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RESEARCH ARTICLE

Optimization of spacing and nutrient levels in browntop millet for enhancing yield and economic benefits

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Abstract

Browntop millet is gaining importance in recent years as a sustainable and viable crop in semi-arid regions of India due to its climate-resilience and nutritional richness. Despite its potential, the crop's inherent productivity and wider adoption are restricted by limited spacing and nutrient application. Thus, the present study was formulated to optimize the plant spacing and nutrient levels to attain higher yield levels. A field study was conducted for three consecutive kharif seasons (2022-2024) in a split-plot design with three replications. The main plot comprised of three varied levels of row spacings (30, 45 and 60 cm), while subplot consisted of three levels of nutrient application (30:15:15, 45:22.5:22.5 and 22.5:10:10 NPK (nitrogen:phosphorus:potassium) kg/ha). The results from the pooled analysis revealed that row spacing with 45 cm resulted in significantly higher grain yield (1604 kg/ha) compared to 30 cm and 60 cm row spacings. Among the varied nutrient levels, the application of higher dose of nutrients, specifically 45:22.5:22.5 kg NPK/ha, recorded significantly higher grain yield, straw yield and net returns up to 14.42, 14.36 and 23.08 % respectively, compared to lower levels of nutrient application. This higher rate also facilitated greater nutrient uptake and maintained higher soil available nutrients post-harvest of the browntop millet crop. Thus, for attaining higher yield, nutrient use efficiency and economic benefits in browntop millet, 45 cm row spacing coupled with application of45:22.5:22.5 kg NPK/ha found to be optimum under semi-arid conditions of Northern Karnataka.

Keywords: browntop millet; economics; nutrient levels; spacing; yield

Introduction

Browntop millet (*Brachiaria ramosa* L.) is one of the lesser known, nutritionally valuable minor millets. In recent years, it is attaining adequate importance due to its climate tolerance, early maturity and remarkable nutritional content (1). Indigenous to the semi-arid tracts of South-East Asia, especially India, this crop has long been an important part of rural subsistence in the states of Karnataka and Andhra Pradesh (2). Its drought tolerance and ability to grow in low-fertility soil have made it a reliable crop for subsistence farmers, particularly where other cereals tend to fail. Archaeological and agronomic evidence have proved that millet cultivation was domesticated between 5000 to 8000 years ago (3). Browntop millet, for instance, manifests the creativity of early farming populations who emphasized cultivating crops with an ability to withstand climatic changes and low-resource conditions.

During the last several years, browntop millet has been successfully reintroduced into the dominant food chain and is gaining attention as a sustainable, health-focused food material compared to key cereals such as rice and wheat (4). The nutritional composition of browntop millet includes 8.98 % protein, 1.89 % fat, 3.9 % minerals and 71.32 % carbohydrates, with 338 kcal per 100 g (5) qualifies it to meet both food and nutritional security, particularly in undernourished individuals. Additionally, its production is compatible with environment-friendly agricultural systems, as it necessitates relatively lower water and synthetic inputs (6). The crop takes about 85 to 90 days to mature, which enables it to be harvested several times in one year, thus increasing productivity and providing an alternative source of revenue for smallholder farmers. As global discussion continues to focus on sustainable agriculture and climate-resilient cropping systems, there has been renewed interest in millets like browntop millet. Policy efforts that enhance traditional grains as a component of climate-smart agriculture to help build food system resilience in the face of mounting environmental pressures further underpin growing interest in the crop.

A major determinant of the agronomic performance of browntop millet is the regulation of plant spacing and nutrient use. Appropriate row spacing is crucial in determining plant health and productivity, as excessive crowding leads to intense competition for essential resources like light, water and soil nutrients (7). Improper spacing often results in stunted growth, increased susceptibility to pests and diseases and reduced overall yield (8). On the other hand, well-managed spacing enhances light interception, reduces weed infestation and facilitates better nutrient uptake.

Besides spacing, application of basic macronutrients, i.e., nitrogen phosphorus and potassium is essential to maximize yield levels (1, 9). Despite their inherent potential, millets tend to underperform because of suboptimal agronomic management practices, viz., abnormal planting density and insufficient fertilization besides, use of low-yielding, traditional varieties (10). Thus, over the years it has been concluded that, systematic assessment of the optimal plant density via standard row spacing and sufficient dose of nutrient application is essential for increasing the productivity and economic feasibility of browntop millet production (7). This study evaluated the effects of varied row spacing and nutrient levels on the growth and yield parameters of browntop millet, aiming to identify best agronomic practices for promoting browntop millet cultivation in the semi-arid tracts of Northern Karnataka in particular and Southern India in general.

Materials and Methods

Experimental site

The field experiment was conducted at the Agricultural Research Station, Hanumanamatti, Haveri district, Karnataka state, India. The site is in the Northern Transition Zone (Zone VIII) of Karnataka, India, at 14°39' N latitude and 75°33' E longitude, with an altitude of 594.36 m above mean sea level. The agro-climatic zone is characterized by a semi-arid climate with variable rainfall and moderate soil fertility. The normal and actual rainfall recorded at the experimental site is depicted in Fig. 1. Similarly, the data pertaining to soil physico-chemical properties prior to experimentation is presented in Table 1.

Experimental details

The current experiment was laid out in a split-plot design with three replications. The main plot treatments consisted of three different row spacings, viz., S_1: 30 cm, S_2: 45 cm and S_3: 60 cm to accommodate 66, 44 and 33 plants/m^2 respectively. In the subplot, three nutrient levels, viz., N_1: 30:15:15 kg NPK/ha (nitrogen, phosphorus and potassium), N_2: 45:22.5:22.5 kg NPK/ha and N_3: 22.5:10:10 kg NPK/ha were imposed. As per the recommendation of University of Agricultural Sciences, Dharwad, 6 t FYM (farmyard manure)/ha was commonly applied to all the plots. The nitrogen, phosphorous and potassium were applied in the form of urea, single super phosphate and muriate of potash, respectively. The 50 % of recommended nitrogen and 100 % of phosphorous and potassium were applied at the time of sowing, while rest of the 50 % of recommended nitrogen was top dressed at 30 days after sowing.

Experimental layout and crop husbandry

The plots of 5.4 m x 3.0 m dimension were formed and separated by small, raised bunds around the plots. The FYM was applied two weeks before sowing and mixed well in the experimental plots. On the day of sowing, seed rows were opened as per the treatments using pickaxe. Fertilizer was incorporated as per the treatments. Seeds were sown and closed with soil. The crop was sown on 23rd June 30th June and 5th July during 2022, 2023 and 2024, respectively. The crop was harvested after attaining proper maturity on 31st October 9th October and 19th October during 2022, 2023 and 2024, respectively. The crop attained maturity in 99, 103 and 105 days respectively during 2022, 2023 and 2024 respectively. This variation in crop maturity is due to prevailing climatic conditions of the respective seasons. The weeds were managed by hand weeding once between 25 to 30 days after crop sowing. The crop was grown completely under rainfed conditions without external irrigation. Rest of the crop husbandry practices were commonly adopted for all the treatments as per package of practices developed and recommended by University of Agricultural Sciences, Dharwad for other millets.

Data collection and statistical analysis

Five randomly selected and tagged plants from the net plot area were harvested separately for recording yield attributes of

Table 1. Soil chemical properties at the experimental site recorded seasonally prior to experimentation

Parameter	2022	2023	2024
Soil pH (1:2.5 soil:water)	6.14	5.86	5.98
Electrical conductivity (dS/m)	0.33	0.32	0.31
Organic carbon (g/kg)	3.66	3.61	3.70
Available nitrogen (kg/ha)	204.78	207.33	199.59
Available P_2O_5 (kg/ha)	23.52	22.54	23.67
Available K_2O (kg/ha)	211.32	198.36	216.16

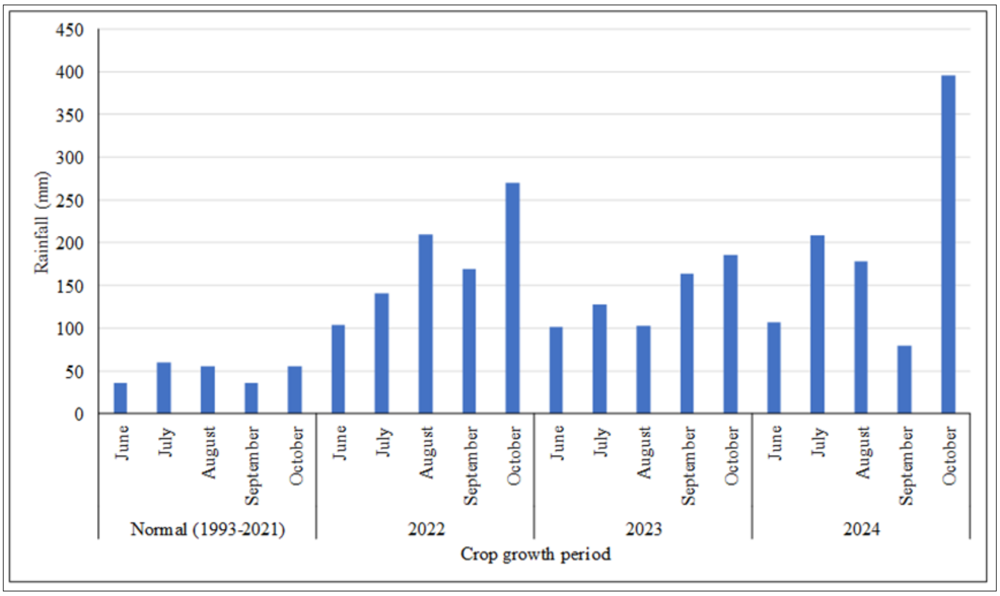

Fig. 1. Normal and actual (2022, 2023 and 2024) monthly rainfall received during the crop growth period at KVK, Hanumanamatti.

browntop millet. The crop in the net plot area was harvested, excluding the gross plot area and the grains were separated using human labour for recording grain and straw yield for each treatment. The standard method of plant sample collection and digestion was adopted for plant sample preparation (11). The same plant samples collected at harvest were oven dried at 65 to 70 °C in a hot air oven, powdered in a grinder with stainless steel blades and stored in polythene bags for further nutrient uptake analysis. The plant nutrients uptake analysis was done following the standard method (11) viz., modified Micro Kjeldahl's method for nitrogen, Vanadomolybdo-phosphoric acid yellow colour method for phosphorous and Flame photometry method for potassium. After the crop harvest, soil samples from the respective treatments were collected from a depth of 0-15 cm, subjected for air drying and grounded to powder form and stored in polythene bags for soil nutrient status analysis. The standard procedures were followed for soil available nutrient status viz., alkaline potassium permanganate method for available nitrogen (12), spectrophotometer using Bray's No. 1 extractant method for available phosphorous (11) and Flame photometry using neutral normal ammonium acetate method for available potassium (11) in post-harvest soil. The total input supplied were quantified for each treatment, multiplied by their unit price prevailing at the time of use and then summed to calculate as the total cost of cultivation per treatment. By considering the market prices of both grain and straw, gross and net returns were calculated. The data thus obtained were subjected for statistical analysis in SPSS software (version 0.27). The correlation analysis was done using OPSTAT statistical software (13). The means of treatment were compared using least significant difference (LSD) at a probability level of 5 %.

Results and Discussion

Yield attributes of browntop millet as influenced by varied row spacing and nutrient levels

The data pertaining to yield attributes of browntop millet as influenced by varied spacing and nutrient levels is presented in Table 2.

The spacing of plants plays a crucial role in determining the yield and physiological efficiency of crops, especially in small millets like browntop millet. Among the varied row spacing, higher panicle length (16.01 cm), number of grains per panicle (449) and number of productive tillers per plant (17.06) were observed significantly higher under a row spacing of 60 cm. Interestingly, 45 cm row spacing recorded values that were on par with the 60 cm spacing for panicle length (15.45 cm) and number of grains per panicle (433). Under wider row spacing, individual plants are freely exposed to sufficient growth resources, viz., sunlight, space, water and nutrients, compared to plants at a higher density under closer spacing, thus providing a relatively competition free environment for the individual plants. These conditions stimulate the individual plants to express their full potential in terms of better yield attributes. Wider spacing stimulates greater leaf area and chlorophyll content, which aids in the production of higher plant biomass and further optimal translocation of the photosynthates across the plant (14). During vegetative stage, most of the photosynthates are translocated throughout the plant for overall plant growth, but once the plant enters reproductive growth, major portion of the photosynthates accumulates in the economic parts (15). This, higher production and translocation of photosynthates is much pronounced under wider spaced crops due to greater availability of the growth resources (least inter-plant competition) compared to closely spaced plants (16). In contrast, when plants are closely spaced, each plant experiences more inter-plant competition for growth resources leading to reduced yield attributes per plant. This is evident in browntop millet grown at a row spacing of 30 cm, which resulted in significantly lower panicle length (13.84 cm), number of grains per panicle (383) and number of productive tillers per plant (9.53).

The fertilization treatments also proved to have a profound influence on the yield attributing characters of browntop millet in the present study. The treatment with the highest fertilizer dose (45:22.5:22.5 kg NPK/ha) recorded

Table 2. Effect of varied row spacing and nutrient levels on yield attributes of browntop millet (pooled data of three years)

Treatment	Panicle length (cm)	No. of grains/panicle	No. of productive tillers/plant	Test weight (g)
Row spacing (S)				
S_1- 30 cm	13.84	383	9.53	2.95
S_2- 45 cm	15.45	433	14.37	3.05
S_3 -60 cm	16.01	449	17.06	3.07
S.Em.±	0.23	6.95	0.26	0.01
CD (p=0.05)	0.77	23.37	1.01	NS
Nutrient levels (N)				
N_1-30:15:15 NPK kg/ha	15.26	427	13.97	3.02
N_2- 45:22.5:22.5 NPK kg/ha	16.02	450	15.27	3.04
N_3-22.5:10:10 NPK kg/ha	14.01	389	11.73	3.00
S.Em.±	0.11	3.46	0.15	0.004
CD (p=0.05)	0.35	10.66	0.46	NS
S x N				
S_1N_1	14.02	389	9.87	2.95
S_1N_2	14.74	411	11.08	2.97
S_1N_3	12.76	351	7.63	2.93
S_2N_1	15.62	438	14.70	3.05
S_2N_2	16.35	460	15.94	3.07
S_2N_3	14.37	400	12.47	3.03
S_3N_1	16.15	454	17.34	3.07
S_3N_2	16.98	479	18.77	3.08
S_3N_3	14.89	415	15.08	3.05
S.Em.±	0.20	5.99	0.26	0.01
CD (p=0.05)	0.60	18.47	0.80	NS

*Note: 6 t FYM/ha was commonly applied to all the treatments; NS: non significant.

significantly higher panicle length (16.02 cm), number of grains per panicle (450) and number of productive tillers per plant (15.27) compared to lower rates of fertilizer application. Higher fertilizer application enhanced yield attributes by ensuring better nutrient availability, leading to improved tillering, longer panicles, higher grain filling and greater biomass accumulation (6). In contrast, lower fertilizer rates restricted nutrient supply, limiting growth and reproductive development, thereby reducing yield potential. Hence, adequate fertilization optimizes physiological processes for superior yield. The present findings corroborated with the previous works of other researchers, who reported that increased RDF application (up to 125 %) significantly enhanced panicle characteristics and yield attributes in other millets (17, 18).

In the present study, it was observed that performance of browntop millet was enhanced with wider row spacing and increased supply of nutrient doses. Specifically, yield parameters like panicle length, number of grains per panicle and number of productive tillers per plant were significantly higher when browntop millet sown at 60 cm row spacing and supplied with 45:22.5:22.5 NPK kg/ha (16.98 cm, 479 and 18.77, respectively) than rest of the interactions. This is because, competition free environment coupled with ample supply of nutrients allows individual plants to develop stronger root systems and greater photosynthetic efficiency besides enhancing cell division, chlorophyll synthesis and assimilate production, which are crucial for reproductive growth. This improved source–sink relationship favours better tiller initiation and survival, resulting in more productive tillers (19). Enhanced nutrient uptake also supports panicle differentiation and grain filling processes, leading to longer panicles and a higher number of grains per panicle (20). In contrast, closer spacing with low nutrient supply limits resources, restricting growth and yield attributes. Hence, significantly lower values of yield attributes were recorded under a row spacing of 30 cm supplied with 22.5:10:10 kg NPK/ha (12.76 cm, 351 and 7.63, respectively).

The test weight of browntop millet ranged between 2.95 to 3.08 g across the imposed treatments. However, neither the varied row spacing nor graded levels of nutrients application had significant influence on test weight.

Yield of browntop millet as influenced by varied row spacing and nutrient levels

The yield of browntop millet as influenced by varied row spacing and nutrient levels is depicted in Table 3. In contrast to the yield attributes, a row spacing of 45 cm proved optimum, resulting in a higher grain yield of 5.76 % and 12.16 % compared to row spacing of 60 cm and 30 cm, respectively. Conversely, grain yield was significantly lowest (1423 kg/ha) under the closer row spacing of 30 cm. This is attributed to the fact that, under closer spacing competition among plants was intensified, reducing the yield parameters (21). On the contrary, under wider spacing (60 cm), although individual plant performance was better, the reduced number of plants per unit area likely contributed to the lower yield per unit area. Due to higher plant density, 30 cm row spaced crop recorded significantly higher straw yield (2386 kg/ha) which reduced gradually with widening the row space in browntop millet. Owing to better performance of individual plants, 60 cm row spacing resulted in significantly higher harvest index (41.53 %), which was at par with row spacing of 45 cm (41.42 %). Under 30 cm row spacing, plants suffered severe inter-plant competition for growth resources, leading to a significantly lower harvest index (37.31 %). This finding is consistent with earlier research, which concluded that optimal plant spacing enhances yield until a threshold population is achieved, beyond which yield declines due to plant stress or sub-optimal population density (22, 23). A similar pattern was documented in pearl millet, affirming the physiological limitation of closer spacings under limited moisture regimes (21).

Similar to the trend observed in yield attributes, the yield of browntop millet showed drastic increase with increased levels of nutrient application. The treatment with 45:22.5:22.5 kg NPK/ha recorded significantly higher grain (1580 kg/ha) and straw (2397 kg/ha) yield. These results were higher than the lower rates of fertilizer application by 5.25 to 14.42 % and 5.22 to 14.36 % for

Table 3. Effect of varied row spacing and nutrient levels on grain yield, straw yield and harvest index of browntop millet (pooled data of three years)

Treatment	Grain yield (kg/ha)	Straw yield (kg/ha)	Harvest index (%)
Spacing (S)			
S_1- 30 cm	1423	2386	37.31
S_2- 45 cm	1596	2257	41.42
S_3 -60 cm	1509	2129	41.53
S.Em.±	24.90	39.81	0.60
CD (p=0.05)	81.32	120.97	2.37
Nutrient levels (N)			
N_1-30:15:15 NPK kg/ha	1523	2278	40.09
N_2- 45:22.5:22.5 NPK kg/ha	1603	2397	40.10
N_3-22.5:10:10 NPK kg/ha	1401	2096	40.08
S.Em.±	12.04	17.91	0.27
CD (p=0.05)	37.10	55.19	0.82
S x N			
S_1N_1	1438	2403	37.37
S_1N_2	1514	2534	37.44
S_1N_3	1316	2221	37.12
S_2N_1	1608	2279	41.37
S_2N_2	1695	2394	41.43
S_2N_3	1485	2097	41.46
S_3N_1	1524	2152	41.52
S_3N_2	1601	2265	41.40
S_3N_3	1402	1970	41.65
S.Em.±	20.86	31.02	0.46
CD (p=0.05)	64.26	95.59	1.42

*Note: 6 t FYM/ha was commonly applied to all the treatments.

grain and straw yield, respectively. It is duly attributed to greater availability of nutrients for enhanced physiological and morphological development of the plants (22). Moreover, the increased yield was likely due to the prolonged nutrient availability facilitated by FYM, which not only improved nutrient use efficiency but also enhanced soil structure and microbial activity. It enabled better partitioning of assimilates to reproductive parts, producing longer and denser panicles. These finding aligns with that of other researchers', who emphasized the synergistic role of organic and inorganic fertilization in promoting tiller growth, leaf area index and grain filling efficiency (20, 24). However, harvest index didn't differ significantly across the nutrient levels. Little millet also showed improved yield levels under increased nutrient supply conditions (17).

The combined effect of plant spacing and nutrient application showed significant variation among the interactions. Attributing to optimal resource use efficiency, the grain yield was significantly higher under 45 cm row spacing supplied with 45:22.5:22.5 kg NPK/ha (1695 kg/ha) over rest of the interactions. On the contrary, due to higher plant density coupled with ample nutrient supply, under 30 cm row spacing with 45:22.5:22.5 kg NPK/ha achieved significantly higher straw yield (2534 kg/ha). These results are due to combination of individual factors' effect. Similar results were also obtained in other studies using different millet crops (14, 25).

Nutrient uptake by browntop millet as influenced by varied row spacing and nutrient levels

The browntop millet showed differential nutrient uptake under varied row spacing and nutrient levels as depicted in Fig. 2. The trend of variation remained same for nitrogen, phosphorous and potassium uptake by browntop millet across the varied row spacing and nutrient levels.

Among the varied row spacing, significantly higher nitrogen, phosphorous and potassium uptake by browntop millet was recorded when sown at a row spacing of 45 cm (28.99, 8.39 and 32.40 kg/ha, respectively) which was found to be at par with row spacing of 60 cm (28.18, 8.21 and 29.94 kg/ha respectively). Wider row spacing (45 cm) in browntop millet facilitated greater nutrient uptake due to improved root proliferation, better soil exploration and reduced inter-plant competition for resources. Enhanced light interception and aeration at optimum spacing promoted higher photosynthetic efficiency, leading to greater biomass accumulation and consequently, higher nutrient assimilation (26, 27). Although 60 cm spacing provided similar uptake, excessively wider spacing may reduce plant population per unit area, offsetting the benefits. Conversely, closer spacing (30 cm) intensified competition for nutrients, moisture and light, restricting root growth and lowering nutrient absorption efficiency, thus resulting in reduced uptake (27.58, 7.69 and 29.00 kg/ha respectively).

The nutrient absorption by browntop millet trend was like that of yield as influenced by varied nutrient levels. Significantly higher nutrient uptake (29.72, 9.05 and 31.97 kg NPK/ha) was noted under the treatment supplied with the highest rate of fertilizer, i.e., 45:22.5:22.5 kg NPK/ha followed by application of 30:15:15 kg NPK/ha and 22.5:10:10 kg NPK/ha. This increased nutrient absorption with increased nutrient supply is attributed to greater availability of nutrients in the root zone, thereby facilitating efficient absorption and utilization (7). Adequate nitrogen supply promoted vigorous vegetative growth and higher chlorophyll synthesis, while phosphorous enhanced root development and energy transfer and potassium improved enzymatic activity and assimilate translocation. This synergistic effect resulted in higher biomass production and nutrient assimilation. A previous study also observed increased nutrient uptake by teff grass with increased nutrient application (16). Moderate and lower fertilizer levels supplied comparatively lesser nutrients, restricting crop growth potential and reducing the capacity of plants to absorb and utilize NPK efficiently.

The resultant effect of individual factors was evident in interactions. Across the different treatment combinations, row spacing of 45 cm coupled with 45:22.5:22.5 kg NPK/ha application recorded significantly higher nutrient uptake (30.46, 9.31 and

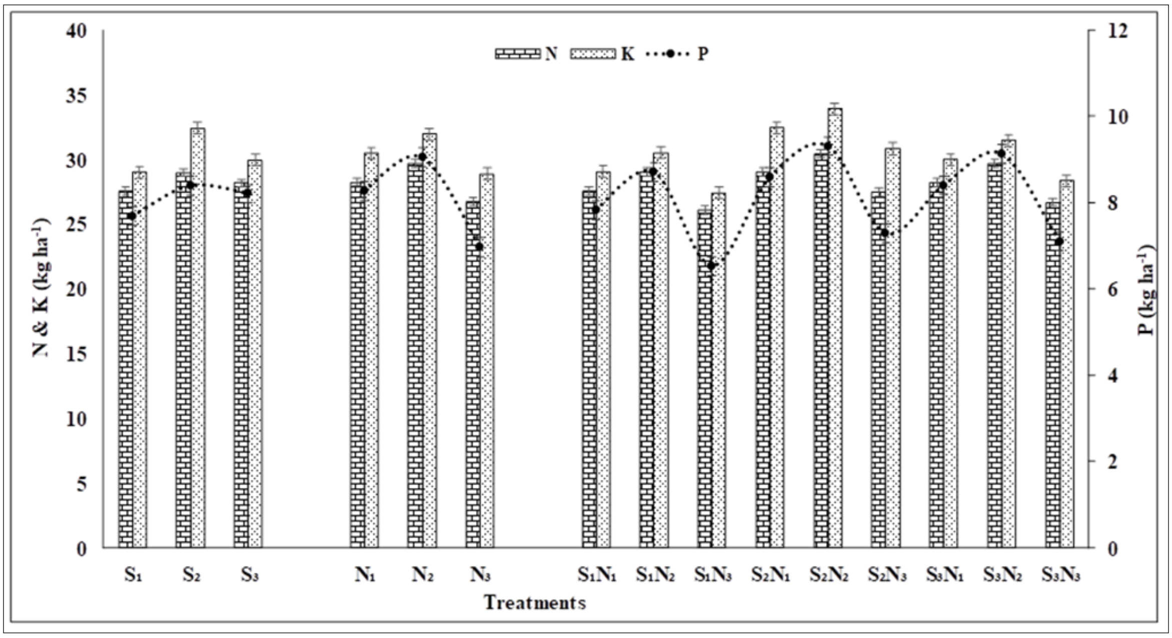

Fig. 2. Effect of varied drilling patterns and nutrient levels on nutrient uptake by browntop millet (3 years pooled data).

Note: Error bars indicate standard deviation (SD); Row spacing, S_1: 30 cm, S_2: 45 cm and S_3: 60 cm; Nutrient levels, N_1: 30:15:15 kg NPK ha^{-1},, N_2: 45:22.5:22.5 kg NPK ha^{-1} and N_3: 22.5:10:10 kg NPK ha^{-1})

33.93 kg NPK/ha) compared to rest of the treatments. On the contrary, closer spacing of 30 cm supplied with 22.5:10:10 kg NPK/ha resulted in significantly lower nutrient uptake (26.11, 6.53 and 27.43 kg NPK/ha). This is attributed to synergetic effect between the optimal row spacing and sufficient nutrient supply. Similar results were also recorded in other studies (1, 24).

Soil available nutrient uptake by browntop millet as influenced by varied row spacing and nutrient levels

The varied row spacing and nutrient levels had profound influence on post-harvest soil available nutrient status as depicted in Fig. 3. Like nutrient uptake, trend of soil available nitrogen, phosphorous and potassium also remain same across the treatments imposed.

The closer row spacing of 30 cm retained significantly higher soil available nutrients (90.55, 24.36 and 105.78 kg N, P_2O_5 and K_2O ha^{-1}, respectively) after harvest of browntop millet over wider spacing. This is primarily attributed to the lower total biomass per unit area, wherein plants suffer severe inter-plant competition, resulting in stunted growth and ultimately lower yield levels (28). In contrast, due to the production of significantly higher biomass under 45 cm row spacing, supported by higher nutrient extraction from the soil, resulted in the least amount of post-harvest soil available nutrients (86.18, 22.94 and 101.41 kg N, P_2O_5 and K_2O ha^{-1}, respectively). However, when row spacing was further widened to 60 cm, the lower plant population per unit area led to lesser nutrient uptake which reflected in medium soil available nutrient status post-harvest of browntop millet.

Among the varied nutrient levels, the treatment with the highest fertilizer dose recorded significantly higher soil available nutrient levels (90.38, 24.64 and 105.61 kg N, P_2O_5 and K_2O ha^{-1}, respectively) over lower doses of fertilizer application. Under reduced levels of nutrient application, plants are subjected to minor nutrient stress resulting in maximum nutrients uptake from the soil (10). Because of this, there was lesser soil nutrient available under the application of 22.5:10:10 kg NPK/ha (85.99, 22.04 and 101.22 kg N, P_2O_5 and K_2O ha^{-1}, respectively). Further, higher doses also reduce the chances of complete nutrient depletion during the crop cycle, leading to greater post-harvest availability compared to lower fertilizer rates, where most nutrients are absorbed or lost, leaving minimal residual fertility (9).

Owing to the synergetic effect between the varied spacing and nutrient levels, the treatment combination of closer spacing supplied with highest fertilizer dose, i.e., application of 45:22.5:22.5 kg NPK/ha to 30 cm row spaced crop recorded the highest post-harvest soil available nutrient status (92.51, 25.56 and 107.74 kg N, P_2O_5 and K_2O ha^{-1} respectively). On the contrary, treatment with optimal plant population receiving lowest fertilizer dose recorded significantly lower status of available soil nutrients (83.74, 21.53 and 98.97 kg N, P_2O_5 and K_2O ha^{-1} respectively). This is attributed to efficient nutrient uptake by plants spaced at optimal density under reduced nutrient supply, resulting in lesser soil nutrient retention post-harvest of browntop millet. Similar results were also recorded by other studies using browntop millet and teff millet (7, 16).

Correlation analysis

To understand the extent of influence of various parameters on yield of browntop millet, various observations recorded in the present study were subjected for correlation analysis and the resultant graph is depicted in Fig. 4. Grain yield showed the strong and positive correlation with potassium uptake (K, 0.992) and was positively correlated with rest of the variables except straw yield. Surprisingly, straw yield showed a non-significant correlation with all the variables studied. Panicle length and number of grains per panicle exhibited perfect correlation (1.000) and were significantly correlated with each other as well as with other yield parameters, grain yield and nutrient uptake except straw yield. Number of productive tillers per plant had the strongest correlation with test weight (0.963) and significant associations with rest of the variables except straw yield and potassium. Similar trend of correlation was observed with test weight. Nitrogen and phosphorus showed the strongest correlation with each other (0.994) and significant associations with rest of the parameters except straw yield. Potassium was strongly correlated with grain yield (0.992), significantly with nitrogen, phosphorus, number of grains per

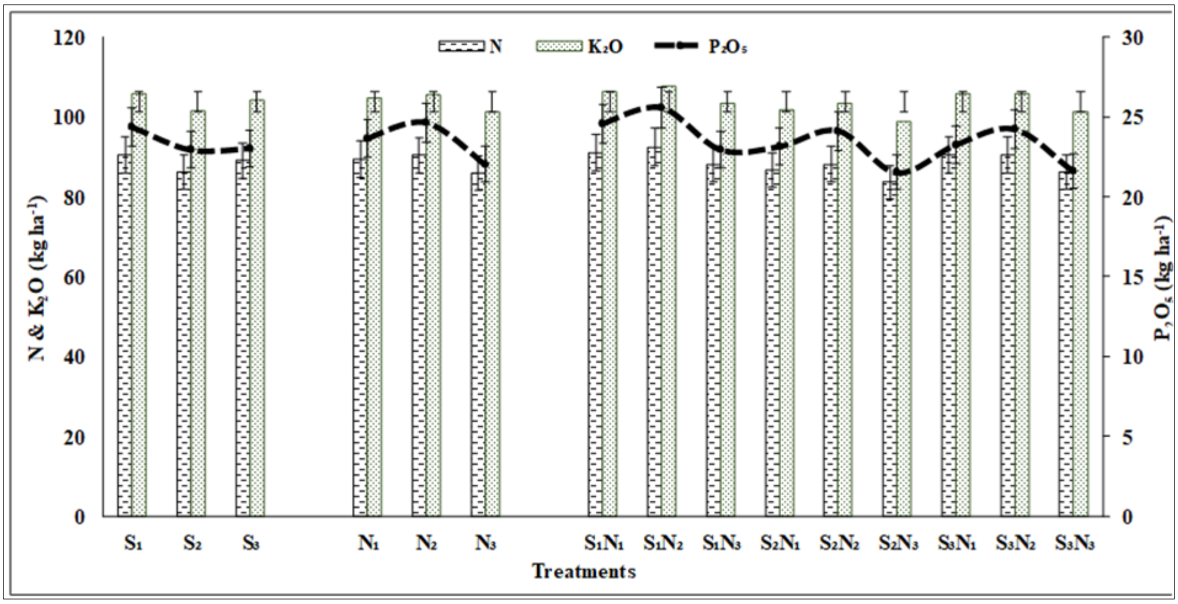

Fig. 3. Effect of varied drilling patterns and nutrient levels on post-harvest soil available nutrients in browntop millet cultivation (3 years pooled data).

Note: Error bars indicate standard deviation (SD); Row spacing, S_1: 30 cm, S_2: 45 cm and S_3: 60 cm; Nutrient levels: N_1: 30:15:15 kg NPK ha^{-1}, N_2: 45:22.5:22.5 kg NPK ha^{-1} and N_3: 22.5:10:10 kg NPK ha^{-1})

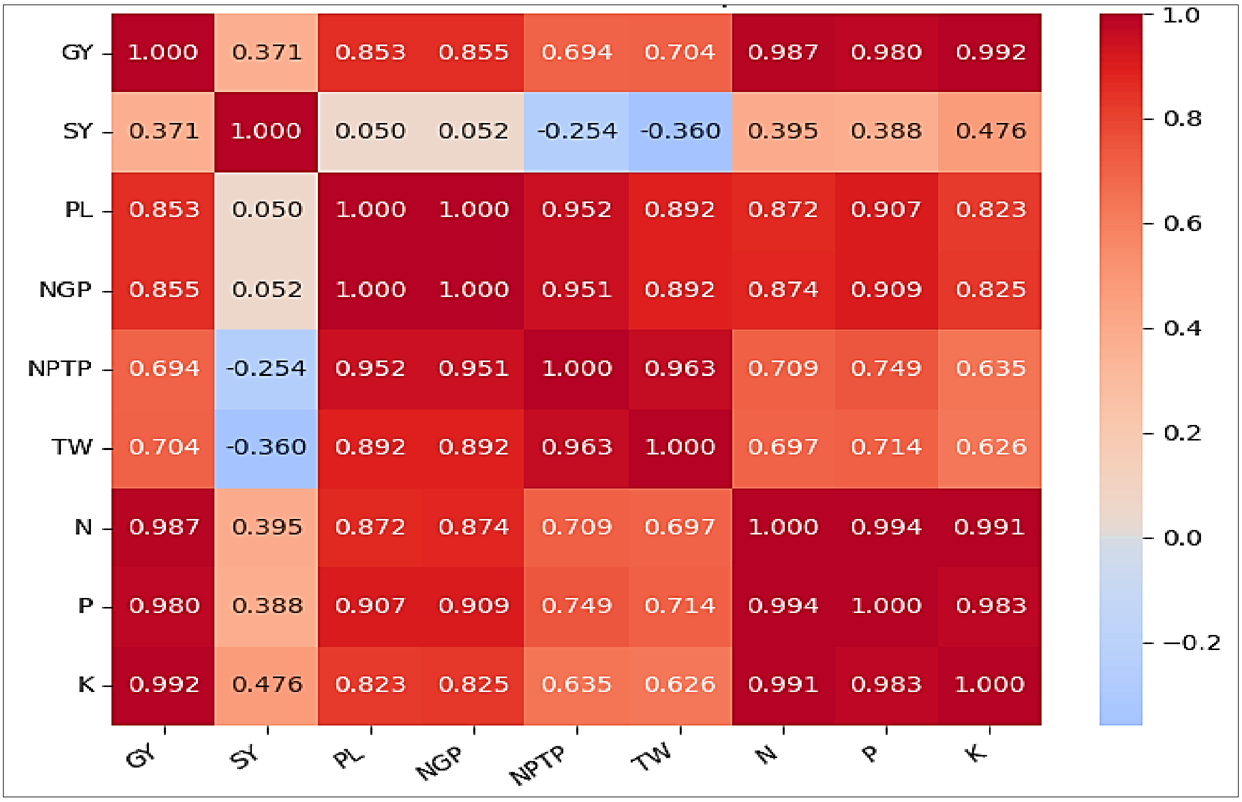

Fig. 4. Correlation heatmap depicting the correlation between yield attributes, nutrient uptake and yield of browntop millet.

Note: The results are interpreted at 5 % level of significance; GY- Grain yield (kg ha^{-1}); SY- Straw yield (kg ha^{-1}); PL- Panicle length (cm); N- Number of grains per panicle; NPTP- Number of productive tillers per plant; TW- Test weight (g); N- Nitrogen uptake (kg ha^{-1}); P- Phosphorous uptake (kg ha^{-1}); K- Potassium uptake (kg ha^{-1}).

panicle and panicle length, but non-significant with straw yield, Number of productive tillers per plant and test weight. The findings of a recent study also confirmed the similar association among the yield attributes, yield and nutrient uptake parameters of browntop millet (14).

Effect of varied row spacing and nutrient levels on economics of browntop millet cultivation

The economic viability of the treatments is critical for farmers considering inputs and market value. Table 4 illustrates that; cost of cultivation reduces with widening the plant spacing due to reduced cost of seeds. The 45 cm row spacing treatment, besides incurring medium cost on cultivation, recorded significantly higher gross (Rs. 74067 ha^{-1}) and net returns (Rs. 38229 ha) ultimately reflecting in higher Benefit-Cost Ratio (BCR) (2.06). This was however found to be at par with row spacing of 60 cm (Rs. 70029 ha^{-1}, Rs. 34668 ha^{-1} and

Table 4. Effect of varied row spacing and nutrient levels on economics of brown top millet cultivation (pooled data of three years)

Treatment	Cost of cultivation (Rs./ha)	Gross returns (Rs./ha)	Net returns (Rs./ha)	B-C ratio
Spacing (S)				
S_1- 30 cm	36025	66423	30397	1.84
S_2- 45 cm	35838	74067	38229	2.06
S_3 -60 cm	35361	70029	34668	1.98
S.Em.±	-	1803	1849	0.05
CD (*p*=0.05)	-	5446	5587	0.16
Nutrient levels (N)				
N_1-30:15:15 NPK kg/ha	35855	70830	34975	1.97
N_2- 45:22.5:22.5 NPK kg/ha	36861	74555	37693	2.02
N_3-22.5:10:10 NPK kg/ha	34507	65133	30626	1.88
S.Em.±	-	2248	1691	0.03
CD (*p*=0.05)	-	6771	5094	0.10
S x N				
S_1N_1	36717	67135	30418	1.83
S_1N_2	36899	70685	33787	1.91
S_1N_3	34460	61447	26987	1.78
S_2N_1	35747	74624	38877	2.08
S_2N_2	37102	78669	41567	2.12
S_2N_3	34663	68907	34244	1.98
S_3N_1	35101	70732	35630	2.01
S_3N_2	36583	74310	37727	2.03
S_3N_3	34398	65045	30647	1.89
S.Em.±	-	1673	1455	0.04
CD (*p*=0.05)	-	5039	4384	0.11

*Note: 6 t FYM/ha was commonly applied to all the treatments; Costs of the inputs and price of outputs prevailing at the time of their use/ sale were considered for estimating the economics.

1.98 respectively). The row spacing of 30 cm owing to the lowest economic output coupled with higher cost of cultivation recorded significantly lower gross returns (Rs. 66423 ha^{-1}), net returns (Rs. 30397 ha^{-1}) and B-C ratio (1.84). These results are in line with the findings of previous reports in pearl millet and browntop millet (21, 29).

The cost of cultivation increased linearly with increased rates of fertilizer application owing to additional cost on the extra dose of fertilizer. Surprisingly, the trend of economic returns also followed the trend of variation in cultivation costs across the nutrient levels. The treatment with the highest dose of fertilizer, i.e., 45:22.5:22.5 kg NPK/ha incurred the higher cost of cultivation (Rs. 36861 ha^{-1}) compared to the lower fertilizer rates. The same treatment yielded significantly higher gross returns (Rs. 74555 ha^{-1}) and net returns (Rs. 37693 ha^{-1}), as well as a higher B-C ratio (2.02), indicating that every additional rupee invested on crop production yielded higher returns compared to lower rates of fertilizer application. A recent study also reported that sufficient nutrient supply is crucial in achieving economic profitability in browntop millet cultivation (3). In contrast, application of the lowest fertilizer rate producing significantly lower output resulted in significantly lower gross returns (Rs. 65133 ha^{-1}), net returns (Rs. 30626 ha^{-1}) and B-C ratio (1.88), making it economically less attractive. Similar results were also reported in little millet (19).

Among the interaction, 45 cm row spacing supplied with 45:22.5:22.5 kg NPK/ha found to be the most economical practice, with significantly higher gross returns (Rs. 78669 ha^{-1}), net returns (Rs. 41567 ha^{-1}) and B-C ratio (2.12), reflecting a strong synergy between plant spacing and nutrient management. These findings reaffirm the results of a recent study, which reported that wider spacing with adequate fertilization yielded higher profitability in small millets. Previous studies also reported findings that substantiate the idea that optimal spacing supported with sufficient nutrient supply improve yield and economic returns (19, 27).

Conclusion

The present study clearly demonstrates that optimal row spacing and adequate nutrient management are crucial for maximizing the productivity and profitability of browntop millet under dryland conditions. Among the treatments, 45 cm row spacing combined with the application of 45:22.5:22.5 kg NPK/ha consistently recorded superior grain yield (1695 kg/ha), nutrient uptake and economic returns (Rs. 78669 ha^{-1} gross returns, Rs. 41567 ha^{-1} net returns and B-C ratio of 2.12). This synergy between proper plant population and sufficient nutrient supply facilitated efficient utilization of available resources, enhanced photosynthetic efficiency and improved source-sink relationships, leading to better yield attributes and higher grain output. From an economic perspective, this combination not only optimized input use efficiency but also ensured higher profitability compared to lower nutrient rates and suboptimal spacing, which suffered from either severe inter-plant competition or low plant population per unit area. Importantly, the findings underscore that investing in recommended nutrient levels for browntop millet under an appropriate row spacing regime is economically viable and sustainable, even in marginal soils. These results hold significant implications for the socio-economic upliftment of small and marginal farmers cultivating in rainfed regions. Adoption of these best agronomic practices can substantially improve returns on investment, ensure a stable income and promote crop diversification under climate-resilient farming systems. By enhancing productivity without compromising resource use efficiency, the study provides a practical strategy to strengthen food and nutritional security while contributing to the resilience of farming communities in dryland ecosystems.

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Authors' contributions

AP formulated and conducted the experiment, recorded observations, reviewed the manuscript, acquired funding and approved the final manuscript. MBN analysed the data, prepared and reviewed the final manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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