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Research article

Agronomic optimization of nitrogen application, planting geometry and harvesting stage for fodder yield and quality in barnyard millet

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Abstract

A field experiment was conducted to evaluate the influence of nitrogen levels, planting geometry and harvesting stages on fodder yield and quality of barnyard millet. The treatments included three nitrogen doses (40 kg N ha^{-1}, 60 kg N ha^{-1} and 80 kg N ha^{-1}), two planting geometries (30 × 10 cm and 22.5 × 10 cm) and two harvesting stages (earhead emergence and physiological maturity). Among the nitrogen levels, 80 kg N ha^{-1} yielded the maximum green fodder (15.73 t ha^{-1}) and dry fodder (3.97 t ha^{-1}). The closer spacing of 22.5 × 10 cm resulted in markedly higher yield of green fodder (14.99 t ha^{-1}) as well as dry fodder (3.60 t ha^{-1}) compared to the wider spacing of 30 × 10 cm. Harvesting at the ear head emergence stage gave the maximum green fodder (16.26 t ha^{-1}), whereas the dry fodder (3.60 t ha^{-1}) yield was greater when harvested at physiological maturity. Increased nitrogen dose (40–80 kg ha^{-1}) decreased hemicellulose content (24.3–21.5%) and other fibre fractions (ADF, NDF and lignin), while improvement in total digestible nutrients (64.1–70.0%), dry matter digestibility (66.4–70.0%) and protein (crude) content (6.26–7.30%) together with crude protein yield (170–293 kg ha^{-1}) was observed with the higher doses of nitrogen. Early harvesting enhanced crude protein (8.17%), total digestible nutrients and dry matter digestibility, whereas physiological maturity led to higher crude fibre (32.29%), ADF (28.61%), NDF (53.2%) and lignin (3.5%) contents. Planting geometry did not significantly affect fodder quality attributes. The results specified that 80 kg N ha^{-1} together with harvesting at earhead emergence phase is optimal for obtaining higher fodder yield with better nutritive quality of barnyard millet under rainfed conditions.

Keywords: Fodder production, Fodder quality, Harvesting stage, Millet, Nitrogen level

Introduction

Agriculture and livestock are interdependent sectors, vital for sustaining rural livelihoods and ensuring food security. India, with the world's largest livestock population (536 million), contributes 30.23% to agricultural Gross Value Added (Anonymous, 2019). Livestock serves as a major source of income for small and marginal farmers, particularly in rainfed and tribal areas, but its productivity is constrained by acute fodder scarcity. At the all-India level, there is a significant gap between the demand and supply of livestock feed resources. Dry fodder availability is 326.4 million tonnes against a requirement of 426.1 million tonnes, indicating a deficit of 23.4%. Green fodder shows an 11.24% deficit, with availability of 734.2 million tonnes compared to a requirement of 827.19 million tonnes. Similarly, concentrate feed availability (61 million tonnes) falls short of the demand (96 million tonnes), resulting in a deficit of about 36% (Roy *et al.*, 2019). Despite this demand, cultivated fodder area has stagnated at 8.4 million ha (4% of total cultivable land), while conventional fodder crops like sorghum, maize, berseem, oat and bajra-napier hybrid remain resource-intensive and unsuitable for marginal lands.

To address the fodder deficit, climate-resilient, short-duration and low-input crops are essential. Small millets such as finger, foxtail, kodo, little, proso, browntop and barnyard millet are valued for adaptability, resilience and dual-purpose use (Sukanya *et al.*, 2023). Barnyard millet (*Echinochloa spp.*), an ancient hexaploid (2n=54) of the Poaceae family, includes two major cultivated species, *E. frumentacea* and *E. utilis*. It is widely distributed across

Asia and ranks as the fourth most important minor millet globally. Barnyard millet, popularly known as "billion-dollar grass," is a short-duration crop, adaptable from tropical to temperate regions up to 2700 m altitude with 200–400 mm rainfall (Khan *et al.,* 2024). Nutritionally, its grains are rich in carbohydrates (55–65.5 g), protein (6–13 g), fiber (9.5–14 g), calcium (11–27 mg), phosphorus (280–340 mg) and iron (15–19.5 mg) in 100 g (Sood *et al*., 2015). It has a higher straw yield and fodder value used as a potential livestock feed crop in the dry areas of the Deccan plateau to the extreme hills of the temperate sub-Himalayan region (Sukanya *et al*., 2022). Its straw is superior to rice and oat, containing 61% Total Digestible Nutrients (TDN) with good digestible fiber (Yabuno, 1987), yielding about 5 t ha^{-1} dry fodder under Indian conditions (Anonymous, 2014) and meeting approximately 11.5% of fodder needs in Uttarakhand (Singh and Singh, 2020). It is suitable for hay, silage and feed, although anti-nutritional factors like phytates and tannins remain limiting.

Fodder yield and quality are strongly influenced by agronomic practices. Planting geometry regulates plant density, canopy and resource use (Janani *et al*., 2022), while nitrogen management enhances tillering, biomass and protein content. The harvesting stage is crucial, with earhead emergence offering higher quality and physiological maturity favoring dry matter accumulation. Optimizing these practices is a key for maximizing its dual-purpose potential. Thus, barnyard millet, with its resilience, high biomass and superior nutritive quality, offers a sustainable alternative to conventional fodder crops. However, limited research on its agronomic management highlights the need for standardized cultivation practices that can enhance productivity and forage quality, ensuring sustainable fodder production amid increasing demand.

Material and Methods

Experimental site and weather conditions: The field experiment was conducted at the University of Agricultural Sciences, Bangalore, Karnataka, India. The location falls under the Eastern Dry Zone (Zone V) of Karnataka, situated at 12°51′ N latitude, 77°35′ E longitude and 930 m above MSL. The location experiences a semi-arid climate with erratic rainfall distribution and moderate soil fertility. The soil was sandy clay loam, a little acidic (pH 5.64), low in organic carbon (0.36%) and available nitrogen (249.7 kg ha^{-1}), while phosphorus (46.8 kg ha^{-1}) was in the high range and potassium (180.4 kg ha^{-1}) was in the medium range.

The existing meteorological conditions during experimentation had a notable impact on the performance of barnyard millet. The maximum temperature fluctuated between 27 and 30°C, while the minimum ranged from 15 to 20°C. Relative humidity remained high (above 85%) during most of the growing season. The peak rainfall was recorded in October, which coincided with the vegetative and early reproductive stages, providing adequate soil moisture conducive to crop growth and grain filling. In contrast, reduced rainfall and slightly higher temperatures during September affected the initial crop establishment, whereas the decline in precipitation during November corresponded with crop maturity. On the whole, the weather situations were supportive for ideal performance of barnyard millet (Fig 1).

Experimental design: The experiment involved twelve treatment combinations formed by three nitrogen levels (40, 60 and 80 kg nitrogen ha^{-1}), two planting geometries (30 × 10 cm and 22.5 × 10 cm) and two stages of harvest (earhead emergence and physiological maturity), laid out in a Randomized Complete Block Design with three replications. Nitrogen was given in equal splits twice, half as basal at sowing and the remaining quantity at 30 days after sowing, while the recommended doses of potassium and phosphorus were applied uniformly to all plots. The gross plot measured 3.6 × 3.0 m (12.96 m²) and the net plot 2.4 × 2.6 m (6.24 m²).

Crop husbandry: The crop was sown on 10th August of 2024, furrows were opened manually at 30 and 22.5 cm apart and seeds were placed at 2 to 3 cm depth with intra-row spacing of 10 cm and covered with soil. To maintain an optimum plant population in the experimental plots, thinning was carried out to remove excess seedlings and gap filling was performed seven days after sowing in areas where seeds failed to germinate. The weeds were managed by hand weeding once between 25 and 30 days after crop sowing. The crop was completely grown under rainfed conditions without external application of irrigation water. Harvesting was done as per the treatment. The plants from the net plot area were harvested separately. After harvesting, the plants were bundled and their fresh weight and allowed for sun drying and the dry weight of the straw was recorded. The crop was threshed by beating with wooden sticks. The seeds were winnowed, cleaned and the seed weight per

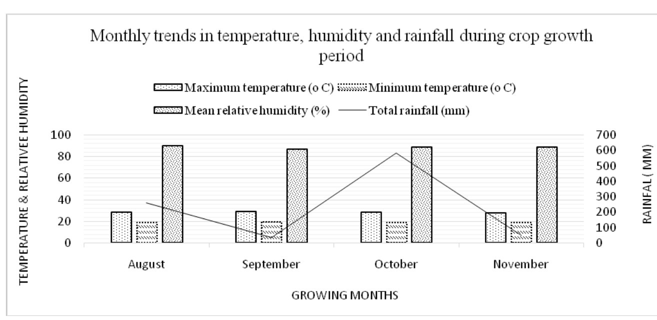

Fig 1. Monthly variations in temperature (maximum and minimum), mean relative humidity and total rainfall recorded during the experimentation (*kharif* 2024)

net plot was recorded. The straw yield from each net plot was weighed after threshing separately and recorded in kilograms per hectare. The rest of the crop husbandry practices were commonly adopted for all the treatments as a package of practices developed and recommended by the University of Agricultural Sciences, Bengaluru.

Data collection: Green fodder yield was determined by harvesting the entire net plot at earhead emergence and physiological maturity and the fresh biomass was weighed immediately after harvest. A representative sub-sample of green fodder was oven-dried at 70 ± 5 °C to a constant weight to determine the content of dry matter, subsequently extrapolated to obtain dry fodder yield. The composition of nutrients in dry fodder was analyzed following standard laboratory procedures. Nitrogen was analyzed by the Kjeldahl method and crude protein (CP %) was computed by multiplying nitrogen content by 6.25. Crude fiber (CF %) was estimated using the acid–alkali digestion method, while the Soxhlet extraction technique determined ether extractable fat (%). Total ash (%) was obtained by igniting the oven-dried sample in a muffle furnace at 550 ± 25 °C until complete ashing. Acid detergent fiber (ADF %) and the neutral detergent fiber (NDF %) were estimated following the procedure of Goering and Van Soest (1975). Lignin (%) was determined using the acid detergent lignin (ADL) method and hemicellulose (%) was calculated as the difference between NDF and ADF. Total digestible nutrients (TDN %), nitrogen-free extract (NFE %) and the dry matter digestibility (DMD %) were calculated with formulae based on ADF and other proximate composition values. Crude protein yield (kg ha^{-1}) was calculated by multiplying the obtained protein content by the dry matter content and dividing by 100.

Statistical analysis: The data recorded during the experiment were analyzed using the ANOVA (Analysis of Variance technique appropriate for a Randomized Block Design (RBD) with a factorial concept, as outlined by Gomez and Gomez (1984). The significance of treatment effects was tested at the probability level of 5%. Wherever significant effects were shown, critical difference (C.D.) values were determined for comparing treatment means.

Results and Discussion

Fodder yield: Different nitrogen levels, planting geometry and harvesting stages had a profound impact on the fodder yield of Barnyard millet. Use of 80 kg nitrogen ha^{-1} produced the higher green fodder yield (GFY) (15.73 t ha^{-1}) and dry fodder yield (DFY) (3.97 t ha^{-1}), followed by 60 kg N ha^{-1}, while the minimum yields were recorded with 40 kg N ha^{-1} (Table 1). The increase in fodder yield with higher nitrogen supply may be attributed to improved vegetative growth, higher tiller density and enhanced leaf area, which favored greater photosynthetic assimilation and dry matter accumulation. Similar responses of small millets to increasing nitrogen have been reported by Shekara *et al.* (2019).

Among row spacings, 22.5 × 10 cm recorded significantly higher GFY (14.99 t ha^{-1}) and DFY (3.60 t ha^{-1}) compared with 30 × 10 cm. Closer spacing likely improved plant population and ground coverage, resulting in better light interception and canopy photosynthesis. Harvesting at earhead emergence significantly enhanced GFY (16.26 t ha^{-1}) compared with physiological maturity. Conversely, DFY was higher at physiological maturity (3.60 t ha^{-1}) due to greater dry matter translocation and lignification at later stages. Results obtained showed that the early harvest favors succulence and green biomass, while delayed harvest increases dry matter accumulation. (Janani *et al*., 2022).

Crude fiber, crude protein, ether extractable ash and fat content: Nitrogen fertilization showed a consistent improvement in crude protein content that rose from 6.26% at 40 kg N ha^{-1} to 7.30% at 80 kg N ha^{-1}, with an intermediate value of 6.82% at 60 kg N ha^{-1}. This increase can be attributed to enhanced nitrogen

Table 1. Fodder yield of barnyard millet as influenced by different nitrogen levels, planting geometry and harvesting stages

Treatment	Green fodder yield (t ha^{-1})	Dry fodder yield (t ha^{-1})
Nitrogen level		
40 kg N ha^{-1}	13.12	2.73
60 kg N ha^{-1}	14.68	3.67
80 kg N ha^{-1}	15.73	3.97
SEM	0.42	0.10
CD (P<0.05)	1.22	0.30
Planting geometry		
30 x 10 cm	14.00	3.31
22.5 x 10 cm	14.99	3.60
SEM	0.34	0.08
CD (*p* <0.05)	1.00	0.25
Harvesting stages		
Earhead emergence	16.26	3.31
Physiological maturity	12.76	3.60
SEM	0.34	0.08
CD (*p* <0.05)	1.00	0.25
Interaction		
SEM	0.83	0.21
CD (*p* <0.05)	NS	NS

assimilation and its role as a structural constituent of amino acids and proteins, resulting in higher protein accumulation in the herbage. Conversely, a significant reduction in crude fiber content with higher nitrogen supply, declining from 32.72% at 40 kg N ha^{-1} to 27.04% at 80 kg N ha^{-1}, was observed. The reduction in fiber with increased nitrogen may be due to delayed lignification and greater synthesis of soluble cell contents, thereby improving fodder digestibility. The fat (Ether extractable) and ash content also showed a marginal but significant improvement with increasing nitrogen, reaching 0.91 and 12.54%, respectively, at 80 kg N ha^{-1}, reflecting improved metabolic activity and mineral uptake under higher nitrogen availability. Nitrogen fertilization enhances crude protein content by stimulating nitrogen assimilation and amino acid–protein synthesis through enzymes like nitrate reductase and glutamine synthetase. Simultaneously, crude fiber declines with nitrogen as delayed lignification and greater soluble cell contents reduce structural carbohydrate accumulation. The ash and ether extractable fat content improved marginally due to enhanced metabolic activity and higher mineral uptake under adequate N nutrition.

Planting geometry exerted no marked influence on any of the quality parameters. This indicates that within the limits tested, variation in plant density did not influence forage nutritive composition, though it may influence biomass yield. Harvesting stages exerted a pronounced effect on quality attributes. At earhead emergence, the highest crude protein (8.17%) content with comparatively lower crude fiber (27.51%), along with higher ether extract (0.93%) and ash (12.21%). By contrast, at physiological maturity, crude protein declined sharply to 5.41%, while crude fiber increased to 32.29%, accompanied by reduced ether extract (0.84%) and ash (11.75%) (Table 2). Harvesting at earhead emergence results in higher crude protein and lower fiber because young tissues are richer in soluble proteins and non-fibrous carbohydrates. At physiological maturity, protein declines and fibre rise due to nutrient translocation to grains and increased cell wall lignification, lowering digestibility (Amandeep and Chaudhary, 2010).

Nitrogen levels, planting geometry and harvesting stages significantly influenced crude protein yield. Among the nitrogen levels, application of 80 kg N ha^{-1} recorded the highest crude protein yield (293.24 kg ha^{-1}), which was markedly superior to 40 and 60 kg N ha^{-1} (Table 2). CP yield is a function of CP content and DM yield. Both attributes increased with nitrogen fertilization, resulting in a significant increase in CP yield.

Table 2. Crude fibre, crude protein, ether extractable fat, ash content and crude protein yield of barnyard millet as influenced by different nitrogen levels, planting geometry and harvesting stages

Treatment	Crude protein (%)	Crude fibre (%)	Ether extractable fat (%)	Ash content (%)	Crude protein yield (kg ha^{-1})
Nitrogen levels					
40 kg N ha^{-1}	6.26	32.72	0.86	11.20	170.46
60 kg N ha^{-1}	6.82	29.94	0.88	12.20	251.87
80 kg N ha^{-1}	7.30	27.04	0.91	12.54	293.24
SEM	0.15	0.91	0.01	0.11	10.41
CD (p <0.05)	0.43	2.68	0.02	0.32	30.54
Planting geometry					
30 x 10 cm	6.83	29.30	0.89	11.91	226.03
22.5 x 10 cm	6.76	30.50	0.88	12.04	251.02
SEM	0.12	0.75	0.00	0.09	8.50
CD (p <0.05)	NS	NS	NS	NS	24.94
Harvesting stages					
Earhead emergence	8.17	27.51	0.93	12.21	280.40
Physiological maturity	5.41	32.29	0.84	11.75	196.65
SEM	0.12	0.75	0.00	0.09	8.50
CD (p <0.05)	0.35	2.19	0.01	0.26	24.94
Interaction					
SEM	0.29	1.83	0.01	0.22	20.83
CD (p <0.05)	NS	NS	NS	NS	NS

Acid Detergent Fiber (ADF), Neutral Detergent Fibre (NDF) and Lignin content: The structural fiber components of barnyard millet were significantly affected by nitrogen levels and harvesting stages, whereas planting geometry had no marked effect. Increasing nitrogen application progressively reduced fiber fractions. At 40 kg N ha^{-1}, the crop recorded the higher ADF, NDF and lignin values of 28.83%, 53.09% and 3.32%, respectively, which declined to 24.31%, 45.77% and 2.68% at 80 kg N ha^{-1}(Table 3). This reduction reflects the role of nitrogen in delaying cell wall thickening and favoring synthesis of soluble cellular components, thereby improving fodder digestibility.

Harvesting stage exhibited a strong influence, with earhead emergence recording the lowest fiber fractions (ADF 24.53%, NDF 46.21%, lignin 2.45%) compared to significantly higher values at physiological maturity (28.61, 53.23, 3.53%). The increase at maturity is attributable to enhanced lignification and structural carbohydrate deposition with advancing crop age, which reduces fodder quality and digestibility (Uyanik and Carpici, 2025). Higher ADF, NDF and acid detergent lignin (ADL) values were reported with low N fertilizer rates and later harvests in desho grass (*Pennisetum glaucifolium*) at Ethiopia (Defar *et al*., 2025)

***Hemicellulose, Total Digestible Nutrients (TDN) and Nitrogen Free Extract (NFE)*:** Increasing nitrogen from 40 kg N ha^{-1} to 80 kg N ha^{-1} resulted in a decrease in hemicellulose content (from 24.26–21.45%), suggesting that higher nitrogen fertilization stimulates the development of new plant tissues, leading to lower cell wall constituents such as hemicellulose. Conversely, Total digestible nutrients (TDN) and dry matter digestibility (DMD) showed an increase with higher nitrogen rates, indicating improved forage quality and digestibility (TDN from 64.13 to 69.96%, DMD from 66.44–69.96%), nitrogen free extract (NFE) slightly decreased with nitrogen increment (50.99–47.74%), possibly due to compositional shifts in carbohydrates within the cell wall (Shekara *et al.,* 2025).

Statistically, planting geometry did not significantly influence hemicellulose, TDN, NFE and DMD in barnyard millet. The harvesting stage has a pronounced impact on the nutritional quality of forage crops, notably affecting parameters such as hemicellulose, TDN, NFE and DMD. Early harvesting at the earhead emergence stage resulted in significantly lower hemicellulose content. Still, higher TDN and DMD values compared to harvest at physiological maturity, this trend is consistent with scientific findings, which show that as plants progress

Table 3: ADF, NDF, lignin, hemicellulose, TDN, NFE and DMD of barnyard millet as influenced by different nitrogen levels, planting geometry and harvesting stages

Treatment	**ADF (%)**	**NDF (%)**	**Lignin content (%)**	**Hemi cellulose (%)**	**TDN (%)**	**NFE (%)**	**DMD (%)**
Nitrogen levels							
40 kg N ha^{-1}	28.83	53.09	3.32	24.26	64.13	50.99	66.44
60 kg N ha^{-1}	26.56	50.30	2.98	23.73	67.05	49.82	68.21
80 kg N ha^{-1}	24.31	45.77	2.68	21.45	69.96	47.74	69.96
SEM	0.71	1.29	0.10	0.62	0.91	0.57	0.55
CD ($P<0.05$)	2.08	3.79	0.29	1.81	2.68	1.68	1.62
Planting geometry							
30 x 10 cm	26.54	49.21	2.94	22.66	67.08	48.91	68.22
22.5 x 10 cm	26.59	50.23	3.04	23.64	67.02	50.12	68.18
SEM	0.58	1.05	0.08	0.50	0.75	0.47	0.45
CD (p <0.05)	NS	NS	NS	NS	NS	NS	NS
Harvesting stages							
Earhead emergence	24.53	46.21	2.45	21.68	69.68	48.80	69.79
Physiological maturity	28.61	53.23	3.53	24.62	64.42	50.23	66.62
SEM	0.58	1.05	0.08	0.50	0.75	0.47	0.45
CD (p <0.05)	1.70	3.09	0.23	1.47	2.19	1.37	1.32
Interaction							
SEM	1.42	0.98	0.19	1.23	1.83	1.14	1.10
CD (p <0.05)	NS	NS	NS	NS	NS	NS	NS

from vegetative to reproductive and maturity stages, fibrous components (like hemicellulose) increase. At the same time, protein, digestibility and soluble carbohydrates gradually decrease (Defar *et al*., 2025).

Conclusion

The present study clearly demonstrated that nitrogen fertilization, planting geometry, and harvesting stage significantly influence the yield and nutritive quality of barnyard millet fodder under rainfed conditions. Application of 80 kg N ha^{-1} proved optimal, as it enhanced green and dry fodder yields while improving crude protein content, total digestible nutrients, and dry matter digestibility, and reducing crude fiber and structural fiber fractions (ADF, NDF, and lignin). Although planting geometry did not markedly affect quality parameters, closer spacing (22.5 × 10 cm) resulted in higher biomass production due to better resource utilization and increased plant population. Harvesting at the earhead emergence stage produced superior forage quality, whereas harvesting at physiological maturity increased fiber content and dry matter yield, reflecting a trade-off between yield and nutritive value.

Overall, cultivating barnyard millet with 80 kg N ha^{-1} at a spacing of 22.5 × 10 cm and harvesting at the earhead emergence stage is recommended to achieve an optimal balance between fodder yield and quality. This approach can enhance forage productivity and contribute to sustainable livestock nutrition in dryland ecosystems.

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