrient cycling, reduced input use efficiency and accelerated environmental pollution (1–4). Optimising nutrient inputs through precision management strategies is therefore not only an agronomic advancement but also a climate resilient approach, as agriculture remains among the foremost contributors to greenhouse gas emissions, particularly through nitrification and denitrification losses from poorly managed nitrogen inputs. Hence, such a situation demands a climate-smart approach to crop production to support the current and future food demands (5–9). Under this changing

climatic scenario, a climate-smart crop such as sorghum (*Sorghum bicolor* L.) can not only emerge as a sentinel crop but also fulfil the world's food and nutritional needs (10). The physiological robustness towards heat adaptation and intermittent water stress defines sorghum as “Camel Crop” (11). Similar to maize, a C4 crop, sorghum is also consumed as grain, feed, fodder and bioenergy. Sorghum demands an adequate amount of nitrogen (N), phosphorus (P) and potassium (K) for optimum growth and productivity (12). P and K play a pivotal role in root proliferation, energy transfer, osmotic regulations, enzymatic activation and stress resilience, whereas N is the major nutrient contributing to vegetative growth and grain filling. However, the conventional blanket application of fertilisers leads to luxury consumption or deficiency of these primary nutrients, resulting in stunted growth, chlorosis, physiological abnormalities and decreased productivity (13). Additionally, the conventional fertiliser recommendation is static and generalised for a larger region, which fails to consider the spatio-temporal variability of crop nutrient demand under the changing climatic scenario (14).

Convincingly, this particular criterion is also essential for state of Odisha where high level of spatial variability exists among the soil fertility status under varied agroclimatic regions of the state.

Nitrogen transformation, particularly in the current scenario, has been accelerated by volatilisation and leaching losses, which not only reduce the N-use efficiency (NUE) but also contribute largely to greenhouse gas (GHG) emissions while strengthening the climate change (15). Amid such a situation, real-time nitrogen management (RTNM) has emerged as a sustainable approach to address the dynamics of N demand. The RTNM through handheld leaf optical sensors, such as chlorophyll meters like Soil Plant Analysis Development (SPAD)-502 (which measures relative leaf chlorophyll content through dual-wavelength optical transmittance, providing rapid, non-destructive spectral assessment of nitrogen status), leaf colour chart (LCC), sensor-based and spectrum-based diagnostic devices and an algorithm-driven diagnostic platform enables real-time N assessment and adjustment (16, 17). In a crop like sorghum, which exhibits rapid vegetative growth, high N response and biomass potential, RTNM can maximise its photosynthetic efficacy and grain development (18). Many recent studies also revealed that application of various optical sensors and indices like NDVI has improved the nutrient use efficiency and observed superior growth and productivity of the crops like rice and maize (19). In recent days, the emphasis on precise application of N has overshadowed the roles of P and K, which act as cornerstones to safeguard a resilient nutrient regime (19). The agronomic efficiency of nitrogenous fertiliser is directly related to the balanced application of P and K availability. An optimum P dose increases N uptake due to root proliferation, whereas sufficient application of K supports N assimilation, enzyme activation and grain filling (20). Hence, the imbalance of P or K invalidates the yield achieved through RTNM strategies. Moreover, P and K are less mobile in soil and thus, managed more as soil amendments or through optimisation (21). The synergistic integration of RTNM and optimisation of P and K can create a critical physiological system which can enhance nutrient uptake partitioning, use efficiency, productivity and profitability while aligning directly and indirectly with various United Nations Sustainable Development Goals (SDGs) such as SDG 2 (Zero hunger), SDG 3 (Good health), SDG 6 (Clean water), SDG 12 (Responsible consumption), SDG 13 (Climate action) and SDG 15 (Life on land). Therefore, with the intent to facilitate an agronomic protocol that aligns with intensive agriculture, adapting resource stewardship and climate risk mitigations, a field study was designed to evaluate the influence of real-time nitrogen management and optimisation of phosphorus and potassium on productivity of grain sorghum under irrigated conditions of Odisha.

Materials and Methods

During the rabi season, a field experiment was carried out at the P.G. Research Farm of M.S. Swaminathan School of Agriculture, Centurian University of Technology and Management, Paralakhemundi, Odisha (18°80' N latitude, 84°18' E longitude) at 64 m above mean sea level. The trial was conducted from 18 January to 13 May 2025. Weekly maximum and minimum temperatures recorded were 44 °C to 33 °C and 25.8 °C to 16.8 °C, respectively. The weekly maximum and minimum relative humidity ranged from 87.6 %–72.1 % and 68.4–59.5.9 % respectively. During the cropping period, the crop received a total of 89.1 mm of rainfall. Initial soil samples were collected from random locations at a depth of 0–15 cm in the experimental field. The texture of the experimental site was sandy loam. The pH was 6.3 and the electrical conductivity was 0.24 dS/m. A chemical analysis of plots revealed that organic carbon content was 0.4 %. The availability of N, P and K was 273.6, 11.7 and 125.3 kg/ha, respectively. The field study used a factorial randomised block design (FRBD) with 12 treatment combinations and 3 replications. Precision N management was the first factor and different levels of P and K were the second. The first factor comprised of four nitrogen management practices: N₁: recommended dose of nitrogen (RDN) (80 N kg/ha), N₂: nitrogen application through SPAD-based sufficiency index < 90 %, N₃: nitrogen application through SPAD-based sufficiency index < 95 % and N₄: nitrogen application based on NDVI reference index (RI) > 1.15 (Table 1). The second factor included three levels of Phosphorus and Potassium (P and K): T₁: 75 % recommended dose of P and K (RD of P and K) (30:30 kg/ha), T₂: 100 % RD of P and K (40:40 kg/ha) and T₃: 125 % RD of P and K (50:50 kg/ha). The sorghum hybrid MLSH-2428 (Mahalaxmi) was considered for the experiment, which has a duration of 120 days. Seeds were sown at a spacing of 45 cm × 15 cm. A pre-emergence application of Atrazine 50 % WP at 2.33 g/L of water was made 3 days after sowing (DAS). A weeding was held on 24 DAS. To manage fall armyworm (*Spodoptera frugiperda*), Emamectin benzoate 5 % SG at 2.33 g/L of water was sprayed at 37 DAS. Seven irrigations were provided as per crop needs. Growth attributes such as plant height, leaf area and dry matter accumulation were recorded at different growth stages. Yield attributes, including panicle length, panicle weight, panicle girth, number of grains/panicle and grain yield, were recorded at harvest. All data collected were analysed statistically using analysis of variance (ANOVA), standard error of means (SEM ±) and critical difference at a 5 % probability level of significance (22).

Table 1. Nitrogen split applications and dosage as per treatment

Treatment details	Nitrogen application (kg/ha)								Total nitrogen
	Basal (0 DAS)	20 DAS	30 DAS	Up to 30 DAS	40 DAS	50 DAS	60 DAS	Up to 60 DAS	
N ₁ T ₁	40	0	20	60	0	20	0	80	80
N ₁ T ₂	40	0	20	60	0	20	0	80	80
N ₁ T ₃	40	0	20	60	0	20	0	80	80
N ₂ T ₁	27	20	20	67	20	0	0	87	87
N ₂ T ₂	27	20	20	67	20	0	0	87	87
N ₂ T ₃	27	20	20	67	20	0	0	87	87
N ₃ T ₁	27	20	20	67	20	20	20	127	127
N ₃ T ₂	27	20	20	67	20	20	20	127	127
N ₃ T ₃	27	20	20	67	20	20	20	127	127
N ₄ T ₁	27	20	20	67	20	20	0	107	107
N ₄ T ₂	27	20	20	67	20	20	0	107	107
N ₄ T ₃	27	20	20	67	20	20	0	107	107

Results and Discussion

Growth attributes

Precision nitrogen management and different levels of Phosphorus (P) and Potassium (K) showed significant influence on plant height, dry matter accumulation (DMA) and leaf area index (LAI) of sorghum (Table 1 and 2). In the case of precision N management, the taller plant height (241.43 cm), the highest DMA (1407.3 g/m²) and LAI (4.37) were recorded in the treatment SPAD-based sufficiency index <95 %, which remained statistically at par with the treatment of NDVI-based relative index >1.15 in expression of plant height of sorghum. Further, the treatment SPAD-based sufficiency index <95 % remained significantly superior to all other nitrogen management treatments in the expression of DMA and LAI. Moreover, the above-mentioned growth attributes registered their lowest values in 100 % RDN application. Such results pronounced the impact of precision nitrogen tools, namely SPAD and NDVI, which influenced the expression of the highest growth attributes of sorghum. The application of nitrogen through precision nutrient tools probably provided a sufficient quantity of nitrogen at the right time, which improved nutrient uptake by sorghum, resulting in robust plant growth throughout the vegetative phase. Moreover, the SPAD-based precision nitrogen management outperformed the NDVI and RDN treatments in some growth attributes, thereby excelling as the most efficient precision tool for enhancing growth in sorghum cultivation. Similar findings in maize were also observed by (23–25).

In case of graded levels of phosphorous and potassium, the higher values of growth attributes, namely, plant height (233.78 cm), DMA (1253.1 g/m²) and LAI (4.17) were recorded in the treatment 125 % recommended dose of P and K. Further this treatment remains on par with 100 % recommended dose of P and K in expression of plant height. However, the 125 % RD of P and K treatment remained significantly superior to all other treatments in expressing DMA and LAI. As expected, 75 % RD of P and K recorded the lowest values of the growth attributes of sorghum. Due to inferior soil nutrient status, the increased application of P and K (125 %) probably improved nutrient availability to sorghum plants, enhancing the growth attributes at

various stages (26, 27). The interaction effect between the precision N management and different levels of P and K showed a significant influence for DMA, where the highest values was observed in SPAD sufficiency index <95 % in combination to 125 % RD of P and K. However, the interaction effect showed non-significant influence in case of plant height and LAI (27).

Yield attributes

Yield attributes, namely panicle length, panicle weight, panicle girth, number of grains/panicle and test weight, were significantly influenced by precision nitrogen management and different levels of P and K (Table 3). The greater value of yield attributes, namely, panicle weight (163.76 g), panicle length (38.69 cm), girth of panicle (17.24 cm), number of grains/panicle (1320) and test weight (36.85 g), were registered in the treatment with SPAD-based sufficiency index <95 % for precision nitrogen management. Further, this treatment showed superiority over all other treatments considered in the study. The lowest value of these yield attributes was recorded in the 100 % RDN application, highlighting its inferiority to precision nitrogen management. Timely nitrogen application guided by SPAD readings ensured continuous nitrogen availability during critical panicle initiation and grain-filling, which directly influenced panicle development and grain formation. Further, sustained nitrogen availability during these key phenological stages enhanced photosynthetic efficiency, maintained chlorophyll stability and improved assimilate production, all of which were essential for effective translocation of photosynthates from source leaves to developing panicles, thereby improving the yield attributes of sorghum (24, 28, 29).

The maximum value of panicle weight (146.93 g), panicle length (34.72 cm), girth of the panicle (15.47 cm), number of grains/panicle (1184) and test weight (33.74 g) were noted with 125 % of RD of P and K in case of varied levels of application. Moreover, this treatment remained on par with the 100 % RD of P and K expressing test weight (31.51 g); however, it showed significant superiority to all other treatments for remaining yield attributes. The treatment consisted of 75 % RD of P and K, which recorded lower values regarding the yield attributes of grain sorghum. Similar to growth attributes, the ample application of P and K (125 % RDF) significantly enhanced the yield attributes (30, 31). The

Table 2. Influence of precision nitrogen management and different levels of P and K on plant height, dry matter accumulation, leaf area index of grain sorghum

Treatments	Plant height at harvest (cm)	Dry matter accumulation at harvest (g/m ²)	Leaf area index at 60 DAS
Precision nitrogen management (N)			
N ₁ : Recommended dose of nitrogen	213.20	913.1	3.32
N ₂ : Nitrogen application through SPAD sufficiency index < 90 %	216.92	952.5	3.53
N ₃ : Nitrogen application through sufficiency index < 95 %	241.43	1407.3	4.37
N ₄ : NDVI-based nitrogen application	228.76	1167.3	3.91
S. Em. ±	4.78	22.8	0.08
CD at 5 %	14.01	66.8	0.24
Different levels of P and K (T)			
T ₁ : 75 % recommended dose of P and K	216.26	981.1	3.40
T ₂ : 100 % recommended dose of P and K	225.20	1096.0	3.78
T ₃ : 125 % recommended dose of P and K	233.78	1253.1	4.17
S. Em. ±	4.14	19.7	0.07
CD at 5 %	12.14	57.9	0.21
N x T interaction			
S. Em. ±	8.28	39.5	0.14
CD at 5 %	NS	115.7	NS

(NS: Not Significant)

Table 3. Influence of precision nitrogen management and different levels of P and K on yield attributes of grain sorghum

Treatments	Yield attributes				
	Weight of panicle (g)	Length of panicle (cm)	Girth of panicle (cm)	Number of grains/panicles	Test weight (g)
Precision nitrogen management (N)					
N ₁ : Recommended dose of nitrogen	108.44	25.52	11.39	877	27.50
N ₂ : Nitrogen application through SPAD sufficiency index < 90 %	112.74	26.65	11.84	905	28.76
N ₃ : Nitrogen application through sufficiency index < 95 %	163.76	38.69	17.24	1320	36.85
N ₄ : NDVI based nitrogen application	141.38	33.42	14.85	1135	32.49
S. Em. ±	3.00	0.67	0.32	23.45	1.04
CD at 5 %	8.81	1.97	0.94	68.76	3.06
Different levels of P and K (T)					
T ₁ : 75 % recommended dose of P and K	113.83	26.83	11.96	918	28.94
T ₂ : 100 % recommended dose of P and K	133.97	31.67	14.07	1076	31.51
T ₃ : 125 % recommended dose of P and K	146.93	34.72	15.47	1184	33.74
S. Em. ±	2.60	0.58	0.28	20.31	0.90
CD at 5 %	7.63	1.70	0.81	59.55	2.65
N x T interaction					
S. Em. ±	5.20	1.16	0.55	40.61	1.81
CD at 5 %	15.26	3.41	1.62	119.09	NS

(NS: Not Significant).

interaction effect between precision nitrogen management and different levels of P and K showed a significant influence on panicle length, panicle weight, panicle girth and number of grains/panicle, whereas the test weight showed a non-significant effect among the treatment combinations.

Yield

Factors such as precision nitrogen management coupled with different levels of P and K influenced the yield in the case of grain sorghum (Table 4). The higher values of grain yield (3274 kg/ha), stover yield (11230 kg/ha) and biological yield (14503 kg/ha) were observed in the SPAD-based sufficiency index < 95 % treatment under precision nitrogen management, which showed significantly superior performance over the other remaining treatments. The lowest values were recorded under the RDN application treatment. The NDVI-based reference index also provided satisfactory values for grain, stover and biological yields of sorghum and it was significantly superior to 100 % RDN. These results can be due to improved synchronisation between nitrogen availability and crop demand under precision nitrogen management, which may enhance nitrogen use efficiency, photosynthetic activity, dry matter accumulation and effective translocation of assimilates towards grain production, whereas fixed nitrogen application under RDN resulted in sub-optimal utilisation and comparatively lower yields (28, 32, 33).

The yields of sorghum were significantly influenced by different levels of P and K application. Among the treatments, 125 % RD of P and K registered the highest grain yield (2935 kg/ha), stover yield (10069 kg/ha) and biological yield (13004 kg/ha) of sorghum. Further, this treatment remained superior to the other treatments of the study. The lowest values were recorded with the treatment of 75 % of RD of P and K application. The significant response of sorghum yields to different levels of phosphorus and potassium application indicated the crucial role of balanced and adequate nutrition in enhancing crop productivity. The superior performance of 125 % RD of P and K could be attributed to improved nutrient availability in the soil, which supported better root growth, efficient nutrient uptake, enhanced photosynthetic activity and greater biomass production (34, 35).

The interaction effect between the precision nitrogen management and different levels of phosphorus and potassium showed a significant influence in case of grain yield, stover yield and biological yield (Fig. 1), where the maximum values were observed in SPAD-based sufficiency index < 95 % in combination with 100 % RD of P and K treatment combination recorded the highest grain yield, stover yield and biological yield of sorghum. Further, this treatment was closely followed by SPAD-based sufficiency index < 95 % in combination with 100 % RD of P and K and NDVI-based relative index > 1.15 in combination with 125 % RD of P and K. Moreover, the lowest grain yield, stover yield and

Table 4. Influence of precision nitrogen management and different levels of P and K on yield of grain sorghum

Treatments	Yield (kg/ha)		
	Grain yield	Stover yield	Biological yield
Precision nitrogen management (N)			
N ₁ : Recommended dose of nitrogen	2159	7448	9606
N ₂ : Nitrogen application through SPAD sufficiency index < 90 %	2245	7699	9944
N ₃ : Nitrogen application through sufficiency index < 95 %	3274	11230	14503
N ₄ : NDVI-based nitrogen application	2815	9655	12470
S. Em. ±	61	201	262
CD at 5 %	178	589	767
Different levels of P and K (T)			
T ₁ : 75 % recommended dose of P and K	2266	7805	10072
T ₂ : 100 % recommended dose of P and K	2667	9149	11816
T ₃ : 125 % recommended dose of P and K	2935	10069	13004
S. Em. ±	53	174	226
CD at 5 %	154	510	664
N x T interaction			
S. Em. ±	105	348	453
CD at 5 %	309	1021	1328

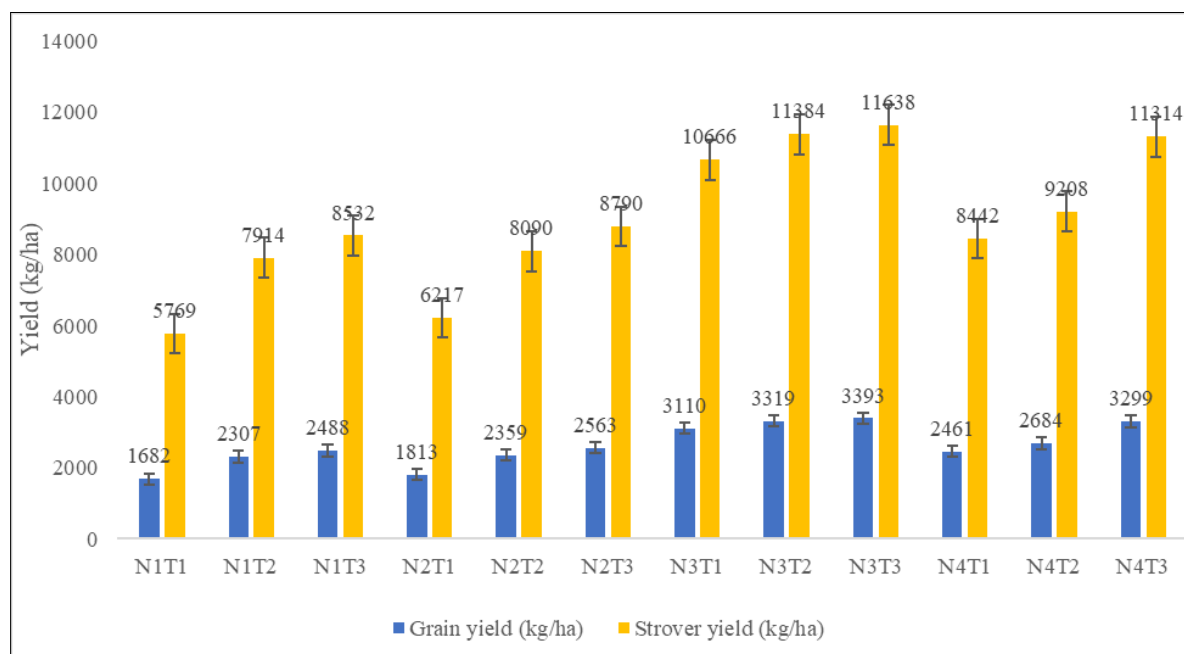


Fig. 1. Interaction effect of precision nitrogen management and different levels of P and K on yield of grain sorghum.

biological yield were recorded with 100 % recommended dose of nitrogen application in combination with 75 % recommended dose of phosphorus and potassium. This was followed by 100 % RDN application in combination with 100 % RD of phosphorus and potassium (36–38).

Principal component analysis

The principal component analysis classified the treatments clearly based on the growth, yield and yield attributes (Fig. 2 and 3). PC1 and PC2 accounted for 94.04 % and 3.5 % of the total variation, respectively. PC1 accounted for the major variation associated with yield contributing traits such as grain yield, dry matter accumulation, number of grains per panicle and panicle weight, indicating a strong positive correlation among these traits. PC2 was primarily influenced by test weight and plant height. Treatments 8 and 9 indicate superior performance; further, the treatments on the negative side of PC1 showed relatively lesser productivity.

Conclusion

Precision nutrient management and varied levels of phosphorus and potassium registered significant influence on growth parameters, yield attributes and yield of grain sorghum. Among the different nutrient management treatments, SPAD-based sufficiency index < 95 % with higher levels of phosphorus and potassium application (125 %) showed a remarkable improvement in growth, yield attributes and grain yield of sorghum. Moreover, sensor-based nitrogen management approaches, particularly nitrogen application as guided by the SPAD and NDVI, resulted in higher yields and remained significantly superior to the conventional recommended dose of nitrogen application. The study concluded that precision nitrogen management integrated with adequate phosphorus and potassium fertilisation could be considered an optimised nutrient dose for grain sorghum cultivation in South Odisha.

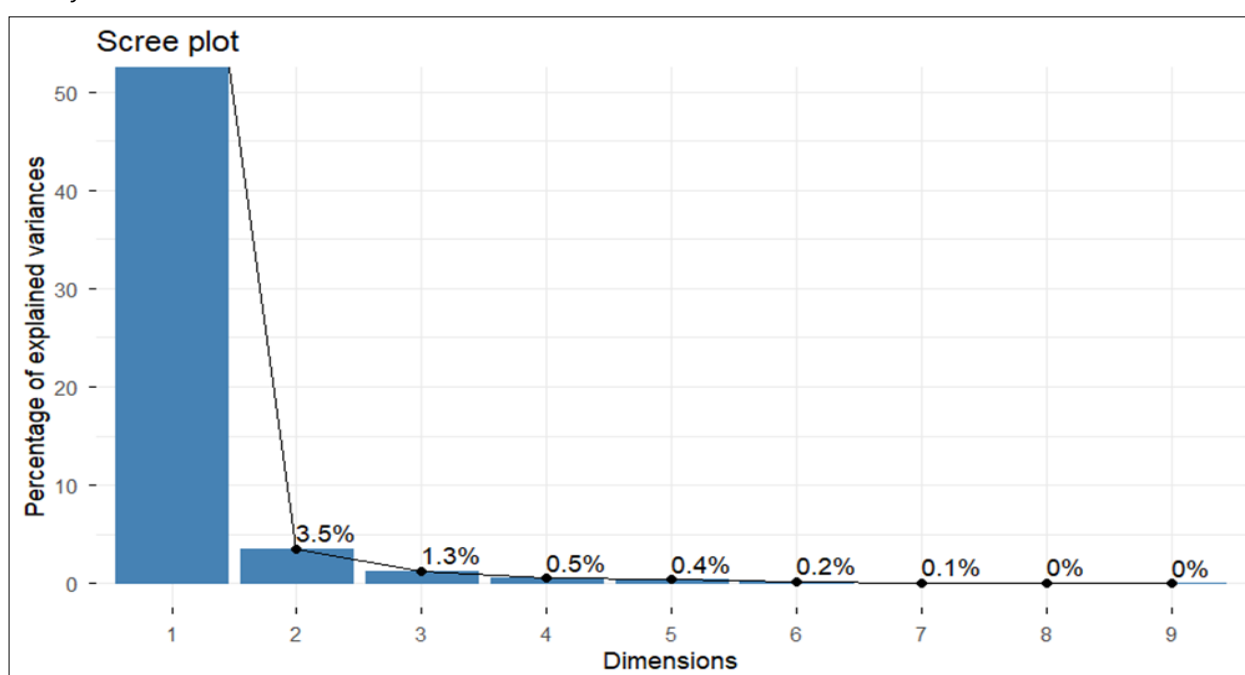


Fig. 2. Scree plot analysis.

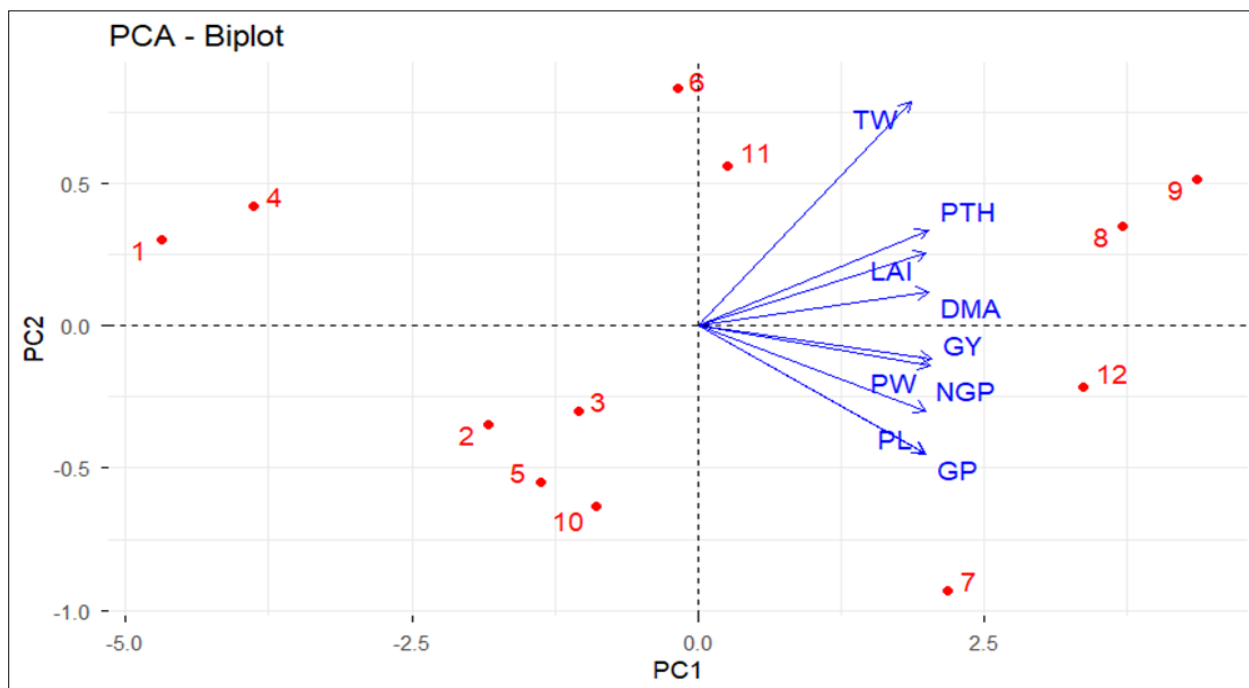


Fig. 3. Principal component analysis biplot. TW: Test weight; PTH: Plant height; LAI: Leaf area index; DMA: Dry matter analysis; Gy: Grain yield; PW: Panicle weight; NGP: Number of grains per panicle; PL: Panicle length; GP: Girth of the panicle.

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Authors' contributions

Conceptualisation was carried out by PP, SM and MS; methodology by SM, MS, LS and PP; validation by PP, SR and SM; analysis by PP, MS, SR and LS; data curation by PP, LS, MS, SM and SR; writing of the original draft by PP, MS, SM and SR; writing, review and editing by MS and SM; and supervision by LS, MS, SM and SR. All authors have read and agreed to the current version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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