Forage Res., **52**(2) : pp. 163-172 (2026) **http://forageresearch.in**

RESOURCE EFFICIENT TECHNIQUES FOR PRODUCTION OF DUAL PURPOSE PEARL MILLET IN DOUBLE CROPPED RICE FALLOWS OF SOUTHERN LATERITES, KERALA

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(Received: 1 September 2026; Accepted: 15 September 2026)

SUMMARY

A study was conducted at College of Agriculture, Vellayani, Thiruvananthapuram, Kerala from December 2023 to March 2024 and November 2024 to February 2025 in double cropped rice fallows for the production of dual purpose pearl millet under conservation agriculture. The treatments included 3 main plots (conventional tillage, minimum tillage and zero tillage) and 8 sub plots (cowpea broadcasting at 12.5 kg ha^{-1} *fb* mulching at 25 DAS, cowpea broadcasting at 12.5 kg ha^{-1} *fb* brown manuring with carfentrazone at 0.02 kg ha^{-1} at 25 DAS, $PE_{pendi\ plus\ imaz}$ @ 800 g ha^{-1}, PE *fb* hand weeding at 30 DAS, PoE_{tembo} @ 80 g ha^{-1}, PoE *fb* hand weeding at 40 DAS, hand weeding at 15 and 30 DAS & weedy check). Different treatments had significant effect on growth parameters and yield parameters of pearl millet. The interaction effect revealed that conventional tillage with hand weeding at 15 DAS and 30 DAS and minimum tillage with hand weeding at 15 DAS and 30 DAS recorded significantly taller plants. Minimum tillage with hand weeding at 15 and 30 DAS recorded significantly higher tiller number and dry matter production in pearl millet, statistically similar to minimum tillage with $PE_{pendi\ plus\ imaz}$ at 800 g ha^{-1} *fb* hand weeding at 30 DAS. The practice of hand weeding at 15 and 30 DAS in each main plot (conventional tillage, minimum tillage and zero tillage) and $PE_{pendi\ plus\ imaz}$ at 800 g ha^{-1} followed by hand weeding at 30 DAS (in conventional tillage and minimum tillage) recorded significantly higher grain yield and straw yield in the first year, and the results were almost similar in second year. Giving more importance to resource conservation practices to mitigate climate change, minimum tillage with $PE_{pendi\ plus\ imaz}$ at 800 g ha^{-1} *fb* hand weeding at 30 DAS can be recommended to farmers as the treatment combination produced statistically similar yield as that of minimum tillage with hand weeding at 15 and 30 DAS.

Note: $PE_{pendi\ plus\ imaz}$: Pre emergence application of pendimethalin + imazethapyr (premix), PoE_{tembo}: Post emergence application of tembotrione

Key words: Pearl millet, tillage, IWM, pendimethalin plus imazethapyr, tembotrione

Rice-rice-fallow is the dominant rice-based cropping system in Kerala (John *et al*., 2014). One of the foremost challenges in rice cultivation is enhancing its economic viability, which necessitates diversification of existing rice-based cropping systems. Rice fallows in Kerala offer considerable scope for enhancing cropping intensity through cultivation of short duration dual purpose crops that provide both grain and quality fodder. In this regard, intensification of the rice-rice-fallow system by incorporating millets as succeeding crops presents a promising strategy with significant agronomic and economic advantages.

Millets, traditionally regarded as subsistence crops or famine reserves, are gaining prominence under the current climate change scenario due to their resilience and adaptability. Recognizing their global importance, the United Nations declared 2023 as the "International Year of Millets." In India, millets were highlighted as "Shri Anna," signifying their superior value, during the Union Budget announcement in February 2023 (Jain, 2023). In Kerala, initiatives such as the Millet Village programme in Attapady promote the cultivation of millets including finger millet and pearl millet. Millets are well suited to the Low External Input Sustainable Agriculture (LEISA) approach and can be effectively integrated into rice fallow systems by adopting resource-efficient practices such as minimum and zero tillage, thereby enhancing cropping system sustainability.

Pearl millet (*Pennisetum glaucum* L.), commonly known as bajra or cumbu, is an important multipurpose millet cultivated for food, feed, and forage, and ranks fourth among cereal crops after rice, wheat, and maize (Girase *et al*., 2017). Adoption of conservation tillage practices can reduce production costs of pearl millet by saving time, fuel, and external inputs. However, wider row spacing and slow initial growth make pearl millet highly susceptible to early-season weed infestation (Chaudhary *et al.,* 2018). Severe weed competition during this critical period can reduce grain yield by 20–72 per cent (Samota *et al.,* 2022), making effective weed management essential for achieving higher yields and quality produce. Traditional hand weeding, commonly practiced in Kerala, has become impractical due to labour shortages and rising wages, necessitating a shift towards integrated weed management approaches. In this context, the present study was undertaken to evaluate the effect of tillage and weed management practices on the grain and fodder productivity of dual purpose pearl millet cultivated in double cropped rice fallows of Kerala.

MATERIALS AND METHODS

The experiment was carried out in wetlands of the Instructional Farm at College of Agriculture, Vellayani, Thiruvananthapuram, which is situated 24.15 metres above mean sea level at 8°25′47′′N latitude and 76°59′04′′E longitude, from December 2023 to March 2024 in the first year and the confirmatory trial was undertaken from November 2024 to February 2025. The experiment was laid out in split plot with 3 main plots and 8 subplots and three replication. The main plot factor was methods of tillage such as conventional tillage (t_1), minimum tillage (t_2) and zero tillage (t_3). In minimum tillage, primary tillage was carried out as usual and secondary tillage operations were restricted to the row zone of the crop. In zero tillage, crop was sown on the residue of the previous rice crop without any prior tillage. The sub plot treatments consisted of w_1 (cowpea broadcasting @ 12.5 kg ha^{-1} *fb* mulching at 25 DAS), w_2 (cowpea broadcasting @ 12.5 kg ha^{-1} *fb* brown manuring with carfentrazone at 0.02 kg ha^{-1} at 25 DAS), w_3 ($PE_{pendi\ plus\ imaz}$ @ 800 g ha^{-1}), w_4 (PE *fb* HW at 30 DAS), w_5 (PoE_{tembo} @ 80 g ha^{-1}), w_6 (PoE *fb* HW at 40 DAS), w_7 (HW at 15 and 30 DAS) & w_8 (weedy check). The post emergence herbicide tembotrione was applied at 2 to 4 leaf stage of weed by protecting the crop. The dual purpose pearl millet variety Co-10, released from TNAU was used in the study. Nutrients were given to the crop at the rate of 70:35:35 kg NPK ha^{-1} according to the Crop Production Guide, Tamil Nadu Agricultural University. Plant height of pearl millet was measured and recorded in cm at 20, 40, and 60 DAS and at harvest. At 20, 40 and 60 DAS, the plant height was measured from the base to the growing tip of the topmost leaf whereas at harvest, it was measured from the base to the tip of the ear. By placing the quadrat 50cm x 50cm randomly at two spots in each treatment plot, tillers m^{-2} were recorded. The number of tillers per plant were counted and was converted to no. m^{-2}. For the determination of DMP per hill, five plants were randomly selected and uprooted from outside the net plot area, after leaving one row on all the four sides at 20 DAS, 40 DAS, 60 DAS and harvest. The plant samples were first shade dried for two days to lower the moisture content, followed by oven-drying at 65 °C till a constant weight was attained. The average was worked out and expressed as g per hill. Net plot area was harvested treatment-wise. Grains were threshed, winnowed, and sun-dried to constant weight and grain yield was expressed as kg ha^{-1}. Straw from the net plot was sun-dried to constant weight and expressed in kg ha^{-1}.

RESULTS AND DISCUSSION

Growth Parameters

Plant height of pearl millet was significantly influenced by tillage methods, weed management practices, and their interaction (Table 1a and 1b). In the first year, conventional tillage recorded significantly taller plants at 20 DAS (59.23 cm), followed by minimum tillage, however there was no significant effect at 20 DAS in the second year. At 40 days after sowing, conventional tillage recorded significantly taller plants (164.48 cm and 165.1 cm respectively in first and second year), statistically on par with minimum tillage in the second year. During the first year, there was no significant effect of tillage on plant height at 60 DAS and harvest; however, conventional tillage recorded significantly taller plants in second year (178.89 cm at 60 DAS and 192.48 cm at harvest). Conventional tillage consistently recorded taller plants across most growth stages, likely due to improved resource availability and reduced weed pressure (Indra *et al.,* 2024). Odhafa *et al.* (2022) reported that conventional tillage generally resulted in taller plants

TABLE 1A
Effect of tillage and weed management on plant height of pearl millet, cm

Treatments	Plant height							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
Tillage								
t_1	59.23	57.72	164.48	165.10	186.31	178.89	192.70	192.48
t_2	56.71	59.36	156.28	161.92	175.59	172.90	182.25	183.12
t_3	50.22	54.34	136.87	140.44	167.17	170.55	174.39	180.90
SE (m) (±)	0.57	1.76	1.20	1.36	4.43	1.27	4.34	1.00
CD (0.05)	2.220	NS	4.706	5.323	NS	5.006	NS	3.936
Weed management								
w_1	65.13	64.75	163.63	161.98	178.39	173.13	184.85	187.62
w_2	61.23	60.10	150.58	155.94	169.54	175.44	176.29	187.97
w_3	45.94	53.05	136.49	137.38	170.87	167.07	177.67	181.55
w_4	47.88	58.18	142.66	162.32	179.72	184.43	186.77	188.97
w_5	55.59	54.53	142.23	145.97	167.55	159.23	174.45	173.01
w_6	56.57	56.49	157.84	148.13	181.94	176.99	188.67	184.11
w_7	56.68	56.86	164.77	173.40	183.96	184.99	190.79	199.75
w_8	54.08	53.19	162.13	161.44	178.86	171.66	185.41	181.03
SE (m) (±)	0.76	3.46	3.19	4.18	4.13	3.86	4.06	1.58
CD (0.05)	2.167	NS	9.099	11.918	NS	11.015	11.599	4.518

TABLE 1B
Interaction effect of tillage and weed management on plant height of pearl millet, cm

Treatments	Plant height							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
t_1w_1	71.58	68.40	164.76	162.92	181.63	176.10	188.13	188.95
t_1w_2	62.90	61.90	160.47	174.41	179.76	191.60	186.27	208.05
t_1w_3	51.62	50.24	150.30	146.92	182.37	169.19	188.88	185.00
t_1w_4	55.90	57.62	170.13	164.93	190.93	174.32	197.44	184.55
t_1w_5	56.25	56.87	158.13	166.60	175.50	179.07	181.84	193.18
t_1w_6	55.58	56.88	158.37	149.60	196.06	173.49	202.37	187.88
t_1w_7	65.63	58.19	191.44	189.80	201.32	196.69	207.52	211.55
t_1w_8	54.38	51.69	162.20	165.59	182.90	170.69	189.17	180.70
t_2w_1	66.97	66.50	177.71	164.51	185.90	171.63	191.94	187.13
t_2w_2	60.40	59.40	145.10	154.89	165.57	161.53	172.10	172.38
t_2w_3	45.93	54.81	134.23	145.31	166.46	159.86	173.22	171.92
t_2w_4	45.48	57.11	138.53	173.21	184.27	198.68	191.31	200.42
t_2w_5	59.30	58.10	145.86	139.61	165.53	147.57	172.14	159.50
t_2w_6	61.50	60.49	159.17	147.89	170.33	159.57	177.13	166.33
t_2w_7	54.77	58.68	165.80	187.10	179.08	195.76	186.04	209.15
t_2w_8	59.35	59.80	183.81	182.81	187.56	188.63	194.07	198.15
t_3w_1	56.83	59.34	148.43	158.50	167.63	171.66	174.47	186.78
t_3w_2	60.38	59.00	146.17	138.51	163.29	173.17	170.51	183.48
t_3w_3	40.27	54.10	124.93	119.90	163.80	172.17	170.92	187.73
t_3w_4	42.27	59.80	119.30	148.81	163.97	180.30	171.57	181.93
t_3w_5	51.23	48.61	122.70	131.69	161.62	151.06	169.36	166.33
t_3w_6	52.62	52.11	156.00	146.91	179.43	197.89	186.50	198.10
t_3w_7	49.65	53.70	137.07	143.30	171.47	162.50	178.79	178.55
t_3w_8	48.50	48.08	140.37	135.91	166.12	155.67	173.01	164.25
SEm (±) [T(W)]	1.32	6.00	5.52	7.23	7.16	6.69	7.04	2.74
CD [T(W)] (0.05)	3.754	NS	15.759	20.643	NS	19.079	NS	7.825

than minimum tillage and zero tillage, although seasonal variations occurred. The effect of IWM practices on pearl millet revealed that w_1 (cowpea mulching at 12.5 kg ha^{-1} *fb* mulching at 25 DAS) recorded significantly taller plants in first year at 20 DAS (65.13 cm), however no significant effect was observed at 20 DAS in the second year. However, w_7 recorded significantly taller plants at 40 DAS (164.77 cm and 173.40 cm respectively across years), statistically similar to w_6, w_1 and w_8 in the first year. In the second year, w_7 was on par with w_1 and w_4. There was no significant effect of IWM on plant height of pearl millet at 60 days after sowing in first year. However, w_7 recorded significantly taller plants at 60 DAS (184.99 cm) in the second year, on par with w_2, w_4 and w_6. At the harvest stage, w_7 recorded significantly taller plants in both years (190.79 cm and 199.75 cm during first year and second year respectively); w_7 was on par with w_1, w_4, w_6, w_8 in the first year. Slight phytotoxicity in pre emergence herbicide-treated plots initially reduced plant height; however, effective weed control at later stages lowered weed biomass and crop–weed competition, thereby enhancing growth. Comparable results were reported in maize by Susha *et al.* (2018). Considering the interaction effect, conventional tillage with cowpea mulching at 25 DAS (t_1w_1) recorded significantly taller plants (71.58 cm) in first year. However, there was no significant effect on plant height at 20 days after sowing in the second year. The interaction effect revealed that t_1w_7 recorded significantly taller plants at 40 DAS (191.44cm), on par with t_2w_1 and t_2w_8 in first year. In the second year t_1w_7 (189.80 cm) was statistically similar to t_2w_4, t_2w_7, t_2w_8 and t_1w_2 at 40 DAS. At the same time, there was no significant interaction effect on plant height at 60 days after sowing and harvest during first year. However, t_2w_4 recorded taller plants (198.68 cm) at 60 DAS, statistically similar to t_1w_2, t_1w_7, t_2w_7, t_2w_8, t_3w_4 and t_3w_6 in the second year. Conversely, t_1w_7 recorded significantly taller plants (211.55 cm) at harvest during second year, on par with t_1w_2 and t_2w_7. The interaction effect indicated that conventional tillage with hand weeding at 15 and 30 DAS and minimum tillage with hand weeding at 15 and 30 DAS produced significantly taller plants. This might be attributed to the combined positive effect of tillage and weed management strategy adopted in enhancing growth attributes of pearl millet.

Method of tillage, integrated weed management (IWM), and their interaction significantly influenced tiller number m^{-2} of pearl millet (Table 2a and Table 2b). At 20 DAS, zero tillage recorded higher tiller number m^{-2} in both years (65.62 and 61.83 respectively), remaining at par with conventional tillage (62.13) in the second year. Meanwhile, no significant interaction was observed for number of tillers at 40 DAS during both years. However, minimum tillage recorded higher tiller number m^{-2} at 60 DAS (62.42 and 80.50 respectively in first and second year) and harvest (53.67 and 76.71), comparable to conventional tillage. The initial advantage under zero tillage may be attributed to better soil moisture conservation, while improved aeration, reduced compaction, and enhanced root growth under conventional tillage likely supported greater tiller production at later stages (Minhas *et al.*, 2023). Minimum tillage also improved moisture availability and enhanced microbial population which positively contributed to enhanced growth attributes in pearl millet. Weed management practices significantly affected tiller density at all growth stages. At 20 DAS, w_7 (hand weeding at 15 and 30 days after sowing) recorded significantly higher number of tillers m^{-2} (75.44 and 76.22) in both years, and in the second year w_7 was on par with w_4 (PE pendimethalin plus imazethapyr at 800 g ha^{-1} *fb* hand weeding at 30 DAS). Moreover, w_4 recorded significantly higher tiller number m^{-2} at 40 DAS (99.56) and 60 DAS (80.11) of pearl millet in the first year, however w_7 recorded significantly higher number of tillers m^{-2} during second year (98 and 101.11 at 40 DAS and 60 DAS respectively), statistically similar to w_4. During the harvest stage, w_7 recorded significantly higher tiller number m-$^{-2}$ (64.56 and 98 respectively over years), on par with w_4 in both years. These observations can be attributed to the proper weed control of the crop in the critical growth stages. Effective weed control during the critical growth period reduced weed biomass and enhanced crop growth (Sangwan *et al.*, 2016). The interaction between tillage and IWM revealed that t_2w_7 (minimum tillage with hand weeding at 15 and 30 DAS) recorded significantly higher number of tillers m^{-2} at 20 DAS (84 and 86.33) during both years; statistically similar to t_3w_5 in the first year. At 40 days after sowing in first year, t_1w_4 recorded significantly higher tiller number m^{-2} (107.33), statistically comparable to t_2w_4. On the other hand, t_2w_7 recorded significantly higher tiller number m^{-2} during the second year (112), on par with t_2w_4 and t_1w_7 at 40 DAS. The treatment combination t_2w_4 recorded significantly higher number of tillers m^{-2} at 60 DAS in the first year (100.33); however, t_2w_7 recorded higher value during second year (114.33), on par with t_2w_4 and t_1w_7. At

TABLE 2A
Effect of tillage and weed management on number of tillers of pearl millet, no. m^{-2}

Treatments	Number of tillers m^{-2}							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
Tillage								
t_1	59.21	62.13	70.58	73.21	62.13	76.42	53.38	73.79
t_2	60.37	61.25	66.50	82.25	62.42	80.50	53.67	76.71
t_3	65.62	61.83	72.04	68.54	53.08	67.96	49.00	66.21
SE (m) (±)	0.34	0.10	1.65	3.96	1.05	2.01	0.59	2.05
CD (0.05)	1.322	0.382	NS	NS	4.129	7.888	2.322	8.044
Weed management								
w_1	56.78	65.33	63.00	72.33	53.67	71.56	51.33	66.89
w_2	53.67	52.11	57.56	63.00	49.00	62.22	40.44	59.11
w_3	60.67	61.44	75.44	73.11	62.22	78.56	59.11	76.22
w_4	68.44	72.33	99.56	95.67	80.11	98.00	61.44	95.67
w_5	60.67	57.56	63.00	67.67	50.56	68.44	48.22	66.11
w_6	60.67	63.78	63.78	73.89	63.00	77.00	52.89	75.44
w_7	75.44	76.22	84.78	98.00	73.11	101.11	64.56	98.00
w_8	57.56	45.11	50.56	53.67	42.00	42.78	38.11	40.44
SE (m) (±)	1.73	1.93	2.05	2.28	1.02	2.20	1.83	2.18
CD (0.05)	4.931	5.499	5.851	6.503	2.901	6.267	5.237	6.215

TABLE 2B
Interaction effect of tillage and weed management on number of tillers of pearl millet, no. m^{-2}

Treatments	Number of tillers m^{-2}							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
t_1w_1	53.67	67.67	58.33	72.33	53.67	72.33	51.33	67.67
t_1w_2	58.33	53.67	58.33	58.33	58.33	63.00	39.67	60.67
t_1w_3	63.00	65.33	88.67	70.00	74.67	79.33	67.67	77.00
t_1w_4	67.67	70.00	107.33	91.00	70.00	95.67	70.00	93.33
t_1w_5	49.00	53.67	58.33	63.00	49.00	67.67	46.67	65.33
t_1w_6	58.33	65.33	63.00	70.00	65.33	77.00	49.00	74.67
t_1w_7	67.67	74.67	84.00	107.33	81.67	109.67	65.33	107.33
t_1w_8	56.00	46.67	46.67	53.67	44.33	46.67	37.33	44.33
t_2w_1	63.00	63.00	58.33	79.33	58.33	79.33	56.00	72.33
t_2w_2	44.33	49.00	49.00	70.00	44.33	65.33	42.00	60.67
t_2w_3	44.33	53.67	74.67	79.33	63.00	84.00	60.67	79.33
t_2w_4	72.33	72.33	100.33	107.33	100.33	109.67	63.00	105.00
t_2w_5	51.33	53.67	46.67	70.00	44.33	70.00	42.00	67.67
t_2w_6	65.33	67.67	67.67	81.67	77.00	84.00	63.00	84.00
t_2w_7	84.00	86.33	88.67	112.00	74.67	114.33	67.67	109.67
t_2w_8	58.33	44.33	46.67	58.33	37.33	37.33	35.00	35.00
t_3w_1	53.67	65.33	72.33	65.33	49.00	63.00	46.67	60.67
t_3w_2	58.33	53.67	65.33	60.67	44.33	58.33	39.67	56.00
t_3w_3	74.67	65.33	63.00	70.00	49.00	72.33	49.00	72.33
t_3w_4	65.33	74.67	91.00	88.67	70.00	88.67	51.33	88.67
t_3w_5	81.67	65.33	84.00	70.00	58.33	67.67	56.00	65.33
t_3w_6	58.33	58.33	60.67	70.00	46.67	70.00	46.67	67.67
t_3w_7	74.67	67.67	81.67	74.67	63.00	79.33	60.67	77.00
t_3w_8	58.33	44.33	58.33	49.00	44.33	44.33	42.00	42.00
SEm (±) [T(W)]	2.99	3.34	3.55	3.95	1.76	3.80	3.18	3.77
CD [T(W)] (0.05)	8.541	9.525	10.133	11.264	5.025	10.854	9.070	10.765

the harvest stage, t_1w_4 recorded significantly higher tiller number m^{-2} in the first year (70), on par with t_1w_3, t_1w_7, t_2w_4, t_2w_6 and t_2w_7. In the second year, t_2w_7 recorded significantly higher number of tillers m^{-2} at harvest stage (109.67), on par with t_2w_4 and t_1w_7. The interaction effect revealed that minimum tillage with hand weeding at 15 and 30 DAS produced higher tiller density at most of the crop growth stages, comparable to minimum tillage with pre emergence herbicide followed by hand weeding. This response may be attributed to reduced weed competition and improved soil physical and biological properties under minimum tillage.

Regarding the plant dry matter production (Table 3a and Table 3b), minimum tillage recorded significantly higher DMP at 20 DAS (3.07 g and 4.66 g at first and second year respectively) and 40 DAS (14.89 g and 13.97 g across years). However, at 60 DAS, minimum tillage recorded significantly higher dry matter only during the first year (94.08 g). Also, minimum tillage recorded higher DMP at harvest stage during both years (108.42 g and 82.59 g respectively), on par with conventional tillage in the second year. Minimum tillage recorded significantly higher dry matter production (DMP) at various growth stages of pearl millet compared to conventional tillage and zero tillage. Minimum tillage combined with residue retention improves soil moisture conservation, enhances soil structure and aggregate stability, increases microbial activity, and promotes nutrient transformation and availability compared to conventional tillage (Li *et al.*, 2020). Conventional and minimum tillage performed comparably, indicating that intensive preparatory tillage may not be essential for sustaining productivity in pearl millet (Sidhpuria *et al.*, 2014). Among weed management practices, hand weeding at 15 and 30 DAS recorded significantly higher DMP at 20 DAS (3.33 g), 40 DAS (15.44 g), 60 DAS (118.2 g) and harvest (135.5 g) in the first year. However, w_4 recorded higher DMP at 20 DAS (7.01 g) in second year, on par with w_3 and w_7. At 40 DAS, w_4 again recorded the highest dry matter production (19.66 g) in the second year. The treatment w_7 recorded higher DMP at 60 DAS (110.63 g), on par with w_4 in the second year. During harvest stage, w_4 marked the higher DMP (118.97 g), statistically similar to w_7 in the second year. Superior biomass accumulation under these treatments was associated with effective weed control, reduced nutrient depletion by weeds, and minimized crop–weed competition. Enhanced nutrient uptake, leaf area index, and chlorophyll content likely improved photosynthetic efficiency and assimilate translocation, resulting in higher DMP (Sneha, 2023). Among the treatment combination, minimum tillage with hand weeding at 15 and 30 DAS recorded significantly higher DMP at 20 DAS in the first year (5.56 g); however, there was no significant effect during second year. At 40 DAS, t_2w_4 (minimum tillage with $PE_{pendi\ plus\ imaz}$ fb hand weeding at 30 DAS) recorded significantly higher DMP (22.25 g and 25.88 g respectively over years); in the second year, t_2w_4 was comparable to t_2w_3 and t_2w_7. Minimum tillage with hand weeding at 15 and 30 DAS resulted in higher DMP of pearl millet at 60 DAS (147.5 g and 138.9 g respectively during first year and second year), on par with w_4 in first year and also with t_1w_7 in second year. There was no significant interaction between tillage and IWM on DMP of pearl millet at harvest in the first year; however t_2w_7 recorded higher DMP in second year (147.39 g), on par with t_2w_4, t_1w_7 and t_3w_4.The interaction effect indicated that minimum tillage with hand weeding produced the highest DMP, comparable to the herbicide-based treatment followed by hand weeding under minimum tillage at most of the crop growth stages.

Yield Parameters

Different methods of tillage significantly affected the grain yield and straw yield of pearl millet during both the years (Table 4a and Table 4b). However, the harvest index was significant only in the second year. Among the different methods of tillage, conventional tillage recorded higher grain yield (2489.29 kg ha^{-1} and 2702.88 kg ha^{-1} over years) and straw yield (4348.51 kg ha^{-1} and 4159.77 kg ha^{-1} respectively during first year and second year), statistically similar to minimum tillage. During the second year, conventional tillage registered significantly higher harvest index (0.389). Conventional tillage recorded lower weed dry weight in critical growth stages and higher nutrient uptake, enhancing the crop yield. The favourable or comparable performance of minimum tillage similar to conventional tillage is well supported by earlier research. Conservation tillage practices, including minimum tillage, have been shown to improve soil physical conditions, enhance moisture conservation, increase crop yields under diverse agro ecological conditions (Busari *et al.*, 2015). Long term experiments demonstrated that reduced soil disturbance improves soil structure and water

TABLE 3A
Effect of tillage and weed management on dry matter production of pearl millet, g per plant

Treatments	Dry matter production							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
Tillage								
t_1	2.02	3.20	12.58	9.47	70.79	69.62	86.95	80.13
t_2	3.07	4.66	14.89	13.97	94.08	71.39	108.42	82.58
t_3	1.64	3.47	7.65	9.26	69.84	63.01	80.80	76.35
SE (m) (±)	0.01	0.24	0.29	0.57	2.87	2.88	4.54	1.14
CD (0.05)	0.050	0.961	1.126	2.248	11.282	NS	17.808	4.482
Weed management								
w_1	2.86	4.25	14.12	11.29	82.40	64.12	88.15	74.34
w_2	1.82	2.16	10.69	6.62	46.40	46.17	65.49	57.61
w_3	1.86	6.21	10.31	14.81	86.00	69.43	98.06	82.11
w_4	3.13	7.01	13.18	19.66	105.93	100.52	113.18	118.97
w_5	2.05	1.42	11.22	6.02	86.10	52.23	91.36	63.22
w_6	1.72	1.57	12.57	6.98	61.33	58.60	80.08	71.28
w_7	3.33	6.51	15.44	16.69	118.20	110.63	135.50	117.52
w_8	1.17	1.06	6.10	5.12	39.50	42.37	64.64	52.45
SE (m) (±)	0.03	0.61	0.45	1.02	3.80	4.27	5.86	6.86
CD (0.05)	0.071	1.728	1.290	2.910	10.834	12.184	16.719	19.582

TABLE 3B
Interaction effect of tillage and weed management on dry matter production of pearl millet, g per plant

Treatments	Dry matter production							
	20 DAS		40 DAS		60 DAS		Harvest	
	1st year	2nd year	1st year	2nd year	1st year	2nd year	1st year	2nd year
t_1w_1	2.44	1.18	16.34	6.18	69.20	50.97	71.33	60.03
t_1w_2	2.03	2.14	9.27	7.11	44.50	51.67	57.13	64.67
t_1w_3	1.92	5.14	15.11	10.74	73.50	67.70	91.27	81.83
t_1w_4	2.35	6.39	9.33	16.60	91.90	71.93	101.23	83.13
t_1w_5	2.03	1.76	10.80	6.89	88.30	65.33	95.91	77.50
t_1w_6	1.51	1.97	16.52	9.22	67.10	73.47	85.23	83.67
t_1w_7	2.86	5.95	16.55	13.47	88.50	130.60	135.67	136.67
t_1w_8	1.06	1.04	6.69	5.54	43.30	45.30	57.81	53.50
t_2w_1	4.15	4.62	17.03	10.65	94.50	51.30	105.06	63.67
t_2w_2	2.11	3.12	17.57	8.37	57.50	44.37	81.57	54.50
t_2w_3	1.78	8.34	8.66	23.44	105.40	80.13	121.57	90.83
t_2w_4	4.81	8.69	22.25	25.88	129.60	122.87	139.93	132.28
t_2w_5	2.37	1.19	15.23	6.19	98.50	40.47	101.43	53.67
t_2w_6	2.35	1.64	14.52	7.64	67.50	50.57	98.07	66.67
t_2w_7	5.56	8.51	17.43	23.95	147.50	138.90	150.00	147.39
t_2w_8	1.43	1.13	6.40	5.64	52.10	42.50	69.73	51.67
t_3w_1	1.99	6.95	8.97	17.04	83.50	90.08	88.07	99.33
t_3w_2	1.33	1.21	5.24	4.39	37.20	42.47	57.77	53.67
t_3w_3	1.88	5.16	7.16	10.26	79.10	60.47	81.33	73.67
t_3w_4	2.24	5.96	7.97	16.51	96.30	106.77	98.37	141.50
t_3w_5	1.77	1.32	7.63	4.99	71.50	50.88	76.73	58.50
t_3w_6	1.31	1.09	6.69	4.07	49.40	51.76	56.93	63.50
t_3w_7	1.57	5.08	12.35	12.64	118.60	62.38	120.83	68.50
t_3w_8	1.01	1.01	5.21	4.19	23.10	39.30	66.37	52.17
SEm (±) [T(W)]	0.04	1.05	0.78	1.77	6.58	7.39	10.15	11.88
CD [T(W)] (0.05)	0.124	NS	2.235	5.040	18.765	21.104	NS	33.917

TABLE 4A
Effect of tillage and weed management on grain yield, straw yield and harvest index of pearl millet

Treatments	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		Harvest index	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
Tillage						
t_1	2489.29	2702.88	4348.51	4159.77	0.358	0.389
t_2	2277.18	2193.05	4330.89	3773.87	0.336	0.360
t_3	1802.25	1681.32	3810.31	2911.74	0.311	0.358
SE (m) (±)	115.72	141.00	113.82	158.58	0.017	0.005
CD (0.05)	454.368	553.653	446.915	622.650	NS	0.019
Weed management						
w_1	2322.93	2334.17	4171.47	3954.48	0.352	0.366
w_2	1843.03	1960.71	3759.70	3378.44	0.325	0.361
w_3	1865.43	2062.92	3816.53	3478.38	0.318	0.365
w_4	2813.93	2908.05	5053.26	4309.14	0.357	0.400
w_5	1979.63	1860.66	3750.76	3196.61	0.341	0.365
w_6	1757.76	2119.39	3712.89	3615.91	0.315	0.365
w_7	3545.86	3151.09	5538.04	4688.69	0.392	0.398
w_8	1388.01	1142.35	3503.24	2299.36	0.280	0.330
SE (m) (±)	151.89	175.45	164.15	240.72	0.020	0.008
CD (0.05)	433.496	500.730	468.492	687.009	0.0558	0.0229

TABLE 4B
Interaction effect of tillage and weed management on grain yield, straw yield and harvest index of pearl millet

Treatments	Grain yield (kg ha^{-1})		Straw yield (kg ha^{-1})		Harvest index	
	1st year	2nd year	1st year	2nd year	1st year	2nd year
t_1w_1	2433.86	2691.40	4490.57	4367.56	0.343	0.379
t_1w_2	2359.79	2722.15	3967.55	4066.17	0.371	0.398
t_1w_3	2322.75	2863.04	3927.60	4318.64	0.368	0.397
t_1w_4	3462.96	2981.66	5670.65	4317.20	0.380	0.400
t_1w_5	1920.63	2340.23	3579.37	3662.47	0.348	0.389
t_1w_6	2353.44	2928.84	4355.46	4535.90	0.346	0.393
t_1w_7	3550.26	3631.28	5460.74	5308.56	0.394	0.406
t_1w_8	1510.58	1464.43	3336.11	2701.65	0.313	0.350
t_2w_1	1889.42	1653.97	4042.88	3131.95	0.317	0.346
t_2w_2	1846.56	1885.38	3571.33	3643.56	0.342	0.341
t_2w_3	1765.61	2000.63	3642.64	3652.47	0.316	0.353
t_2w_4	3015.87	3007.89	5693.70	4443.77	0.346	0.402
t_2w_5	2794.71	2079.23	4854.08	3820.64	0.366	0.353
t_2w_6	1632.80	2144.17	3249.41	3924.52	0.326	0.353
t_2w_7	3677.25	3742.96	5845.70	5378.87	0.386	0.411
t_2w_8	1595.24	1030.16	3747.37	2195.16	0.291	0.321
t_3w_1	2645.50	2657.14	3980.95	4363.93	0.396	0.374
t_3w_2	1322.75	1274.59	3740.22	2425.58	0.263	0.344
t_3w_3	1507.94	1325.08	3879.35	2464.04	0.271	0.346
t_3w_4	1962.96	2734.59	3795.44	4166.45	0.345	0.398
t_3w_5	1223.54	1162.53	2818.84	2106.71	0.309	0.354
t_3w_6	1287.04	1285.17	3533.80	2387.30	0.273	0.349
t_3w_7	3410.05	2079.01	5307.67	3378.65	0.394	0.377
t_3w_8	1058.20	932.46	3426.24	2001.27	0.236	0.319
SEm (±) [T(W)]	263.08	303.89	284.32	416.94	0.034	0.014
CD [T(W)] (0.05)	750.837	867.290	811.452	1189.935	NS	NS

retention, which directly contributes to enhance crop productivity (Eden *et al.*, 2020). Furthermore, minimum tillage promotes higher microbial activity and nutrient availability, leading to improved nutrient cycling and yield advantages over time (Bhattacharya *et al.*, 2025). Different weed management practices significantly affected the grain yield, straw yield and harvest index of pearl millet. Hand weeding at 15 and 30 days after sowing of pearl millet recorded significantly higher grain yield (3545.86 kg ha^{-1} and 3151.09 kg ha^{-1}) and straw yield (5538.04 kg ha^{-1} and 4688.69 kg ha^{-1}) during both years. However, in the second year, w_7 was on par to w_4. Regarding the harvest index, w_7 recorded higher value (0.392), statistically similar to w_1, w_4 and w_5 in the first year; at the same time, w_4 recorded higher HI in second year (0.400), statistically similar to w_7. The improvement in yield in hand weeding and $PE_{pendi\ plus\ imaz}$ fb hand weeding can be attributed to better weed control during critical growth stages. The early weed control reduced the seed rain and further additions of weed seeds to the soil seed bank. As reported by Chinyo *et al.* (2023), PE pendimethalin followed by post emergence herbicides or hand weeding significantly improved weed control efficiency and produced yields comparable to or higher than sole hand weeding. Similarly, research findings by Yadav *et al.* (2018) indicated that integration of herbicides with manual weeding resulted in higher yield stability due to season long weed suppression. The convergence of yield in the second year may be attributed to improved weed control efficacy and reduced weed seed bank under integrated treatments, leading to similar resource availability as in hand weeding. Thus, the present findings reinforce that herbicide based IWM practices can match the effectiveness of conventional hand weeding while reducing labour dependency. The data on interaction effect revealed that t_2w_7 (Minimum tillage with hand weeding at 15 and 30 DAS) recorded higher grain yield (3677.25 kg ha^{-1}), on par with t_2w_4 (3016 kg ha^{-1}), t_1w_4, t_1w_7, and t_3w_7 in the first year. The same trend was also observed for grain yield in the second year, with t_2w_7 in the apex position (3742.96 kg ha^{-1}), statistically similar to t_2w_4 (3008 kg ha^{-1}), t_1w_4, t_1w_6 and t_1w_7. Regarding the straw yield of pearl millet, t_2w_7 recorded higher value (5845.70 kg ha^{-1}), on par with t_2w_4 (5694 kg ha^{-1}), t_1w_4, t_1w_7 and t_3w_7 in the first year. In the second year, t_2w_7 (5378.87 kg ha^{-1}) was on par with t_2w_4 (4444 kg ha^{-1}), t_1w_1, t_1w_3, t_1w_4, t_1w_6, t_1w_7 and t_3w_1. The data revealed that there was no significant interaction effect on harvest index of pearl millet during both years. The higher yield observed under hand weeding in minimum tillage, which remained comparable with PE application of pendimethalin + imazethapyr followed by hand weeding under both conventional and minimum tillage, indicates that effective weed control can offset the influence of tillage systems on crop productivity. However, from a resource conservation perspective, the superiority of integrated approaches involving minimum tillage assumes greater significance. Earlier studies have demonstrated that minimum tillage combined with herbicide-based weed management ensures efficient weed suppression, reduced labour requirement, and improved soil moisture conservation, ultimately sustaining yields. For instance, Teja and Duary (2018) reported that conservation tillage along with recommended herbicide (pendimethalin at 0.75 kg ha^{-1}) + one hand weeding recorded lower weed dry weight and higher seed yield in mustard. Studies in pearl millet-based systems by Chinyo *et al.* (2023) further confirmed that integrated weed management practices provide season-long weed control and yield stability comparable to hand weeding alone. Therefore, although minimum tillage with hand weeding at 15 and 30 DAS achieved slightly higher yield, the combination of minimum tillage and $PE_{pendi\ plus\ imaz}$ at 800 g ha^{-1} followed by hand weeding at 30 DAS is more desirable due to its ability to conserve resources, reduce drudgery, and enhance productivity.

CONCLUSION

The study demonstrated that minimum tillage integrated with pre emergence application of pendimethalin + imazethapyr at 800 g ha^{-1} followed by hand weeding at 30 DAS of pearl millet provided better weed control and resulted in higher grain yield and straw yield, similar to minimum tillage with hand weeding at 15 DAS and 30 DAS. The higher biomass production, along with increased grain yield, highlights the suitability of this production system for simultaneously addressing fodder and forage requirements. Giving more importance to mitigating climate change and adopting conservational agricultural practices, minimum tillage with proper weed management strategy (PE pendimethalin plus imazethapyr at 800 g ha^{-1} followed by hand weeding at 30 DAS) can be recommended to farmers over conventional hand weeding for enhancing the grain yield and straw yield of pearl millet grown in double cropped rice fallows of AEU8 in Kerala.

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