



RESEARCH ARTICLE

Weed dynamics, nutrient removal and weed smothering efficiency in pearl millet (*Pennisetum glaucum* (L.) R. Br.) - based intercropping systems under lowland summer rice fallows

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Abstract

Weed infestation is a major constraint to crop productivity in lowland summer rice fallows. In southern India, high residual soil moisture and nutrient availability during summer fallows favour rapid weed proliferation, leading to nutrient depletion and increased weed pressure in the succeeding rice crop. However, information on weed suppression and nutrient removal in pearl millet-legume-based intercropping under lowland summer rice fallows is limited. A field experiment was carried out during the summer season of 2024–2025 at the Integrated Farming Systems Research Station, Karamana, Thiruvananthapuram, Kerala, to investigate the weed dynamics, nutrient removal and weed smothering efficiency of pearl millet (*Pennisetum glaucum* (L.) R. Br.) - based intercropping systems in lowland rice fallows. The experiment comprised 13 intercropping treatments involving pearl millet with bush cowpea, fodder cowpea, green gram and black gram in 1:1 and 2:1 planting ratios under an additive series (an intercropping system, where the base crop population is maintained at 100 % and intercrops are added according to main crop geometry), along with their respective sole crops. The treatments were laid out in a randomised block design (RBD) with three replications. The predominant weed flora observed during the crop growth period consisted mainly of broad-leaf weeds at 30 and 60 days after sowing (DAS). Weed growth and nutrient depletion were significantly influenced by the intercropping systems. The lowest total weed dry matter (87.50 g m⁻² at 60 DAS) and the highest weed smothering efficiency (56.72 %) were recorded in pearl millet + bush cowpea (1:1). In contrast, the highest weed dry matter (202.15 g m⁻²) was observed in the sole crop of pearl millet. The inclusion of legumes significantly reduced nutrient depletion by weeds due to complementary resource use and efficient canopy closure. Intercropping systems, pearl millet + bush cowpea (1:1) and pearl millet + black gram (1:1), were more efficient in suppressing weed growth, reducing nutrient losses and improving crop competitiveness compared to sole cropping. The study concluded that legume-based intercropping effectively minimised weed interference, conserved soil nutrients and enhanced ecological weed control in summer rice fallows.

Keywords: legume intercropping; nutrient removal; pearl millet; rice fallows; weed dynamics; weed smothering efficiency

Introduction

Weeds are among the most persistent biological constraints in crop production, often causing yield reductions ranging from 30–60 % depending on the crop and management practices (1). Their competitive ability is particularly pronounced in lowland rice fallows of southern India, where high residual soil moisture and nutrient-rich conditions favour profuse weed germination and growth (2). Uncontrolled weed proliferation during summer fallows not only depletes soil nutrient reserves but also aggravates weed infestation in the succeeding rice crop, thereby reducing productivity and increasing production costs (3). Although manual weeding is effective, it is increasingly uneconomical due to labour scarcity and rising wages, while continuous reliance on herbicides has resulted in the evolution of herbicide-resistant weed biotypes and shifts in weed flora composition (4). Hence, ecologically sustainable and resource-efficient cropping systems such as intercropping are gaining prominence for integrated weed

management (5, 6). Intercropping of cereals with legumes enhances canopy coverage, modifies light interception and suppresses weed emergence through spatial and temporal complementarity (7, 8). Pearl millet (*Pennisetum glaucum* (L.) R. Br.), a hardy and fast-growing cereal, exhibits strong competitiveness against weeds owing to rapid ground coverage and possible allelopathic interactions (3, 9). When intercropped with short-duration legumes such as cowpea, black gram or green gram, pearl millet not only improves weed smothering efficiency but also enhances soil fertility through biological nitrogen fixation and efficient nutrient recycling (10). Therefore, the present investigation entitled weed dynamics, nutrient removal and weed smothering efficiency in pearl millet (*P. glaucum*) based intercropping systems under lowland summer rice fallows was undertaken. The study aimed to evaluate the influence of pearl millet - legume intercropping systems on weed composition, nutrient removal by weeds and weed smothering efficiency under summer fallow conditions in the lowlands of Kerala.

Materials and Methods

A field experiment was conducted during the summer season of 2024–2025 at the Integrated Farming System Research Station (IFSRS), Karamana, Thiruvananthapuram, Kerala (8°28' N latitude, 76°57' E longitude, 29 m MSL). The soil was sandy clay loam, moderately acidic (pH 6.23), with medium available N (338.69 kg ha⁻¹) and K (182 kg ha⁻¹) and high P (63.05 kg ha⁻¹). The experiment was conducted from 23 January to 7 May 2025, corresponding to the lowland summer rice fallow period. The mean maximum and minimum temperatures during the season were 32.0 °C (30.9–33.4 °C) and 24.7 °C (22.4–26.1 °C), respectively, with morning and afternoon relative humidities averaging 88.3 and 70.5 %. The total rainfall received was 328.9 mm over 13 rainy days, with an average wind speed of 6.0 km hr⁻¹. The experiment was laid out in a randomised block design (RBD) with 13 treatments and three replications. The treatments comprised different intercropping combinations of pearl millet and legumes in 1:1 and 2:1 row ratios along with five sole crops (Table 1). Each plot measured 4.5 × 3 m. The varieties used were CO 10 (pearl millet, 85–90 days), Bhagyalakshmi (bush cowpea, 80 days), Aiswarya (fodder cowpea, 45 days), CO 8 (green gram, 55–60 days) and Sumanjana (black gram, 70–90 days). The spacing adopted was 45 × 10 cm for pearl millet, 30 × 15 cm for bush and fodder cowpea and 25 × 15 cm for green and black gram. Pearl millet was raised as per the recommendations of Tamil Nadu Agricultural University (11) and intercrops as per Kerala Agricultural University package of practices recommendations (12).

Table 1. Treatment details

Treatments	
T ₁	Pearl millet + bush cowpea in a 1:1 ratio
T ₂	Pearl millet + bush cowpea in a 2:1 ratio
T ₃	Pearl millet + fodder cowpea in a 1:1 ratio
T ₄	Pearl millet + fodder cowpea in a 2:1 ratio
T ₅	Pearl millet + green gram in a 1:1 ratio
T ₆	Pearl millet + green gram in a 2:1 ratio
T ₇	Pearl millet + black gram in a 1:1 ratio
T ₈	Pearl millet + black gram in a 2:1 ratio
T ₉	Sole crop of pearl millet
T ₁₀	Sole crop of bush cowpea
T ₁₁	Sole crop of fodder cowpea
T ₁₂	Sole crop of green gram
T ₁₃	Sole crop of black gram

Nutrient management was as per the respective crop recommendations using urea, single super phosphate and muriate of potash as sources of nitrogen, phosphorus and potassium. Nitrogen was applied in split doses and phosphorus and potassium were applied as basal. Farmyard manure was incorporated uniformly before sowing to maintain soil organic matter. Weeding was done at monthly intervals in all the plots uniformly by leaving an area of 1 m² per plot for taking observations related to weeds at 30 and 60 DAS. The weed flora was identified and grouped as grasses, sedges and broad-leaved weeds. Oven-dried weed samples (70 °C to constant weight) provided weed dry matter (WDM) in g m⁻². Weed smothering efficiency (WSE) was calculated by using the following formula (13).

$$\text{WSE (\%)} = [(WDM_{sc} - WDM_{ic}) / WDM_{sc}] \times 100 \quad (\text{Eqn. 1})$$

Where, WDM_{sc}– weed dry matter in sole crop and WDM_{ic}– weed dry matter in intercrop

Nutrient removal by weeds was estimated by using the following formula:

Nutrient removal (kg ha⁻¹)

$$= [\text{Nutrient content (\%)} \times \text{Weed dry matter (kg ha}^{-1}\text{)}] / 100 \quad (\text{Eqn. 2})$$

Weed control efficiency (WCE) was computed by using the following formula:

$$\text{WCE (\%)} = [(WDM_c - WDM_t) / WDM_c] \times 100 \quad (\text{Eqn. 3})$$

Where WDM_c = weed dry matter in control and WDM_t = weed dry matter in treatment.

The data were analysed statistically using R and AI solutions for inferential statistics (RAISINS), the online analysis platform of Kerala Agricultural University, Vellayani (14, 15).

Results and Discussion

Weed flora

The weed flora of the experimental area comprised grasses, broad-leaf weeds, sedges and ferns (Table 2). Broad-leaf weeds were the predominant group, including *Cleome rutidospermum*, *Euphorbia hirta*, *Oldenlandia umbellata*, *Ludwigia perennis*, *Alternanthera sessilis*, *Phyllanthus niruri*, *Commelina benghalensis* and *Lindernia grandiflora*. Grasses included, *Echinochloa colona*, *Digitaria ciliaris*, *Cynodon dactylon*, *Eleusine indica*, *Setaria barbata*, *Isachne miliacea* and *Panicum repens* were observed. Sedges included *Cyperus rotundus*, *Fimbristylis miliacea* and *Cyperus iria* were observed and the fern species *Marsilea quadrifolia* was noted.

Weed density

Weed density (no. m⁻²) differed significantly among the treatments at both 30 and 60 DAS. At 30 DAS (Table 3), among the weeds present, broad-leaf weeds dominated in the majority of the treatments. Grassy weeds were significantly lower in pearl millet + bush cowpea (1:1) (T₁) and sole crop of bush cowpea (T₁₀), both registering 11 no. m⁻², whereas pearl millet + fodder cowpea (2:1) (T₄) recorded the highest count with 38 no. m⁻². Broad-leaf weeds were the lowest in the sole crop of cowpea (T₁₀) with 11 no. m⁻², while they were most abundant in the sole crop of pearl millet (T₉) with 72 no. m⁻². The lowest sedge count of 4 no. m⁻² was recorded in sole fodder cowpea (T₁₁), whereas the highest sedge count occurred in pearl millet + black gram (1:1) (T₇) with 40 no. m⁻². Regarding the total weed count, sole crop of fodder cowpea (T₁₁) maintained the lowest overall count with 45 no. m⁻². In contrast, the sole crop of pearl millet (T₉) had the highest density with 114 no. m⁻². At 60 DAS (Table 4), weed density increased in all treatments due to continuous emergence and growth. The total weed population ranged from 99.95–233.00 no. m⁻². Lower weed density was maintained in pearl millet + bush cowpea in 1:1 ratio (T₁) (99.95 no. m⁻²), followed by pearl millet + green gram in 1:1 ratio (T₅) (120.00 no. m⁻²), while a higher weed density was recorded in the sole crop of pearl millet (T₉) (233.00 no. m⁻²). Intercropping with legumes reduced the weed count considerably due to quicker canopy coverage, better ground shading and reduced space and light availability for weed establishment. These findings are consistent with previous studies, which also reported a reduction in weed population in cereal-legume intercropping systems due to competitive canopy interference (13).

Table 2. Weed flora composition in the experimental field

Grasses	Broad-leaf weeds	Sedges	Fern
<i>Echinochloa colona</i>	<i>Cleome rutidospermum</i>	<i>Cyperus rotundus</i>	<i>Marsilea quadrifolia</i>
<i>Digitaria ciliaris</i>	<i>Euphorbia hirta</i>	<i>Fimbristylis miliacea</i>	
<i>Cynodon dactylon</i>	<i>Oldenlandia umbellata</i>	<i>Cyperus iria</i>	
<i>Eleusine indica</i>	<i>Ludwigia perennis</i>		
<i>Setaria barbata</i>	<i>Alternanthera sessilis</i>		
<i>Isachne miliacea</i>	<i>Phyllanthus niruri</i>		
<i>Panicum repens</i>	<i>Commelina benghalensis</i>		
	<i>Lindernia grandiflora</i>		

Table 3. Effect of intercropping on weed count at 30 DAS (number m⁻²)

Treatments	Grasses	Broad-leaf weeds	Sedges	Total
T ₁ : Pearl millet + bush cowpea in a 1:1 ratio	3.32 ^h (11.00)	7.21 ^d (52.00)	3.87 ⁱ (15.00)	8.83 ^g (78.00)
T ₂ : Pearl millet + bush cowpea in a 2:1 ratio	5.00 ^c (25.00)	6.93 ^e (48.00)	3.61 ^k (13.00)	9.27 ^f (86.00)
T ₃ : Pearl millet + fodder cowpea in a 1:1 ratio	4.80 ^d (23.00)	5.83 ^h (34.00)	3.74 ^j (14.00)	8.43 ^h (71.00)
T ₄ : Pearl millet + fodder cowpea in a 2:1 ratio	6.16 ^a (38.00)	5.74 ^h (33.00)	5.10 ^d (26.00)	9.85 ^b (97.00)
T ₅ : Pearl millet + green gram in a 1:1 ratio	5.10 ^c (26.00)	6.40 ^g (41.00)	4.00 ^h (16.00)	9.11 ^f (83.00)
T ₆ : Pearl millet + green gram in a 2:1 ratio	5.48 ^b (30.00)	6.48 ^f (42.00)	4.90 ^e (24.00)	9.80 ^b (96.00)
T ₇ : Pearl millet + black gram in a 1:1 ratio	4.80 ^d (23.00)	5.00 ⁱ (25.00)	6.32 ^a (40.00)	9.38 ^e (88.00)
T ₈ : Pearl millet + black gram in a 2:1 ratio	3.87 ^e (15.00)	6.78 ^e (46.00)	5.48 ^c (30.00)	9.54 ^d (91.00)
T ₉ : Sole crop of pearl millet	5.48 ^b (30.00)	8.49 ^a (72.00)	3.46 ^l (12.00)	10.68 ^a (114.00)
T ₁₀ : Sole crop of bush cowpea	3.32 ^h (11.00)	7.81 ^b (61.00)	4.47 ^f (20.00)	9.59 ^c (92.00)
T ₁₁ : Sole crop of fodder cowpea	3.61 ⁱ (13.00)	5.29 ^j (28.00)	2.00 ^m (4.00)	6.71 ⁱ (45.00)
T ₁₂ : Sole crop of green gram	3.46 ^g (12.00)	6.32 ^g (40.00)	5.66 ^b (32.00)	9.16 ^f (84.00)
T ₁₃ : Sole crop of black gram	4.69 ^d (22.00)	7.55 ^b (57.00)	4.12 ^g (17.00)	9.80 ^b (96.00)
SEm (±)	0.04	0.05	0.03	0.06
CD (0.05)	0.129	0.155	0.09	0.164

Weed count: Original values in parentheses and the data were subjected to a square root transformation. DAS: Days after sowing; SEm: Standard error of the mean; CD: Critical difference. Different letters represent significant differences at a $p < 0.05$ probability level.

Table 4. Effect of intercropping on weed count at 60 DAS (number m⁻²)

Treatments	Grasses	Broad-leaf weeds	Sedges	Total
T ₁ : Pearl millet + bush cowpea in a 1:1 ratio	5.10 ^b (26.00)	5.66 ^g (32.00)	6.48 ^f (41.95)	10.00 ^b (99.95)
T ₂ : Pearl millet + bush cowpea in a 2:1 ratio	4.51 ^c (20.33)	9.17 ^c (84.00)	6.22 ^g (38.60)	11.96 ^e (143.00)
T ₃ : Pearl millet + fodder cowpea in a 1:1 ratio	-	-	-	-
T ₄ : Pearl millet + fodder cowpea in a 2:1 ratio	-	-	-	-
T ₅ : Pearl millet + green gram in a 1:1 ratio	4.47 ^d (20.00)	7.75 ^f (60.00)	6.32 ^g (40.35)	10.95 ^g (120.00)
T ₆ : Pearl millet + green gram in a 2:1 ratio	4.24 ^e (18.00)	8.94 ^d (80.00)	7.62 ^d (58.00)	12.49 ^c (156.00)
T ₇ : Pearl millet + black gram in a 1:1 ratio	4.36 ^e (19.00)	8.72 ^e (76.00)	5.29 ^h (28.12)	11.09 ^g (123.00)
T ₈ : Pearl millet + black gram in a 2:1 ratio	5.00 ^b (25.00)	7.62 ^f (58.00)	8.60 ^b (74.37)	12.53 ^c (157.00)
T ₉ : Sole crop of pearl millet	4.58 ^c (21.00)	10.20 ^a (104.00)	10.39 ^a (108.92)	15.26 ^a (233.00)
T ₁₀ : Sole crop of bush cowpea	3.74 ^g (14.00)	5.29 ^h (28.00)	10.39 ^a (108.24)	12.25 ^d (150.00)
T ₁₁ : Sole crop of fodder cowpea	-	-	-	-
T ₁₂ : Sole crop of green gram	5.29 ^a (28.00)	9.59 ^b (92.00)	6.93 ^e (48.14)	12.96 ^b (168.00)
T ₁₃ : Sole crop of black gram	4.00 ^f (16.00)	7.75 ^f (60.00)	7.81 ^c (60.45)	11.70 ^f (137.00)
SEm (±)	0.04	0.05	0.04	0.07
CD (0.05)	0.117	0.138	0.12	0.199

Weed count: Original values in parentheses and the data were subjected to a square root transformation. DAS: Days after sowing; SEm: Standard error of the mean; CD: Critical difference. Different letters represent significant differences at $p < 0.05$ probability level.

Weed dry weight

Weed dry matter production (g m⁻²) followed a pattern similar to weed count (Table 5). At 30 DAS, weed dry matter production was lower in sole fodder cowpea (T₁₁) with 22.46 g m⁻², followed by pearl millet + fodder cowpea (1:1) (T₃) with 26.13 g m⁻², whereas it was significantly higher in the sole crop of pearl millet (T₉) with 52.00 g m⁻². At 60 DAS, weed dry matter production was lower in pearl millet + bush cowpea in 1:1 ratio (T₁) with 87.50 g m⁻², pearl millet + green gram (1:1) (T₅) with 89.45 g m⁻² and pearl millet + black gram (1:1) (T₇) with 90.40 g m⁻², whereas it was significantly higher in the sole crop of pearl millet (T₉) with 202.15 g m⁻². The increase in dry weight in the sole crop might be due to greater resource availability and the absence of shading from intercrops. In contrast, intercropped legumes reduced weed biomass through canopy interference, faster growth and efficient resource utilisation (2, 10, 16).

Nitrogen (N) removal by weeds

Nitrogen removal by weeds (Table 6) varied widely among the treatments. At 30 DAS, the lowest nitrogen removal by weeds was recorded in T₄ (pearl millet + fodder cowpea in a 2:1 ratio) with 4.69 kg ha⁻¹, followed by T₁₁ (sole crop of fodder cowpea) with 4.76 kg ha⁻¹. At 60 DAS, the lowest nitrogen removal was observed in T₁ (pearl millet + bush cowpea in a 1:1 ratio) with 17.53 kg ha⁻¹, followed by T₂ (pearl millet + bush cowpea in a 2:1 ratio) with 18.16 kg ha⁻¹. The lower N removal in intercropped treatments could be attributed to reduced weed growth and effective N utilisation by the crop components. The nitrogen-fixing ability of legumes and their competitive growth restricted nutrient access to weeds, thereby reducing N removal (16, 17).

Table 5. Effect of intercropping on weed dry matter production and weed smothering efficiency

Treatments	Weed dry matter production (g m ⁻²)		Weed smothering efficiency (%)	
	30 DAS	60 DAS	30 DAS	60 DAS
T ₁ : Pearl millet + bush cowpea in a 1:1 ratio	28.80 ± 0.47 ^g	87.50 ± 1.97 ^e	44.62	56.72
T ₂ : Pearl millet + bush cowpea in a 2:1 ratio	35.12 ± 0.82 ^e	97.26 ± 2.37 ^d	32.46	51.89
T ₃ : Pearl millet + fodder cowpea in a 1:1 ratio	26.13 ± 0.99 ^h	-	49.75	-
T ₄ : Pearl millet + fodder cowpea in a 2:1 ratio	31.38 ± 0.06 ^f	-	39.65	-
T ₅ : Pearl millet + green gram in a 1:1 ratio	28.86 ± 1.09 ^g	89.45 ± 2.18 ^e	44.50	55.75
T ₆ : Pearl millet + green gram in a 2:1 ratio	41.00 ± 0.70 ^c	99.52 ± 2.96 ^d	21.15	50.77
T ₇ : Pearl millet + black gram in a 1:1 ratio	35.56 ± 0.96 ^e	90.40 ± 3.18 ^e	31.62	55.28
T ₈ : Pearl millet + black gram in a 2:1 ratio	38.23 ± 0.97 ^d	98.85 ± 4.01 ^d	26.48	51.10
T ₉ : Sole crop of pearl millet	52.00 ± 2.11 ^a	202.15 ± 2.37 ^a	-	-
T ₁₀ : Sole crop of bush cowpea	38.60 ± 1.25 ^d	127.65 ± 4.03 ^c	-	-
T ₁₁ : Sole crop of fodder cowpea	22.46 ± 0.57 ⁱ	-	-	-
T ₁₂ : Sole crop of green gram	43.52 ± 1.25 ^b	131.22 ± 1.78 ^{bc}	-	-
T ₁₃ : Sole crop of black gram	43.00 ± 1.82 ^b	136.44 ± 3.94 ^b	-	-
SEm (±)	0.61	1.81	-	-
CD (0.05)	1.77	5.38	-	-

Table 6. Effect of intercropping on nutrient removal by the weeds (kg ha⁻¹)

Treatments	N		P		K	
	30 DAS	60 DAS	30 DAS	60 DAS	30 DAS	60 DAS
T ₁ : Pearl millet + bush cowpea in a 1:1 ratio	8.06 ± 0.26 ^f	17.53 ± 0.54 ^g	1.84 ± 0.03 ^e	4.22 ± 0.05 ^g	7.79 ± 0.01 ^{fg}	26.66 ± 0.67 ^h
T ₂ : Pearl millet + bush cowpea in a 2:1 ratio	7.21 ± 0.31 ^g	18.16 ± 0.07 ^g	1.37 ± 0.00 ^g	4.92 ± 0.05 ^e	9.96 ± 0.19 ^{de}	34.92 ± 0.19 ^e
T ₃ : Pearl millet + fodder cowpea in a 1:1 ratio	5.85 ± 0.08 ⁱ	-	1.03 ± 0.01 ^j	-	5.65 ± 0.01 ⁱ	-
T ₄ : Pearl millet + fodder cowpea in a 2:1 ratio	4.69 ± 0.06 ^j	-	1.42 ± 0.06 ^g	-	7.88 ± 0.27 ^{fg}	-
T ₅ : Pearl millet + green gram in a 1:1 ratio	6.73 ± 0.27 ^h	27.77 ± 0.07 ^d	1.23 ± 0.04 ^h	3.10 ± 0.03 ⁱ	7.13 ± 0.02 ^h	29.11 ± 0.08 ^g
T ₆ : Pearl millet + green gram in a 2:1 ratio	8.42 ± 0.06 ^e	29.72 ± 0.91 ^c	1.77 ± 0.01 ^e	4.74 ± 0.06 ^f	13.04 ± 0.32 ^b	34.53 ± 0.59 ^e
T ₇ : Pearl millet + black gram in a 1:1 ratio	13.28 ± 0.01 ^a	25.31 ± 0.66 ^{ef}	1.49 ± 0.02 ^f	4.88 ± 0.00 ^e	8.07 ± 0.06 ^f	31.61 ± 0.88 ^f
T ₈ : Pearl millet + black gram in a 2:1 ratio	7.14 ± 0.12 ^g	26.76 ± 0.14 ^{de}	1.82 ± 0.02 ^e	3.61 ± 0.09 ^h	9.75 ± 0.34 ^e	37.60 ± 1.25 ^d
T ₉ : Sole crop of pearl millet	11.16 ± 0.23 ^b	39.62 ± 1.36 ^b	2.04 ± 0.09 ^c	7.08 ± 0.08 ^a	13.69 ± 0.23 ^a	54.11 ± 1.02 ^a
T ₁₀ : Sole crop of bush cowpea	8.65 ± 0.25 ^{de}	41.70 ± 1.50 ^a	1.93 ± 0.08 ^d	5.87 ± 0.04 ^d	10.33 ± 0.46 ^d	44.68 ± 1.37 ^b
T ₁₁ : Sole crop of fodder cowpea	4.76 ± 0.14 ^j	-	1.12 ± 0.04 ⁱ	-	5.99 ± 0.18 ⁱ	-
T ₁₂ : Sole crop of green gram	8.94 ± 0.37 ^d	24.49 ± 0.60 ^f	2.49 ± 0.04 ^a	6.59 ± 0.10 ^b	12.20 ± 0.39 ^c	53.67 ± 0.87 ^a
T ₁₃ : Sole crop of black gram	9.63 ± 0.19 ^c	40.75 ± 1.25 ^{ab}	2.24 ± 0.06 ^b	6.21 ± 0.03 ^c	7.54 ± 0.03 ^{gh}	41.93 ± 0.83 ^c
SEm (±)	0.12	0.51	0.03	0.03	0.14	0.52
CD (0.05)	0.356	1.506	0.081	0.104	0.414	1.154

Phosphorus (P) removal by weeds

At 30 DAS, the lowest phosphorus removal by weeds (Table 6) was recorded in T₃ (pearl millet + fodder cowpea in a 1:1 ratio) with 1.03 kg ha⁻¹, followed by T₁₁ (sole crop of fodder cowpea) with 1.12 kg ha⁻¹. At 60 DAS, the lowest phosphorus removal was observed in T₅ (pearl millet + green gram in a 1:1 ratio) with 3.10 kg ha⁻¹, followed by T₈ (pearl millet + black gram in a 2:1 ratio) with 3.61 kg ha⁻¹. Phosphorus removal followed a trend similar to nitrogen removal, wherein intercropping treatments consistently restricted nutrient depletion by weeds compared to sole cropping. The reduction in P removal under intercropping may be due to the synergistic effect of legumes that enhance phosphorus solubilisation and uptake by crops, leaving less availability to weeds (17).

Potassium (K) removal by weeds

Potassium removal by weeds (Table 6) followed a pattern comparable to that of N and P. At 30 DAS, T₃ (pearl millet + fodder cowpea in a 1:1 ratio) recorded the lowest K removal (5.99 kg ha⁻¹), followed by T₁₁ (sole crop of fodder cowpea). At 60 DAS, the lowest potassium removal was observed in T₁ (pearl millet + bush cowpea in a 1:1 ratio) with 26.66 kg ha⁻¹, followed by T₅ (pearl millet + green gram in a 1:1 ratio) with 29.11 kg ha⁻¹. The reduced K uptake by weeds in intercropping plots could be attributed to enhanced crop competition and complementary nutrient use between cereals and legumes. Similar findings have been reported earlier, indicating that intercropping minimises nutrient loss through efficient root-zone utilisation (16).

Weed smothering efficiency (WSE)

Weed smothering efficiency (Table 5) varied significantly among the treatments. At 30 DAS, the highest WSE of 49.75 % was recorded in pearl millet + fodder cowpea (1:1) (T₃), followed by pearl millet + bush cowpea (1:1) (T₁) with 44.62 % and pearl millet + green gram (1:1) (T₅) with 44.50 %. The lowest WSE of 21.15 % was observed in pearl millet + green gram in a 2:1 ratio (T₆). At 60 DAS, weed smothering efficiency was the highest in pearl millet + bush cowpea (1:1) (T₁) with 56.72 %, followed by pearl millet + green gram (1:1) (T₅) with 55.75 % and pearl millet + black gram (1:1) (T₇) with 55.28 %. The lowest WSE at this stage of 50.77 % was recorded in pearl millet + green gram (2:1) (T₆). The superior smothering ability of bush cowpea was due to its spreading canopy, faster growth rate and dense foliage, which restricted light availability to emerging weeds. These findings are consistent with previous studies demonstrating that vigorous legumes effectively suppress weeds through canopy interference and competitive effects (10, 18, 19).

Conclusion

The study indicates that pearl millet-legume intercropping systems significantly reduced weed density, weed dry weight and nutrient removal by weeds compared to sole cropping. Among the treatments, pearl millet + bush cowpea (1:1) recorded the lowest total weed density (99.95 no. m⁻²) and weed dry matter production (87.50 ± 1.97 g m⁻²), along with the highest weed smothering efficiency (56.72 %) at 60 DAS, followed by pearl millet + green gram (1:1). The superior weed suppression observed in these systems was attributed to rapid canopy closure and improved ground coverage,

which restricted light interception by weeds. Hence, pearl millet + bush cowpea (1:1) intercropping can be recommended as an efficient system for effective weed management and sustainable utilisation of lowland summer rice fallows.

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Authors' contributions

GM conducted field-level experimentation and drafted the manuscript. JJ and SPP visualised and framed the concept. BJS contributed to field-level experimentation in drafting the manuscript. MAV contributed to the lab analysis. All authors read and approved the final manuscript.

Compliance with ethical standards

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During the preparation of this work, the authors used Grammarly to improve grammar, clarity and language quality. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final manuscript.

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