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RESEARCH ARTICLE

Synergistic impact of cotton-legume intercropping and integrated weed management on soil health and productivity

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Abstract

Cotton is a globally important crop that serves as a major source of fibre and edible oil while supporting millions of livelihoods. With increasing demand for sustainable materials, improving cotton productivity in an eco-friendly way has become essential. One promising approach is the integration of legume intercropping with efficient weed management to reduce the potential yield loss of up to 86 % caused by weed competition. A two-year field experiment during 2021 and 2022 at Agronomy Research Farm, Chaudhary Charan Singh (CCS) Haryana Agricultural University, Hisar, Haryana, India, assessed the impact of various management practices on cotton yield, economic returns and soil health. Using a split-plot design, the study contrasted monoculture cotton with a cotton + green gram (1 : 2) intercropping system under 11 weed management treatments. Results revealed that sole cotton recorded greater plant height (177.05 cm) and dry matter accumulation (427.40 g plant^{-1}). However, intercropping with green grams significantly improved soil fertility, with higher available nitrogen (N) (126.7 kg ha^{-1}) and phosphorus (P) (17.6 kg ha^{-1}) observed at harvest. Among the weed management treatments, the weed-free treatment recorded the highest seed cotton yield (26.64 q ha^{-1}), followed by two hoeings at 25–30 and 40–45 days after sowing (24.20 q ha^{-1}). Notably, the integrated application of pendimethalin (1000 g ha^{-1}, PRE) followed by single hoeing at the 35–40 days proved highly effective, increasing seed cotton yield by approximately 40 % compared with herbicide use alone. Cotton-legume intercropping enhances soil fertility and profitability. Combining chemical and cultural weed management practices ensures better weed control, improved productivity and sustainable soil health.

Keywords: cotton; green gram; integrated weed management; productivity; sustainable

Introduction

As the backbone of the textile industry, cotton provides nearly 80 % of the essential raw materials for manufacturers worldwide. Due to the unique properties of its fibre, it is often hailed as the “King of appraisal fibre”. Ranking as the world's second most important oilseed crop, cottonseed contains 15–20 % oil, widely utilised in the culinary, cosmetic and soap industries. The by-product, cotton seed cake, is a nutrient-dense animal feed featuring 20 % protein and 3.5 % starch, with a nutrient profile of 6.4 % nitrogen (N), 2.9 % phosphorus (P) and 2.2 % potassium (K). Production-wise, the plant yields approximately 1.65–1.85 kg of seed for every 1.0 kg of lint (1). Although legume intercropping and weed management have been widely studied in cotton, their combined effects on productivity, soil health and profitability remain inadequately understood. Existing studies primarily focus on weed control and yield in sole cotton, with limited evaluation of integrated weed management (IWM) (chemical + mechanical) under cotton-legume intercropping systems. Moreover, the influence of these integrated practices on soil nutrient dynamics (N and P), economic returns and sustainability, particularly under the semi-arid conditions of northwestern India, has not been comprehensively quantified.

This study provides a comprehensive evaluation of the synergistic effects of cotton-green gram intercropping and IWM on crop productivity, soil fertility and economic returns under semi-arid conditions. It identifies pendimethalin (PRE) followed by one hoeing at 35–40 days after sowing (DAS) as an effective and practical IWM strategy, while demonstrating the role of legume intercropping in enhancing soil N and P availability. The findings, validated over two consecutive years, offer a robust and sustainable management package for improving cotton productivity and reducing reliance on herbicides.

Intercropping is established as a highly efficient production strategy, optimising resource utilisation and cropping intensity to enhance input management and economic returns (2). Under ideal configurations, the complementary interactions within an intercropping system manifest as improved biomass productivity and increased profitability in an agro-ecosystem (3, 4). Although cotton-legume intercropping is recognised for improving resource use efficiency, soil fertility and system productivity, it also alters weed dynamics by changing crop canopy structure, light interception and crop-weed competition (5, 6). Consequently, weed management strategies developed for sole cotton may not perform

similarly under intercropping systems, where herbicide efficacy and the effectiveness of cultural and mechanical practices can differ. Therefore, IWM which combines chemical and non-chemical approaches, should be evaluated specifically within cotton-green gram intercropping to identify sustainable weed control practices that maximise productivity while enhancing soil health and profitability (7).

Significant yield reductions in cotton are frequently observed when weed competition occurs during the critical window of 30–60 days post-emergence, when the crop is most vulnerable to weed interference (8). Competitive weed pressure accounts for the loss of 30–50 % of applied nutrients and 20–40 % of moisture, severely limiting resource availability for the primary crop uncontrolled weeds during the cotton crop growing season can cause yield losses of up to 86 % (9). Dominant weed flora in cotton can be efficiently managed through an integrated strategy combining mechanical or cultural practices with the sequential application of pre-emergence (PE) and post-emergence (PoE) herbicides, including pendimethalin, pyrithiobac-sodium and quizalofop-ethyl, glyphosate and paraquat (10, 11). Weed suppression in intercropping is influenced by a complex interplay of variables, such as cultivar choice, population density, seeding ratios, spatial configurations and environmental conditions like soil fertility and moisture levels (5). Post-emergence herbicide application presents significant challenges in intercropping systems, particularly when managing complex combinations of monocotyledonous and dicotyledonous species (12).

Weed management in cotton plays a pivotal role in improving crop productivity; therefore, selecting an appropriate combination of cultural practices with PE and PoE herbicides is essential for sustainable weed control and enhanced crop growth and development. In addition, weeds may emerge even after the critical period of weed control (CPWC) due to frequent rainfall, necessitating effective follow-up weed management to prevent further losses in cotton productivity.

Considering these concerns of a cotton-green gram intercropping with IWM may provide synergistic benefits by improving weed suppression, soil nutrient availability, crop productivity and profitability compared with sole cotton or individual weed management practices. A field study was carried out to determine the interactive effects of cotton-green gram intercropping and IWM on soil health, productivity and profitability under semi-arid conditions.

Materials and Methods

The investigation was conducted during the 2021 and 2022 seasons at the Agronomy Research Farm of CCS HAU, Hisar which is situated at 29°10′ N latitude and 75°46′ E longitude at an altitude of 215.2 m above mean sea level in Haryana state of India. The weather during the experimental period was characterised by a maximum air temperature of 44.6 °C and a minimum air temperature of 14.0 °C. The total rainfall received during the crop seasons was 773.2 mm in 2021 and 591.9 mm in 2022, resulting in a cumulative rainfall of 1365.1 mm over the two years. Most of the rainfall occurred during the monsoon season, which influenced crop growth and development. The site soil profile was characterised by a sub alkaline pH (8.0), low organic carbon (OC) (0.43 %) and available N (124.96 kg ha^{-1}) and moderate concentrations of available P (15.25 kg ha^{-1}) and K (261.63 kg ha^{-1}). All herbicides were applied using a knapsack sprayer fitted with a flat-fan nozzle, calibrated to deliver the recommended spray volume uniformly across the experimental plots. The study employed a split-plot design (SPD) featuring 3 replications, comprising two cropping systems in main-plots viz: cotton sole (M_1) and cotton (RCH-773) + green gram (MH 421) in a 1 : 2 row ratio (M_2) and 11 weed management treatments sub plot viz. PRE 1000 g ha^{-1} pre-emergence PE (S_1), PRE 1000 g ha^{-1} PE followed by one hoeing at 35–40 DAS (S_2), PRE 1000 g ha^{-1} PE followed by one hoeing after intercrop harvest (S_3), PRE 1000 g ha^{-1} PE followed by paraquat 0.3 % post-emergence (PoE, protected spray) after intercrop harvest (S_4), PRE 1000 g ha^{-1} PE followed by glyphosate 0.5 % PoE (protected spray) after intercrop harvest (S_5), PRE 1000 g ha^{-1} PE followed by quizalofop-ethyl 60 g ha^{-1} PoE after intercrop harvest (S_6), PRE 1000 g ha^{-1} PE followed by fenoxaprop 67.5 g ha^{-1} PoE after intercrop harvest (S_7), PRE 1000 g ha^{-1} PE followed by pyrithiobac-sodium 62.5 g ha^{-1} PoE after intercrop harvest (S_8), two hoeing (25–30 and 40–45 DAS) (S_9), weed free (S_{10}) and weedy check (S_{11}) in subplots. Fertilisers were applied according to the CCS HAU, Hisar package of practices for Haryana. *Bacillus thuringiensis* (Bt) cotton received the recommended dose of 175 kg N, 60 kg phosphorus pentoxide (P_2O_5), 60 kg potassium oxide (K_2O) and 25 kg zinc sulfate ($ZnSO_4$) ha^{-1}. One-third of the N was applied at sowing, while the remaining two-thirds were top-dressed equally at square formation and flowering. The full doses of P_2O_5, K_2O and $ZnSO_4$ were applied as basal during field preparation. Green gram received 40 kg P_2O_5 and 20 kg K_2O ha^{-1} as basal and its seeds were treated with the recommended rhizobium culture before sowing. Urea, diammonium phosphate (DAP), muriate of potash (MOP) and $ZnSO_4$ served as the sources of N, P, K and zinc (Zn) respectively, during both years. The plot size was 9.0 × 2.7 m and 100 × 45 cm cotton and 22.5 × 15 cm green gram spacing. In the first-year trial sowing of the crop was done on 1st May 2021 and sowing of second trial was done on 2nd May 2022.

A representative soil sample was collected from each plot to a depth of 0–15 cm and analysed to determine nutrient availability. Specifically, available N was analysed using the alkaline permanganate method (13), P via Olsen's method (14), K using the flame photometer method (15) and Zn via atomic absorption spectrophotometry (AAS)(16). These analyses were conducted both before sowing and after the harvest of the cotton crop. The data were statistically analysed using OPSTAT software available at CCS HAU, Hisar (17).

Results and Discussion

The growth parameters of cotton, including plant height, dry matter accumulation and number of sympodial branches, increased progressively from the early growth stages to maturity in both years of the study, with comparatively higher values recorded during the second year.

The most rapid increment in plant height was observed within the interval of 30–60 DAS, while dry matter accumulation increased markedly between 90–120 DAS. Among cropping systems, sole cotton consistently exhibited significantly greater plant height, higher dry matter and more sympodial branches/plant than the cotton + green gram intercrop across all growth stages. At maturity, intercropping was found to reduce these parameters by approximately 10, 16 and 15–3 % respectively, compared to sole

cotton. Plant height, dry matter and no. of fruiting (sympodial) branches/plant of cotton varied significantly with the cropping system and different weed management practices (Table 1–3). In the second year of the study, cotton exhibited enhanced growth performance, characterised by increased plant height, greater dry matter and higher number of sympodial branches than in the first year. This improvement is likely attributable to more favourable agroclimatic conditions during the second growing season.

Table 1. Effect of cropping system and different weed management practices on plant height (cm) of cotton (pooled data of two years)

Treatments	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS	At harvest
Main plot-cropping system						
M_1	32.6	85.25	116.45	143.2	167.6	177.05
M_2	30.4	79.45	108.05	130.85	153.15	159.85
SE (m) ±	0.3	0.40	0.95	1.05	1.20	1.25
CD (p = 0.05)	1.2	1.60	4.05	4.15	5.00	5.20
Sub plots-weed management practices						
S_1	31.3	81.8	107.75	129.85	152.0	159.65
S_2	31.7	84.8	114.95	141.1	163.8	173.0
S_3	31.6	82.6	112.8	137.95	161.55	169.7
S_4	31.6	82.5	112.1	137.75	162.4	169.5
S_5	31.7	82.7	113.25	137.3	161.8	168.9
S_6	31.2	81.3	111.9	136.95	159.65	168.4
S_7	31.3	81.4	111.9	137.25	160.65	168.95
S_8	31.6	82.5	112.8	138.05	160.65	169.8
S_9	31.9	84.6	115.15	141.3	165.95	173.4
S_{10}	33.1	85.6	119.5	146.1	171.3	179.7
S_{11}	29.5	76.0	102.5	123.3	144.3	151.55
SE (m) ±	0.50	0.60	1.40	1.60	1.75	2.10
CD (p = 0.05)	1.50	1.80	4.15	4.75	5.30	6.20

DAS: days after sowing; CD: critical difference.

Table 2. Effect of cropping system and different weed management practices on number of sympodial branches per plant of cotton (Pooled data of two years)

Treatments	90 DAS	120 DAS	At harvest
Main plot-cropping system			
M_1	11.0	17.2	21.8
M_2	9.8	13.3	18.4
SE (m) ±	0.1	0.1	0.2
CD (p = 0.05)	0.4	0.6	1.2
Sub plots-weed management practices			
S_1	9.7	13.1	16.6
S_2	11.0	17.5	23.3
S_3	10.8	15.6	20.8
S_4	10.4	14.7	19.7
S_5	10.6	15.0	20.4
S_6	10.4	14.6	19.4
S_7	10.3	14.5	19.2
S_8	10.1	14.5	19.1
S_9	11.1	17.7	23.5
S_{10}	12.4	19.8	25.9
S_{11}	7.9	11.0	13.1
SE(m)±	0.2	0.7	0.8
CD (p = 0.05)	0.4	1.9	2.4

DAS: days after sowing; CD: critical difference.

Table 3. Effect of cropping system and different weed management practices on dry matter accumulation (g plant^{-1}) of cotton (pooled data of two years)

Treatments	30 DAS	60 DAS	90 DAS	120 DAS	150 DAS	At harvest
Main plot-cropping system						
M_1	3.7	56.65	105.30	317.25	347.90	427.40
M_2	3.5	52.80	94.25	244.75	292.50	359.35
SE (m) ±	0.0	0.25	0.75	2.15	2.85	3.55
CD (p = 0.05)	0.2	1.05	3.70	10.35	18.65	22.90
Sub plots-weed management practices						
S_1	3.6	54.40	92.80	240.75	264.70	325.20
S_2	3.6	56.35	105.40	321.70	371.45	456.25
S_3	3.6	54.90	103.25	286.60	331.30	406.95
S_4	3.6	54.80	99.85	270.95	313.90	385.60
S_5	3.6	54.90	101.55	275.70	325.95	400.40
S_6	3.6	54.05	99.20	269.00	308.40	378.85
S_7	3.6	54.10	98.50	267.15	306.30	376.20
S_8	3.6	54.80	97.15	267.35	305.15	374.85
S_9	3.7	56.20	106.35	326.35	374.35	459.90
S_{10}	3.8	56.85	118.10	363.80	412.30	506.45
S_{11}	3.4	50.55	75.30	201.70	208.50	256.15
SE(m)±	0.1	0.40	1.35	12.75	13.15	16.10
CD (p = 0.05)	0.2	1.15	4.20	34.25	37.65	46.30

DAS: days after sowing; CD: critical difference.

Different weed management regimes substantially altered all three growth parameters. Superior growth parameters were consistently maintained in the weed-free plots throughout the entire crop cycle. This was followed by two hand hoeings (at 25–30 and 40–45 DAS) and a PE application of PRE (1000 g ha^{-1}) supplemented by one hoeing; notably, these two treatments were statistically at par. Conversely, weedy check resulted in significantly lower growth metrics, reflecting the impact of intense crop-weed competition.

Enhanced growth parameters including plant height, dry matter and sympodial branching likely resulted from lower weed density. By minimising competition for moisture and essential nutrients, this environment provided the favourable conditions necessary for superior crop development. Compared to weed-free conditions, weed competition resulted in a reduction of approximately 15.6 % in plant height and a 50 % decrease in both sympodial branching and dry matter accumulation. These observations are in agreement with the previous findings (1, 9, 11, 18). Cropping system and different weed management treatments exerted no significant influence on the final plant population of the cotton crop across both years of investigation (Table 1–3).

Morphological growth parameters of green gram (plant height and dry matter)

Weed management practices substantially enhanced both plant height and the accretion of dry matter of intercropped green gram during both years of experimentation (Table 4 and 5). Across all growth stages, the highest at 30 DAS, both plant height and dry matter accumulation (38.3 cm and 4.9 g plant^{-1}) respectively, were observed under weed-free treatment. This treatment performed statistically at par with the two-hoeing regimen (at 25–30 and 40–45 DAS) and significantly outperformed all other interventions. This enhancement is likely attributable to reduced weed competition, which facilitated superior resource utilisation by the crop. Similar trends persisted at 60 DAS and maturity, where the

weed-free treatment remained statistically equivalent to two hoeings and the application of PRE (1000 g ha^{-1}) followed by a single hoeing at 35–40 DAS. Conversely, the weedy check consistently yielded the lowest growth parameters throughout the study period.

Table 4. Effect of different weed management practices on plant height (cm) of green gram intercropped in cotton (pooled data of two years)

Treatments	30 DAS	60 DAS	At harvest
S_1	32.4	66.8	67.1
S_2	32.6	77.4	77.7
S_3	31.9	65.8	66.0
S_4	31.9	65.7	65.8
S_5	32.6	67.0	67.2
S_6	31.9	65.7	65.9
S_7	31.9	65.8	66.1
S_8	33.0	68.0	68.3
S_9	37.8	77.9	78.1
S_{10}	38.3	78.9	79.2
S_{11}	25.1	51.8	52.1
SE (m) ±	1.30	2.75	2.85
CD (p = 0.05)	3.90	8.00	8.10

DAS: days after sowing; CD: critical difference.

Table 5. Effect of different weed management practices on dry matter accumulation (g $plant^{-1}$) of green gram intercropped in cotton (pooled data of two years)

Treatments	Dry wt. (g $plant^{-1}$) at 30 DAS	Dry wt. (g $plant^{-1}$) at 60 DAS	Dry wt. (g $plant^{-1}$) at harvest
S_1	4.0	17.7	18.1
S_2	4.1	20.5	21.0
S_3	3.9	17.5	17.8
S_4	4.0	17.4	17.7
S_5	4.0	17.8	18.1
S_6	3.9	17.4	17.8
S_7	4.0	17.4	17.8
S_8	4.1	18.0	18.4
S_9	4.7	20.6	21.1
S_{10}	4.9	20.9	21.4
S_{11}	3.1	13.8	14.1
SE (m) ±	0.2	0.8	0.8
CD (p = 0.05)	0.5	2.2	2.2

DAS: days after sowing; CD: critical difference.

Dry matter accumulation increased progressively with crop stage. At 30 DAS, highest dry matter accumulation (4.6 g) was observed in the weed-free treatment. This result was statistically comparable to both the "two hoeing" and "PRE at 1000 g ha^{-1} followed by one hoeing" treatments yet remained significantly superior to all other interventions across both years. This consistency was maintained at 60 DAS and through to harvest. Conversely, the weedy check consistently yielded the minimum dry matter accumulation at every growth stage throughout the study. Similar results were also observed in early results (19, 20).

Yield and yield attributes of green gram

The yield attributes of green gram were significantly influenced by different weed management practices during both years, except test weight. Weed free treatment recorded the maximum number of branches per plant, number of pods per plant and "number of seeds per pod" at harvest of green gram were recorded in weed free treatment which statistically at par with two hoeing (25–30 and 40–45 DAS) and PRE at 1000 g ha^{-1} followed by one hoeing at 35–40 DAS. However, it remained significantly superior to all other treatments throughout both years of the study. This might be because of efficient weed management by PE application of PRE in combinations with hoeing which finally influenced growth parameters and yield attributes of green gram. Significantly lower number of branches per plant, lower number of pods per plant and lesser number of seeds per pod at harvest of green gram were recorded in weedy check treatment as compared to all other weed management practices during both years of study (Tables 6 and 7).

Table 6. Effect of different weed management practices on yield attributes of green gram intercropped in cotton (pooled data of two years)

Treatments	No. of branches per plant at harvest	No. of pods per plant at harvest	No. of seeds per pod at harvest	Test weight (g)
S_1	4.8	20.0	9.5	3.52
S_2	5.7	23.1	11.3	3.64
S_3	4.8	19.6	9.5	3.62
S_4	4.8	19.6	9.5	3.57
S_5	4.9	20.0	9.6	3.61
S_6	4.8	19.6	9.4	3.56
S_7	4.8	19.7	9.5	3.55
S_8	4.9	20.3	9.7	3.56
S_9	5.8	23.3	11.5	3.68
S_{10}	6.0	23.6	11.8	3.76
S_{11}	3.6	15.5	7.0	3.50
SE (m) ±	0.3	0.9	0.5	0.14
CD (p = 0.05)	0.8	2.4	1.4	NS

CD: critical difference.

Table 7. Effect of cropping system and different weed management practices on yield (kg ha^{-1}) of green gram (pooled data of two years)

Treatments	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)
S_1	355	758	1114	31.9
S_2	421	868	1290	32.6
S_3	353	743	1096	32.2
S_4	353	741	1094	32.3
S_5	358	759	1117	32.1
S_6	350	745	1095	31.9
S_7	355	741	1096	32.4
S_8	362	771	1133	31.9
S_9	429	869	1298	33.2
S_{10}	440	876	1315	33.5
S_{11}	260	604	864	30.0
SE (m) ±	19	31	46	-
CD (p = 0.05)	53	91	134	-

CD: critical difference.

Lower number of branches per plant, number of pods per plant and number of seed per pod at harvest of green gram were observed in weedy check treatment because of aggressive weed growth, resulted in depletion of soil moisture and nutrients, so reduction in plant growth and development. In case both years of study, the weedy check produced 34.67 % fewer pods per plant compared to the weed free treatment. Test weight of green gram was not significantly affected by weed management practices during either year; however, numerically higher test weight was observed under weed free conditions. Similar results were also recorded previously (19, 21, 22).

Evaluation of different weed suppression techniques significantly influenced the seed, stover and biological yields, as well as the harvest index of green gram intercropped with cotton over both study years. The weed-free treatment achieved the maximum seed yield (440 kg ha^{-1}), which was statistically comparable to both the dual hoeing (25–30 and 40–45 DAS) and the application of PRE at 1000 g ha^{-1} followed by a single hoeing at 35–40 DAS. Notably, these superior treatments increased seed yield by 69.0 and 64.9 %

respectively, relative to the weedy check. It might be due to crop improvement may be attributed to enhanced weed control provided by the integrated use of PE herbicides and manual hoeing, which optimised the growth environment and subsequent yield components of green gram. The weedy check consistently produced the lowest seed yield (260 kg ha^{-1}) in both years of study (Table 7). Similar results were reported by previous studies (2, 20, 23, 24).

Maximum stover yield (876 kg ha^{-1}) and biological yield (1315 kg ha^{-1}) were also recorded under weed-free treatment during both years of the study and were statistically at par with two hoeing and pendimethalin followed by hoeing, but significantly superior to rest of treatments. The weedy check recorded the lowest stover and biological yields in both years. Harvest index was highest under weed-free conditions (33.5 %) and lowest in the weedy check (30.0 %) during both the years.

Yield of cotton (q ha^{-1})

Seed cotton, stalk and biological yields of cotton were consistently higher during both years in (Table 8). Among cropping systems, sole cotton recorded significantly higher seed cotton yield (22.20 q ha^{-1}), stalk yield (54.32 q ha^{-1}) and biological yield (76.52 q ha^{-1}) compared with the cotton + green gram system during both seasons. Sole cotton produced about 13–19 % higher seed cotton yield, 13–17 % higher stalk yield and 12–17 % higher biological yield than the intercrop in both years. Our results corroborate the findings of (18, 25–27). All weed management practices significantly improved seed cotton, stalk and biological yields over the under weed-free conditions throughout the study. This treatment consistently achieved the maximum yields, recording seed cotton yield of 26.64 q ha^{-1}, stalk yield of 64.73 q ha^{-1} and biological yield of 91.37 q ha^{-1} during both the years. Treatments involving two hoeings (25–30 and 40–45 DAS) and PRE at 1000 g ha^{-1} PE followed by one hoeing at 35–40 DAS were statistically at par with rest of other and produced significantly higher yields than other herbicidal treatments, though they remained inferior to the weed-free treatment. Pendimethalin at 1000 g ha^{-1} applied as PE alone resulted in significantly lower yields compared to its sequential or integrated applications but remained superior to the weedy check.

Table 8. Effect of cropping system and different weed management practices on yield of cotton (Pooled data of two years)

Treatments	Seed cotton yield (q ha^{-1})	Stalk yield (q ha^{-1})	Biological yield (q ha^{-1})
Main plot-cropping system			
M_1	22.20	54.32	76.52
M_2	19.20	46.21	65.40
SE (m) ±	0.18	0.40	0.58
CD (p = 0.05)	1.19	2.59	3.78
Sub plots-weed management practices			
S_1	17.13	41.57	58.69
S_2	24.00	58.30	82.30
S_3	21.41	51.99	73.39
S_4	20.31	49.29	69.59
S_5	21.06	51.15	72.21
S_6	19.93	48.39	68.31
S_7	19.80	48.08	67.87
S_8	19.72	47.89	67.61
S_9	24.20	58.77	82.96
S_{10}	26.64	64.73	91.37
S_{11}	13.49	32.74	46.22
SE (m) ±	0.85	2.06	2.91
CD (p = 0.05)	2.44	5.92	8.35

CD: critical difference.

Sequential application of PRE PE followed by hoeing increased seed cotton yield by about 40 % over PRE PE alone. The weedy check consistently recorded the lowest yields and resulted in approximately 49 % reduction in seed cotton, stalk and biological yields compared to the under weed-free treatment during both years. Interaction effects between cropping system and weed management practices were non-significant. The weedy check significantly suppressed seed cotton yield relative to all other treatments. These results are in conformity with early findings (26, 28–31).

Available soil nutrients

Available soil nutrients after crop harvest were significantly influenced by cropping system and weed management practices throughout both years of investigation (Table 9), except Zn. The intercropping system (cotton + green gram) consistently recorded significantly higher available N, P and K compared to sole cotton during both years. Available N ranged from 126.7–123.5 kg ha^{-1}, available P from 17.6–16.6 kg ha^{-1} and available K from 267.5263.4 kg ha^{-1} under intercropping and sole cotton respectively, during both the years. Overall, a build-up of K was observed after crop harvest compared to initial soil values in both years.

Table 9. Effect of cropping system and different weed management practices on N, P, K and Zn status at harvest in experimental field soil during both years (2021–22)

Treatments	Nitrogen (kg ha^{-1})	Phosphorus (kg ha^{-1})	Potassium (kg ha^{-1})	Zinc (mg ha^{-1})
Main plot-cropping system				
M_1	123.5	16.6	263.4	1.70
M_2	126.7	17.6	267.5	1.75
SE(m)±	0.5	0.1	0.4	0.15
CD (p = 0.05)	2.1	0.6	1.9	NS
Sub plots-weed management practices				
S_1	126.8	18.6	268.3	1.73
S_2	122.8	15.9	262.8	1.74
S_3	124.0	16.7	263.9	1.74
S_4	125.3	17.1	265.2	1.73
S_5	125.1	16.5	264.9	1.73
S_6	125.3	17.0	266.0	1.73
S_7	125.4	17.7	266.3	1.70
S_8	126.2	17.8	266.8	1.73
S_9	123.2	16.1	262.8	1.71
S_{10}	120.9	15.6	262.7	1.69
S_{11}	131.7	18.9	270.4	1.77
SE (m) ±	1.1	0.2	0.7	0.17
CD (p = 0.05)	3.45	0.75	2.05	NS

CD: critical difference.

Various weed management practices exerted a significant influence on available N, P and K. The weedy check treatment recorded significantly higher available N (131.7 and 120.9 kg ha^{-1}), P (18.9 and 15.6 kg ha^{-1}) and K (270.4 and 262.8 kg ha^{-1}) during both the years, followed by PRE 1000 g ha^{-1} as PE.

However, the lowest available N, P and K were recorded in weed free treatment during both years. The higher nutrient content in soil after crop harvest was found in weedy check and other treatments where lower cotton yield was recorded due to which applied fertiliser remained unutilised in the soil. These results are supported by early results (2, 17). Available Zn content was not significantly influenced by either cropping system or weed management practices during both years. However, numerically higher Zn content was observed under the intercropping system and weedy check treatment, while the minimum values were recorded under weed-free conditions.

Conclusion

The two-year study demonstrates that both cropping systems and weed control strategies significantly influence the growth, yield and soil nutrient status of cotton and green gram. While sole cotton exhibited superior growth parameters and approximately 13–19 % higher seed cotton yield compared to the intercropping system, the cotton + green gram intercropping model provided a notable advantage in soil fertility, resulting in significantly higher post-harvest levels of available nitrogen (N), phosphorus (P) and potassium (K).

Effective weed management proved critical, as uncontrolled weeds (weedy check) reduced seed cotton yield by nearly 49 % and dry matter by 50 %. Among the treatments, weed-free conditions and the integration of pendimethalin (PRE) (1000 g ha^{-1}) followed by one hoeing emerged as the most effective strategies, consistently yielding the highest growth and yield parameters Conversely, the weedy check showed higher residual soil nutrients, primarily due to poor crop uptake under heavy competition. Overall, integrating green gram with cotton and employing pre-emergence herbicides alongside mechanical hoeing offers a balanced approach to maintaining crop productivity and soil health.

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Authors' contributions

BS supervised the manuscript, participated in sequence alignment and drafted the manuscript. VSH completed the writing and reviewed the collected data. TMP participated in manuscript editing, data validation and the final review of the manuscript. RK contributed to the interpretation of the results, critical revision of the manuscript and overall scientific input. HD collected and reviewed the literature and made appropriate corrections. AY contributed to data curation. AS visualised the data and written content and analysed and interpreted the data using software. All authors have read and approved the final manuscript.

Compliance with ethical standards

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