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CONVENTIONAL TILLAGE COMBINED WITH MULCHING AND INTEGRATED NUTRIENT MANAGEMENT ENHANCES GROWTH AND YIELD OF PEARL MILLET IN SEMI-ARID REGIONS OF WESTERN INDIA

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SUMMARY

Excessive tillage and heavy dependence on chemical fertilizers contribute to soil degradation, lower crop productivity, and environmental problems in semi-arid areas. To address this, a study was conducted at the Agronomy Farm of Rajasthan Agricultural Research Institute (RARI), Durgapura, Jaipur, during *kharif* seasons of 2023 and 2024 to assess the impact of tillage, mulch and nutrient management practices on pearl millet. Treatments imposed were four tillage and mulch combinations in main plots and five nitrogen management practices (Control, 100% RDN; Recommended dose of nitrogen through Chemical, 75% RDN through Chemical and 25% RDN through FYM, 50% RDN through Chemical and 50% RDN through FYM and 100% RDN through FYM; Farm Yard Manure) in sub-plots with three replications. Conventional tillage with mustard stover mulch (3 t ha^{-1}) recorded significant increase in growth metrics, including dry matter accumulation (131.9 g/plant^1), crop growth rate (19.91 g/m^2/day) during 30-45 DAS, net assimilation rate (1.74 g/g^1/day^1), and leaf area index (3.94 at 60 DAS). On an average, Conventional tillage with mustard stover mulch recorded significantly higher grain yield (19.37%) and stover yield (19.60%). The application of 75% RDN through chemical fertilizer and 25% through FYM proved to be most effective in enhancing growth, physiological parameters and yield, recording 62.56 and 62.27% increase in grain and stover yield, respectively.

Key words: Tillage, mulch, nitrogen, pearl millet, growth, yield

Pearl millet (*Pennisetum glaucum* (L.) R. Br. Emend Stuntz) is a climate-resilient cereal crop widely cultivated in the semi-arid regions of India, particularly in Rajasthan, where it serves as a staple food and a vital source of fodder. Despite its inherent tolerance to drought and high temperatures, pearl millet yields remain suboptimal due to poor soil health, erratic rainfall, and inadequate nutrient management. Addressing these challenges requires the adoption of agronomic practices that not only improve crop productivity but also ensure long-term sustainability of soil and water resources.

Tillage is a foundational soil operation that influences the physical environment of the root zone. It affects parameters like soil aeration, porosity, water infiltration, and weed suppression. Conventional tillage remains the predominant land preparation method in western India. While it facilitates seedbed preparation and initial weed control, its continuous and unregulated use often leads to soil degradation and loss of organic matter (Pareek *et al.*, 2018). To mitigate these adverse effects, conservation practices such as mulching and integrated nutrient management (INM) are gaining attention. Mulching helps in reducing evaporation losses, moderating soil temperature, and enhancing moisture retention (El-Beltagi *et al.*, 2022). The judicious combination of organic manures, chemical fertilizers, and biofertilizers improves nutrient availability, promotes microbial activity, and sustains soil fertility (Xing *et al.*, 2025). The combined application of conventional tillage, mulching, and INM may offer a synergistic effect on crop performance by improving soil physical properties, enhancing nutrient use efficiency, and supporting robust plant growth under semi-arid conditions (Akhtar *et al.*, 2023). However, empirical evidence on the interactive effects of these practices in the context of pearl millet cultivation in western India remains limited. Mulching can improve soil temperature and enhance early seedling vigour and crop emergence. For instance, Aniekwe *et al*. (2004) observed that straw mulch increased soil surface temperature compared to unmulched plots, thereby supporting faster crop establishment. Furthermore, Van Derwerken and Wilcox (1988) reported that mulching reduces soil erosion, nutrient loss, and water vapor escape, making it a reliable intervention for sustaining crop growth in fragile ecosystems. The synergistic effects of reduced tillage and mulching lead to a more stable and productive soil environment. Together, these practices contribute to maintaining soil fertility, reducing input costs, and improving water and nutrient-use efficiency, which are essential for climate-resilient agriculture. Their combined adoption can help address the pressing challenges of land degradation, moisture stress, and yield variability in pearl millet cultivation across semi-arid landscapes like those in Rajasthan.

Nitrogen (N) is an essential nutrient that significantly influences plant growth and productivity. As a key component of chlorophyll, amino acids, enzymes, nucleic acids, and vitamins, it supports critical physiological and biochemical functions. In pearl millet a fast-growing crop with high biomass production nitrogen is particularly important for promoting vigorous vegetative growth and ensuring proper grain development. However, in the sandy soils of semi-arid regions, nitrogen availability is often limited due to inherently low organic matter and a high susceptibility to leaching. Split applications of nitrogen fertilizers, timed with the crop's critical growth stages, are known to increase efficiency by synchronizing supply with plant demand, thereby reducing nutrient losses (Liu *et al*., 2019). This strategy is particularly suitable for pearl millet under rainfed conditions where nutrient uptake windows are tightly linked to moisture availability. Moreover, the global emphasis on conservation agriculture, resource-use efficiency, and climate resilience makes it imperative to evaluate sustainable production systems that combine low-cost, low-risk interventions to improve both productivity and soil health. Therefore, the present study was undertaken to evaluate the impact of conventional tillage, mulch application, and integrated nutrient management on the growth and yield of pearl millet under the semi-arid agro-climatic conditions of western Rajasthan. The findings aim to contribute to the development of context-specific, resource-efficient strategies for sustainable pearl millet production in dryland regions.

MATERIALS AND METHODS

A field experiment was conducted at Agronomy Farm, RARI, Durgapura, Jaipur (Rajasthan), during kharif seasons of 2023 and 2024. This location is situated at 26° 85' N latitude and 75° 78' E longitude at an altitude of 431 meters above mean sea level in Rajasthan State of India. The region experiences a semi-arid climate, characterized by harsh winters with severe cold and hot, dry, desiccating winds during the summer months. In 2023, the weekly maximum and minimum temperatures ranged from 30.5 to 36.0/ °C and 18.7 to 25.2/ °C, respectively, while in 2024, they ranged from 29.8 to 36.5/ °C and 23.6 to 26.1/ °C, respectively. The weekly relative humidity varied between 54-91 and 43-94% in 2023 and 2024, respectively. Total rainfall received during crop growing seasons was 494.7 mm in 24 rainy days during 2023 and 1330.0 mm in 20 rainy days during 2024.

The experimental field soil had a loamy sand texture and was slightly alkaline, with a pH of 8.2 in 2023 and 8.1 in 2024. It was low in organic carbon (Walkley and Black, 1934) with 0.22% and 0.23%, available nitrogen (Subbiah and Asija, 1956) of 140.1 and 142.2/ kg/ha, but high in available phosphorus of (Olsen *et al*., 1954) 26.3 and 26.1/ kg/ha and potassium (Richards, 1954) of 128.5 and 126.2/ kg/ha during 2023 and 2024, respectively.

The experiment, comprising 20 treatment combinations with three replications, was conducted using a split plot design. The main plot treatments included four tillage and mulch practices (Conventional Tillage without Mulch, Conventional Tillage with Mustard stover Mulch at 3/ t/ ha^{-1}, Minimum Tillage without Mulch and Minimum Tillage with Mustard stover mulch at 3/ t/ ha^{-1}). The sub-plot treatments consisted of five nitrogen management strategies (Control, N- Dose, 100% through Chemical, N- Dose, 75% through Chemical and 25% through FYM, N-Dose, 50% through Chemical and 50% through FYM and N-Dose 100% through FYM).

The designated plots were initially harrowed after the pre-monsoon showers, and final seedbed preparation was carried out with a second harrowing followed by planking at the commencement of rainfall. Pearl millet variety RHB 233 was sown on 13th July 2023 and 15th July 2024 at a seed rate of 4/ kg/ha, using the 'pora' method, with row and plant spacing of 50/ cm and 15/ cm, respectively. Sun-dried mustard stover at 3.0/ t/ ha^{-1} was uniformly applied as mulch between rows 20 days after sowing. Farmyard manure (FYM) was incorporated 10-15 days before sowing as per the treatments. Nitrogen was applied in two equal splits, half as a basal dose and the remaining half as top dressing at 30 days after sowing (DAS) using urea. The recommended phosphorus dose (40/ kg/ P_2O_5/ ha^{-1}) was applied at sowing through single super phosphate (SSP) during both years of the study. Dry matter accumulation was recorded by oven drying (at 70 °C) five randomly selected plants from each plot at 30, 45, 60 DAS and at harvest. The crop growth rate (CGR) was calculated as suggested by Enyi (1962).

$$\text{CGR} = \frac{W_2 - W_1}{P\,(t_2 - t_1)}$$

Where, W_2 and- W_1 are the dry matter weight of the plant at time t_2 and t_1, respectively and P is the ground area occupied by the plant in m^2. The relative growth rate (RGR) represents the dry weight gained in time interval in relation to initial weight. The mean RGR was calculated as suggested by Blackman (1919).

$$\text{RGR} = \frac{\log_e W_2 - \log_e W_1}{t_2 - t_1}$$

Where, W_2 and- W_1 are the dry matter weight of the plant at time t_2 and t_1 respectively, and it is expressed in mg g^{-1} $day^{-}1$. The leaf area was recorded with the help of leaf area meter. The leaf area index (LAI) being a primary factor for calculation of other growth parameters was calculated as per Watson's formula (1952).

$$\text{Leaf area index} = \frac{\text{Leaf area}}{\text{Ground area}}$$

Net assimilation rate (NAR) was calculated as suggested by Williams (1946).

$$\text{Net assimilation rate} = \frac{(W_2 - W_1)}{(t_2 - t_1)} \times \frac{(\log_e L_2 - \log_e L_1)}{(L_2 - L_1)}$$

Where,

W_1 and W_2 are dry weights of whole plant at time t_1 and t_2 respectively, L_1 and L_2 are leaf weights or leaf area at time t_1 and t_2 respectively, t_1 and t_2 are time interval in days NAR is expressed as the grams of dry weight increase per unit dry weight or area per unit time (g/g/day)

Chlorophyll was extracted in DMSO (Dimethyl sulfoxide), and transmittance was recorded with spectrophotometer at 645 and 663 nm. Arnon's equation (1949) was used to work out chlorophyll content.

$$\text{Chlorophyll "a" (mg/g fresh weight of leaves)} = \frac{(12.7 \text{ x } A_{663}) - (2.69 \text{ x } A_{645})}{1000} \times \frac{\text{Volume of DMSO}}{\text{Weight of leaf sample}}$$

$$\text{Chlorophyll "b" (mg/g fresh weight of leaves)} = \frac{(22.9 \text{ x } A_{645}) - (4.65 \text{ x } A_{663})}{1000} \times \frac{\text{Volume of DMSO}}{\text{Weight of leaf sample}}$$

Total chlorophyll content was worked out by adding chlorophyll "a" and chlorophyll "b" as under: Total Chlorophyll (mg g^{-1} fresh weight of leaves) = Chlorophyll a + Chlorophyll b

Data from the split-plot design involving two factors (tillage+mulch and nitrogen management) were analyzed using two-way analysis of variance (ANOVA). Treatment means within each factor were compared using the Critical Difference (CD) at a 5% significance level.

RESULTS AND DISCUSSION

Growth attributes

Conventional tillage with mulch recorded maximum dry matter accumulation at 45 DAS (26.97 and 28.17 g $plant^{-1}$), 60 DAS (98.28 and 103.53 g $plant^{-1}$) and at harvest (129.51 and 134.34 g $plant^{-1}$), which remained at par with conventional tillage without mulch and minimum tillage with mulch, and significantly superior to minimum tillage without mulch in both years, respectively (Table 1). This enhancement can be attributed to the improved soil environment created by the combined effect of tillage and mulching, which likely enhanced soil aeration, moisture retention, and nutrient availability factors conducive to greater biomass production.

Application of 75% RDN through chemical fertilizer combined with 25% RDN through FYM recorded maximum dry matter accumulation (g $plant^{-}$

[1]) at 45 (26.97 and 28.17 g plant^{-1}), 60 (98.28 and 103.53 g plant^{-1}) DAS and at harvest (129.51 and 134.34 g plant^{-1}), which was statistically at par with 100% RDN through chemical fertilizer and significantly superior to the control, 50% RDN through chemical + 50% RDN through FYM, and 100% RDN through FYM during both years, respectively (Table 1). This can be attributed to the complementary roles of chemical and organic nutrient sources. Chemical fertilizers supply immediately available nitrogen required for early vegetative growth, while FYM ensures sustained nutrient release, enhances soil structure, and supports microbial activity (Singh *et al*., 2020). These findings are supported by Yadav *et al*. (2019) and Prakash *et al*. (2021).

The highest crop growth rate (CGR) of 19.47 and 20.35/ g/ m^{-2}/ day^{-1} at 30-45 DAS and 63.37 and 66.97 g/ m^{-2}/ day^{-1} at 45–60 DAS (Table 2), along with the highest net assimilation rate (NAR) of 1.69 and 1.79/ g/ g^{-1}/ day^{-1} at 30–45 DAS and 6.24 and 6.68 g/ g^{-1}/ day^{-1} at 45-60 DAS (Table 4) were recorded under conventional tillage with mulch. Similarly, the highest relative growth rate (RGR) of 111.37 and 111.89/ mg/ g^{-1}/ day^{-1} during 30–45 DAS was also observed under the same treatment (Table 3). These values were statistically at par with conventional tillage without mulch and minimum tillage with mulch but significantly higher than those recorded under minimum tillage without mulch during both years, respectively. However, RGR between 45-60 DAS remained statistically non-significant. Interestingly, during the period between 60 DAS and harvest, the highest RGR was observed under minimum tillage without mulch (9.34 and 8.46 mg g^{-1} day^{-1}), which was significantly superior to the other treatments, including conventional tillage with mulch, conventional tillage without mulch and minimum tillage with mulch. This trend may be attributed to the benefits of reduced soil disturbance under minimum tillage, which helps preserve soil structure and maintain a stable root environment, thereby supporting sustained root activity and nutrient uptake during the later stages of crop growth (Kumar *et al*., 2021). These results are in agreement with Meena *et al*. (2020).

The highest crop growth rate (Table 2) of 2.34 and 2.47 g m^{-2} day^{-1} (0-30 DAS), 19.94 and 20.60 g m^{-2} day^{-1} (30-45 DAS), 63.95 and 67.85 g m^{-2} day^{-1} (45-60 DAS), and 13.79 and 12.68 g m^{-2} day^{-1} (60 DAS to harvest), as well as relative growth rate (Table 3) of 110.25 and 109.67 mg g^{-1} day^{-1}; 85.64 and 86.54 mg g^{-1} day^{-1}; 8.94 and 7.86 mg g^{-1} day^{-1} and net assimilation rate (Table 4) of 1.80 and 1.87 g g^{-1} day^{-1}; 6.51 and 6.97 g g^{-1} day^{-1}; 1.42 and 1.31 g g^{-1} day^{-1} at 30-45 DAS; 45-60 DAS; 60 DAS to harvest, were

TABLE 1

Effect of different tillage, mulch and N-management on dry matter accumulation of pearl millet

Treatments	Dry matter accumulation (g/plant)							
	30 DAS		45 DAS		60 DAS		At harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
Tillage and Mulch								
CT without Mulch (T_1)	5.01	5.13	26.29	26.86	95.61	100.01	126.09	130.00
CT with Mulch (T_2)	5.06	5.26	26.97	28.17	98.28	103.53	129.51	134.34
MT without Mulch (T_3)	4.80	5.00	22.05	23.67	83.03	86.14	114.05	116.78
MT with Mulch (T_4)	4.95	5.08	25.88	26.33	93.14	98.05	123.27	128.22
S.Em.±	0.07	0.13	0.65	0.70	2.58	2.69	2.86	2.91
CD at 5 %	NS	NS	2.25	2.41	8.92	9.30	9.89	10.07
CV	5.64	10.14	9.94	10.28	10.79	10.74	8.98	8.85
Nitrogen management								
Control (N_0)	4.41	4.49	21.86	22.93	83.70	85.34	108.54	108.86
100% RDN through Chemical (N_1)	5.19	5.45	27.19	28.31	96.57	102.00	131.15	135.35
75% RDN through Chemical and 25% RDN through FYM (N_2)	5.27	5.55	27.70	28.73	99.66	105.09	134.83	139.34
50% RDN through Chemical and 50% RDN through FYM (N_3)	5.00	5.09	25.55	26.23	92.48	97.42	123.66	128.27
100% RDN through FYM (N_4)	4.91	5.01	24.19	25.08	90.16	94.81	117.97	124.86
S.Em.±	0.08	0.13	0.58	0.58	2.09	2.11	2.68	2.75
CD at 5 %	0.23	0.36	1.67	1.67	6.02	6.09	7.71	7.93
CV	5.50	8.52	7.93	7.64	7.83	7.56	7.52	7.49

TABLE 2
Effect of different tillage, mulch and N-management on crop growth rate of pearl millet

Treatments	Crop growth rate (g/m^{-2}/day)							
	0-30 DAS		30-45 DAS		45-60 DAS		60 Days to harvest	
	2023	2024	2023	2024	2023	2024	2023	2024
Tillage and Mulch								
CT without Mulch (T_1)	2.22	2.28	18.91	19.32	61.60	65.00	11.95	11.11
CT with Mulch (T_2)	2.25	2.34	19.47	20.35	63.37	66.97	12.24	11.41
MT without Mulch (T_3)	2.13	2.22	15.33	16.58	54.19	55.51	12.16	11.35
MT with Mulch (T_4)	2.20	2.26	18.60	18.88	59.77	63.74	11.81	11.17
S.Em.±	0.03	0.06	0.59	0.71	1.83	1.96	0.17	0.33
CD at 5 %	NS	NS	2.04	2.44	6.32	6.77	0.57	1.15
CV	5.64	10.14	12.61	14.54	11.85	12.07	5.31	11.42
Nitrogen management								
Control (N_0)	1.96	2.00	15.51	16.38	54.96	55.47	9.74	8.71
100% RDN through Chemical (N_1)	2.30	2.42	19.55	20.32	61.66	65.48	13.56	12.35
75% RDN through Chemical and 25% RDN through FYM (N_2)	2.34	2.47	19.94	20.60	63.95	67.85	13.79	12.68
50% RDN through Chemical and 50% RDN through FYM (N_3)	2.22	2.26	18.26	18.79	59.48	63.26	12.22	11.43
100% RDN through FYM (N_4)	2.18	2.22	17.13	17.84	58.62	61.97	10.90	11.13
S.Em.±	0.03	0.06	0.54	0.55	1.81	1.98	0.45	0.60
CD at 5 %	0.10	0.16	1.56	1.59	5.22	5.70	1.30	1.72
CV	5.50	8.52	10.37	10.19	10.50	10.91	12.98	18.34

observed under the application of 75% RDN through chemical fertilizer and 25% RDN through FYM. These values were statistically at par with 100% RDN through chemical fertilizer, but significantly superior to the control, 50% RDN through chemical + 50% RDN through FYM, and 100% RDN through FYM across both experimental years, respectively. The enhanced growth indices under the 75% RDN through chemical + 25% RDN through FYM treatment may be attributed to the synergistic effects of rapid nutrient availability from chemical fertilizers and the long-term soil health benefits provided by FYM. Chemical fertilizers deliver readily available nitrogen, which is essential for photosynthetic activity and vigorous vegetative growth during early crop stages (Kumar *et al.*, 2018). Concurrently, FYM contributes to improved soil physical properties, microbial activity, and moisture retention, while also providing a slow and sustained nutrient release (Singh *et al.*, 2021)

Leaf area index

Conventional tillage with mulch recorded significantly higher Leaf Area Index (LAI) of pearl millet at 45 DAS (4.20 and 4.38) and 60 DAS (4.70 and 4.88), which was significantly superior to minimum tillage without mulch, but remained statistically at par with conventional tillage without mulch and minimum tillage with mulch during both years, respectively (Table 5). The enhanced LAI under conventional tillage with mulch can be attributed to the synergistic effects of improved soil aeration, root proliferation, and nutrient availability from tillage, coupled with the moisture conservation, temperature moderation, and weed suppression benefits provided by mulching (Kumar *et al.*, 2019). These findings are consistent with those reported by Patel and Singh (2020). Application of 75% RDN through chemical and 25% RDN through FYM recorded highest leaf area index of 4.35 and 4.49 (at 45 DAS), and 4.85 and 5.01 (at 60 DAS), which was was significantly superior to the control, 50% RDN through chemical and 50% RDN though FYM and 100% RDN through FYM, but it had remained at par with 100% RDN through chemical during both years, respectively (Table 5). The improved LAI under the integrated nitrogen treatment can be attributed to the combined effects of immediate nutrient availability from chemical fertilizers and the sustained release and soil health benefits associated with FYM. While, chemical nitrogen supports rapid vegetative growth and leaf expansion, FYM enhances soil structure, water retention capacity, and microbial activity, all of which are critical for sustained leaf development and canopy growth

TABLE 3

Effect of different tillage, mulch and N-management on relative growth rate of pearl millet

Treatments	Relative growth rate (mg/g/day)					
	30-45 DAS		45-60 DAS		60 Days to harvest	
	2023	2024	2023	2024	2023	2024
Tillage and Mulch						
CT without Mulch (T_1)	110.33	110.10	86.28	87.79	8.10	7.25
CT with Mulch (T_2)	111.37	111.89	86.27	86.80	8.10	7.22
MT without Mulch (T_3)	101.37	103.53	88.60	86.10	9.34	8.46
MT with Mulch (T_4)	110.10	109.95	85.41	87.70	8.19	7.40
S.Em.±	2.20	3.22	1.06	1.32	0.17	0.27
CD at 5 %	7.62	11.15	NS	NS	0.59	0.94
CV	7.87	11.46	4.72	5.87	7.86	13.89
Nitrogen management						
Control (N_0)	106.57	108.71	89.61	87.60	7.65	6.79
100% RDN through Chemical (N_1)	110.21	109.61	84.47	85.34	9.03	7.91
75% RDN through Chemical and 25% RDN through FYM (N_2)	110.25	109.67	85.64	86.54	8.94	7.86
50% RDN through Chemical and 50% RDN through FYM (N_3)	108.26	108.96	85.77	87.47	8.60	7.65
100% RDN through FYM (N_4)	106.17	107.39	87.71	88.54	7.93	7.72
S.Em.±	2.11	2.38	1.89	2.08	0.27	0.39
CD at 5 %	6.09	6.86	5.43	5.98	0.77	1.12
CV	6.76	7.58	7.54	8.26	10.97	17.77

(Choudhary *et al.*, 2020). These results are in line with the findings of Singh *et al.* (2019).

Chlorophyll content

Chlorophyll content at 35 and 50 days after sowing (DAS) was not significantly influenced by different tillage and mulch treatments (Table 5). This suggests that chlorophyll synthesis in pearl millet may be less sensitive to soil physical modifications brought about by tillage and mulching during early and mid-growth stages. However, chlorophyll content was significantly affected by nitrogen management during both years (Table 5). The highest chlorophyll content of 2.95 and 2.98 mg g^{-1} at 35 DAS, and 3.03 and 3.02 mg g^{-1} at 50 DAS was recorded under the application of 75% recommended dose of nitrogen (RDN) through chemical fertilizers combined with 25% RDN through farmyard manure (FYM). This treatment was statistically at par with other nitrogen management treatments involving chemical fertilizer use but significantly superior to the control and 100% RDN applied solely through FYM during both years, respectively. This combination likely improves plant metabolic efficiency, contributing to higher chlorophyll concentration and improved overall plant vigour. These results are consistent with findings reported by Sharma *et al.* (2020) and Jadhav *et al.* (2019), who also highlighted the positive impact of integrated nutrient management on chlorophyll content in field crops.

Grain and stover yield

Grain and stover yields were significantly influenced by the tillage and mulch treatments (Fig. 1). The highest grain yields (2484 and 2583/ kg/ ha^{-1}) and stover yields (5712 and 5940/ kg/ ha^{-1}) were obtained under conventional tillage combined with mulch, which was significantly superior to minimum tillage without mulch. However, it remained statistically comparable to both conventional tillage without mulch and minimum tillage with mulch across both years. Compared to minimum tillage without mulch, the grain and stover yield under conventional tillage with mulch increased by 19.14% and 19.50% in 2023, and by 19.69% each in 2024. This yield enhancement can be attributed to the synergistic effects of tillage and mulching practices. Conventional tillage improves soil structure, facilitates deeper root growth, and enhances water and nutrient uptake (Jat *et al.*, 2018). Mulching further contributes by conserving soil moisture, moderating soil temperature and suppressing weed

TABLE 4
Effect of different tillage, mulch and N-management on net assimilation rate of pearl millet

Treatments	Net assimilation rate (g/g/day)					
	30-45 DAS		45-60 DAS		60 Days to harvest	
	2023	2024	2023	2024	2023	2024
Tillage and Mulch						
CT without Mulch (T_1)	1.59	1.62	5.87	6.19	1.16	1.07
CT with Mulch (T_2)	1.69	1.79	6.24	6.68	1.22	1.15
MT without Mulch (T_3)	1.33	1.46	5.32	5.52	1.21	1.14
MT with Mulch (T_4)	1.67	1.71	6.08	6.53	1.21	1.15
S.Em.±	0.05	0.06	0.20	0.21	0.02	0.03
CD at 5 %	0.18	0.22	0.71	0.74	0.08	0.11
CV	12.82	14.74	13.51	13.34	7.38	11.12
Nitrogen management						
Control (N_0)	1.27	1.32	5.11	5.07	0.91	0.80
100% RDN through Chemical (N_1)	1.70	1.79	6.09	6.55	1.35	1.24
75% RDN through Chemical and 25% RDN through FYM (N_2)	1.80	1.87	6.51	6.97	1.42	1.31
50% RDN through Chemical and 50% RDN through FYM (N_3)	1.62	1.69	5.97	6.43	1.25	1.17
100% RDN through FYM (N_4)	1.47	1.56	5.70	6.11	1.07	1.11
S.Em.±	0.05	0.05	0.19	0.20	0.05	0.06
CD at 5 %	0.13	0.14	0.55	0.59	0.13	0.16
CV	10.14	10.26	11.16	11.37	13.51	17.43

growth factors essential for optimizing crop performance in arid and semi-arid environments (Patil *et al.*, 2019). These results are in alignment with earlier findings that have reported significant improvements in pearl millet yield due to the combined benefits of tillage and mulching (Reddy and Baisakh, 2021). Nitrogen management significantly influenced both grain and stover yields of pearl millet across the two years of study (Figure 1). The highest grain yields (2682 and 2763/ kg/ ha^{-1}) and stover yields (6148 and 6355/ kg/ ha^{-1}) were recorded with the application of 75% of the recommended nitrogen dose (RDN) through chemical fertilizers combined with 25% RDN through farmyard manure (FYM). This treatment performed significantly better than the control, 50% RDN through chemical fertilizers + 50% through FYM, and 100% RDN through FYM, while remaining statistically at par with the treatment receiving 100% RDN through chemical fertilizers. The superior performance of the 75% chemical + 25% FYM treatment can be attributed to the synergistic benefits of both sources chemical fertilizers provide readily available nitrogen for early crop development, while FYM improves soil structure, microbial activity, and nutrient retention capacity. This integrated approach supports sustained nutrient availability throughout the growing season (Kumar *et al.*, 2018). These results corroborate the findings of Meena *et al.* (2020) and Verma *et al.* (2020).

Nutrient balance sheet

Tillage and mulch treatments significantly influenced the available nitrogen balance sheet during both years (Table 6). The highest net gain of available nitrogen (2.5 and 1.1 kg ha^{-1}), phosphorus (0.3 and 0.9 kg ha^{-1}) and potassium (-0.7 and 1.8 kg ha^{-1}) in the soil was observed under minimum tillage with mulch, which was superior to the other treatments during both years, respectively. This trend can be attributed to the protective organic layer provided by mulch and the positive effects of reduced soil disturbance, helping to preserve soil organic matter and structure, thereby enhancing nutrient availability (Lal, 2015; De B *et al.*, 2021). The retention of organic mulch on the soil surface enhances microbial activity and organic matter decomposition, thereby increasing nitrogen availability and facilitating nutrient cycling (Bhattacharyya *et al.*, 2013). Additionally, the gradual decomposition of organic mulch contributes to a steady release of potassium, supporting its continued availability in the soil (Ghosh *et al.*, 2010). The net

TABLE 5

Effect of different tillage, mulch and N-management on leaf area index and chlorophyll content of pearl millet

Treatments	Leaf area index				Chlorophyll content (mg/g)			
	45 DAS		60 DAS		35 DAS		50 DAS	
	2023	2024	2023	2024	2023	2024	2023	2024
Tillage and Mulch								
CT without Mulch (T_1)	4.08	4.23	4.54	4.70	2.81	2.82	2.87	2.86
CT with Mulch (T_2)	4.20	4.38	4.70	4.88	2.84	2.85	2.90	2.89
MT without Mulch (T_3)	3.66	3.69	4.09	4.12	2.77	2.79	2.83	2.82
MT with Mulch (T_4)	3.99	4.17	4.47	4.63	2.79	2.83	2.87	2.85
S.Em.±	0.09	0.11	0.11	0.12	0.06	0.06	0.07	0.07
CD at 5 %	0.32	0.38	0.38	0.40	NS	NS	NS	NS
CV	8.99	10.46	9.53	9.83	8.33	8.84	9.61	9.03
Nitrogen management								
Control (N_0)	3.45	3.39	3.83	3.89	2.51	2.55	2.55	2.54
100% RDN through Chemical (N_1)	4.21	4.38	4.78	4.93	2.91	2.90	2.97	2.95
75% RDN through Chemical and 25% RDN through FYM (N_2)	4.35	4.49	4.85	5.01	2.95	2.98	3.03	3.02
50% RDN through Chemical and 50% RDN through FYM (N_3)	4.02	4.23	4.48	4.62	2.87	2.89	2.95	2.93
100% RDN through FYM (N_4)	3.87	4.10	4.31	4.48	2.77	2.79	2.83	2.82
S.Em.±	0.09	0.09	0.10	0.10	0.05	0.06	0.06	0.05
CD at 5 %	0.26	0.27	0.28	0.28	0.14	0.17	0.18	0.16
CV	7.97	7.90	7.67	7.26	6.10	7.08	7.70	6.61

TABLE 6

Effect of different tillage, mulch and N-management on Available N of soil after harvest of crop

Treatments	Nutrient balance sheet (kg ha^{-1})					
	Net gain or loss					
	N		P		K	
	2023	2024	2023	2024	2023	2024
Tillage and Mulch						
CT without Mulch (T_1)	-2.1	-3.4	-0.6	-0.5	-4.6	-2.0
CT with Mulch (T_2)	0.5	-0.9	0.0	0.4	-2.5	0.1
MT without Mulch (T_3)	-0.4	-1.8	-0.1	0.2	-3.2	-0.6
MT with Mulch (T_4)	2.5	1.1	0.3	0.9	-0.7	1.8
Nitrogen management						
Control (N_0)	-9.7	-13.1	-1.0	-0.7	-6.5	-5.6
100% RDN through Chemical (N_1)	-2.0	-4.1	-0.7	-0.5	-5.8	-4.3
75% RDN through Chemical and 25% RDN through FYM (N_2)	1.8	1.0	0.0	0.3	-2.5	0.6
50% RDN through Chemical and 50% RDN through FYM (N_3)	3.7	3.1	0.3	0.8	-0.8	2.8
100% RDN through FYM (N_4)	6.7	6.8	0.8	1.4	1.8	5.7

gain in available nitrogen (6.7 and 6.8 kg ha^{-1}), phosphorus (0.8 and 1.4 kg ha^{-1}) and potassium (1.8 and 5.7 kg ha^{-1}) in the soil was highest under 100% RDN through FYM, followed by 50% RDN through chemical + 50% FYM, and 75% RDN through chemical + 25% FYM, as compared to 100% RDN through chemical fertilizer and the control during both years, respectively (Table 6). The superior nutrient gains in FYM-based treatments reflect the positive effect of organic amendments on nutrient retention, microbial activity, and long-term soil fertility. The slow and sustained release of nitrogen from organic sources, such as FYM, contributed to improved nitrogen availability throughout the crop growth period, thereby enhancing soil nitrogen status (Bhattacharyya *et al.*, 2013). The improvement in phosphorus and potassium

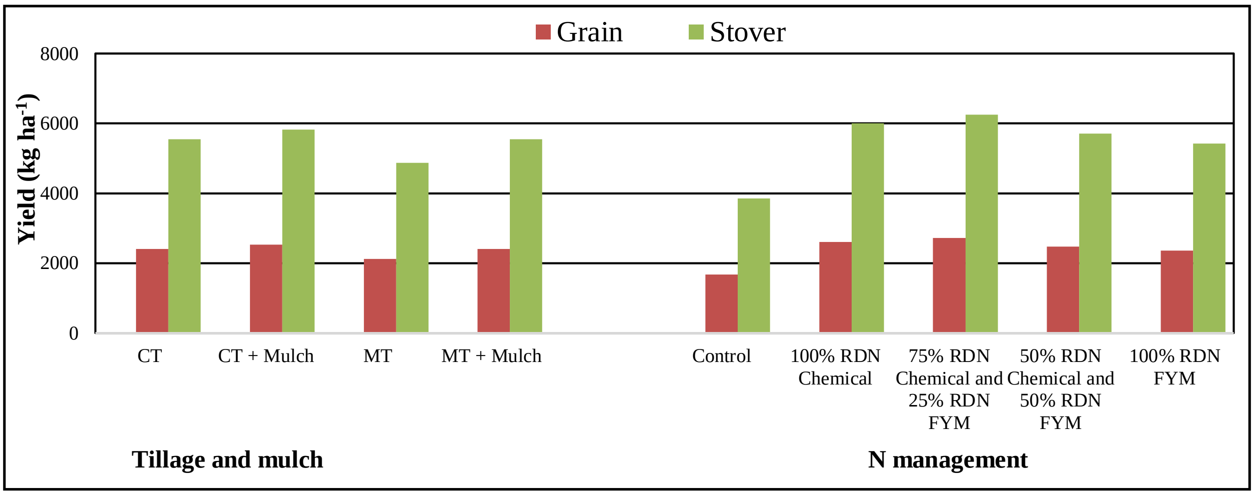

Fig. 1. Effect of different tillage, mulch and N-management on yields of pearl millet.

availability can be attributed to the synergistic interaction between organic matter from FYM and soil phosphorus and potassium dynamics (Makwana *et al.*, 2023; Sharma *et al.*, 2020).

CONCLUSION

Conventional tillage with mustard stover mulch (3 t/ha) significantly improves plant growth, physiology and yield in semi-arid regions. Applying 75% RDN through chemical fertilizers and 25% through FYM maximizes grain and stover yield, while 100% FYM enhances soil nitrogen availability and long-term soil health by boosting organic matter and microbial activity.

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