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ORIGINAL ARTICLE

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Green Manuring with *Sesbania aculeata* for Weed Suppression, Rice Productivity, and Soil Carbon Sequestration in Central India

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ABSTRACT

Continuous monocropping coupled with suboptimal management practices accelerates soil degradation and exacerbates environmental stress. In this context, legume-based green manuring has emerged as a sustainable strategy for enhancing soil health, environmental quality, and crop productivity in rice-based systems. It was hypothesized that incorporation of 45-day-old *Sesbania aculeata* biomass (4.73-5.03 t ha^{-1}) prior to rice transplanting would enhance rice productivity and profitability, suppress weed infestation, and promote soil carbon stabilization. A three-year field study (2014–2016) was conducted on large plots (4000 m^2 per field) comparing rice fields with and without *S. aculeata* incorporation. The results revealed that *S. aculeata* incorporation significantly ($p < 0.05$) reduced weed density and biomass (41.7-57.3% and 36.6-38.4%, respectively), while substantially increasing rice grain and straw yields (5.84-7.52 and 6.84-8.65 t ha^{-1}, respectively). Furthermore, green manuring with *S. aculeata* improved soil physical properties, notably reducing bulk density (1.39 Mg m_{-3} from 1.42), and significantly enhanced soil organic carbon (SOC) content (0.37% to 0.45%). Continuous incorporation over three years contributed appreciable carbon to the soil profile, resulting in higher soil carbon stocks than in the non-incorporated system. Incorporation of *S. aculeata* as green manure effectively suppresses weeds, enhances rice yield, improves soil health, increases carbon sequestration, and allows a reduction of synthetic nitrogen fertilizer by ~20 kg N ha^{-1}, thereby lowering production costs and mitigating potential environmental pollution.

1 | INTRODUCTION

Rice (*Oryza sativa* L.) is a principal staple food for millions of people worldwide, with Asia accounting for the largest share of production and consumption (DES, 2024). Consequently, rice-based production systems are pivotal to food and nutritional security in the region. Compared with other crops of similar growth duration, rice cultivation is highly input-intensive, requiring substantial amounts of water (1100-1800 mm ha_{-1}), nutrients (100:60:40 kg N, P_2O_5, and K_2O ha^{-1}), and repeated tillage operations (3-4 numbers). In efforts to maximize yields, farmers frequently apply excessive quantities of fertilizers and irrigation, practices that strongly influence rice productivity and system performance (Choudhary *et al.,* 2022). However, the sustainability of rice production is largely determined by the nature and efficiency of agronomic management practices adopted.

Improper cultivation practices, such as excessive and repeated tillage, indiscriminate fertilizer use, prolonged flooding, inefficient water management, and other unsound interventions, and open-field burning of crop residues poses serious threats to agricultural sustainability and environmental quality (Parihar *et al.,* 2018). Among these, residue burning is particularly detrimental, as it releases large quantities of greenhouse gases (GHGs) including methane (CH_4), nitrogen oxides (NO_x), and carbon- and sulfur-containing compounds into the atmosphere, thereby aggravating air pollution and climate change (Choudhary *et al.,* 2020). In addition to atmospheric impacts, residue burning accelerates soil degradation by increasing soil compaction, enhancing oxidation and depletion of soil organic carbon (SOC), reducing water-holding capacity, depleting readily available nutrients, and suppressing microbial activity within the soil profile.

Similarly, intensive tillage operations promote soil structural breakdown, erosion, and nutrient losses, ultimately leading to deterioration of soil quality. Such land degradation, largely driven by inappropriate land and crop management practices, threatens both crop productivity and long-term soil sustainability (Baskey *et al.,* 2025). Incorporation of green manure in transplanted rice is highly beneficial for improving soil fertility and crop productivity.

It enriches soil organic matter, enhances nitrogen availability through biological fixation, and improves soil structure. Green manure incorporation also suppresses weed growth during early crop stages and promotes better root development. Additionally, it reduces dependence on chemical fertilizers, lowers production costs, and supports sustainable rice cultivation in intensive cropping systems.

Transplanted rice is severely affected by weeds such as *Echinochloa crus-galli, Echinochloa colona, Cyperus difformis,* and *Monochoria vaginalis*. These weeds compete strongly for nutrients, light, and space, causing significant yield losses. The problem is intensified by continuous rice cultivation, poor water management, and the overuse of herbicides, which lead to shifts in weed flora and the development of herbicide resistance. Effective weed management is therefore essential for sustaining productivity. Green manure crops are typically fast-growing, exhibit rapid canopy closure, intercept solar radiation efficiently, and possess deep root systems that improve soil structure and nutrient acquisition (Baskey *et al.,* 2025). Although initial tillage and irrigation may stimulate the simultaneous emergence of weeds and green manure crops, the rapid biomass accumulation and canopy dominance of green manures subsequently suppress weed growth, reduce weed biomass, and gradually deplete the soil weed seed bank, thereby lowering weed pressure in the succeeding main crop (Hazbavi & Sadehi, 2016). In addition, incorporating green manure biomass can release allelochemicals that inhibit weed seed germination and early seedling growth (Farooq *et al.,* 2011). Incorporation of crop or weed biomass at an optimal growth stage, particularly before flowering in leguminous green manures, has been shown to enhance crop yield and improve produce quality by improving nutrient availability and soil biological activity (Ladha *et al.,* 2000).

Sesbania aculeata is an important leguminous green manure crop widely used in rice-based systems. It can be grown as a sole crop, intercrop, or mixed crop with cereals and is often utilized as a cover crop or brown manure when grown in association with rice (Capoen *et al.,* 2010). In most production systems, *S. aculeata* is incorporated into the soil or retained on the surface as mulch. Its extensive, deep root system enables efficient recycling of nutrients from deeper soil layers (Naher *et al.,* 2019). Incorporation of *S. aculeata* biomass stimulates microbial activity, accelerates nutrient mineralization, and enhances the availability of essential plant nutrients to the succeeding rice crop. Incorporation of 45–60 days old *S. aculeata* can contribute approximately 4.73-5.03 t ha^{-1} of biomass and 60–90 kg ha^{-1} of nutrients, particularly nitrogen, phosphorus, and potassium (Mirza *et al.,* 2005). Extended retention or incorporation of *S. aculeata* biomass improves soil moisture retention, suppresses weeds, supports rice growth and development, and enhances yield attributes, ultimately resulting in higher grain yield. Moreover, crop diversification through green manuring reduces dependence on external inputs, improves soil health, conserves natural resources, enhances land-use efficiency, and disrupts pest and disease cycles (Gill & Ahlawat, 2006).

HIGHLIGHTS

- *Sesbania aculeata* incorporation reduced weed density (41.7–57.3%) and biomass (36.6–38.4%), boosting rice grain yield by 11.6–20.3% over three years.
- Green manuring added ~1,982.8 kg C ha^{-1} yr^{-1}, significantly improving SOC, bulk density, and nutrient availability across the 0–15 cm soil profile.
- *S. aculeata* incorporation reduced synthetic nitrogen use by ~20 kg ha^{-1} yr^{-1}, improving net profitability by 8.3–20.0%, supporting climate-smart rice production.

The return of organic biomass, including crop residues and green manures, to the soil improves the hydrothermal regime by increasing soil water retention, which has been associated with higher crop yields and improved water-use efficiency (WUE) in maize-based systems in northern China (Yu *et al.,* 2018). However, the magnitude of these benefits is influenced by soil type, climate, and management practices. Retention or incorporation of biomass also mitigates GHG emissions associated with residue burning, while simultaneously enhancing SOC content, improving soil physicochemical properties, increasing soil moisture storage, and improving bulk density (Li *et al.,* 2019).

Incorporation of *Sesbania aculeata* significantly reduced weed density and biomass while enhancing rice grain and straw yields under transplanted conditions. It also improved soil physical properties by lowering bulk density and increasing soil organic carbon content. Long-term incorporation enhanced soil carbon stocks and enabled a reduction of synthetic nitrogen fertilizer, supporting sustainable nutrient management. Despite the recognized benefits of green manuring, comprehensive and systematic evaluations of *S. aculeata* incorporation for weed suppression, soil water retention, rice productivity, profitability, and soil health remain limited. It was hypothesized that incorporation of *S. aculeata* biomass into the soil would enhance sustainable rice productivity while minimizing environmental pollution. Therefore, the present study was undertaken to assess the effects of *S. aculeata* incorporation on weed suppression, rice productivity and profitability, and soil carbon stabilization under transplanted rice conditions.

2 | MATERIALS AND METHODS

2.1 | Experimental Site and Soil Characteristics

A field experiment was conducted for three consecutive years (2014–2016) at the ICAR–National Institute of Biotic Stress Management, Raipur, Chhattisgarh, India. The experimental site is located at 21°22′50.4″ N latitude and 81°49′31.9″ E longitude, at an elevation of 289 m above mean sea level. The region experiences a tropical sub-humid climate with a long-term mean annual rainfall of approximately 1250 mm, of which nearly 80% is received during the southwest monsoon period (June–September). The surface soil (0–20 cm) of the experimental field was clay loam in texture, neutral in reaction (pH 7.2), and low in soil organic carbon (SOC; 3.7 g kg^{-1}). The soil was characterized by low available nitrogen, medium available phosphorus, and high exchangeable potassium contents, with values of 215.2, 17.2, and 342.0 kg ha^{-1}, respectively.

2.2 | Experimental Design and Treatments

The experiment was laid out in a randomized complete block design (RCBD) with ten replications. Two treatments were evaluated (i) rice without *Sesbania aculeata* incorporation and (ii) rice with *S. aculeata* incorporation. Each treatment was applied to large plots of 4,000 m^2. *Sesbania aculeata* was sown at a seed rate of 25 kg ha^{-1} in well-tilled soil during the third week of May, followed immediately by irrigation to ensure uniform germination. Additionally, two irrigations were provided based on need. At 45 days after sowing, the *S. aculeata* crop was incorporated into the soil using a rotavator under standing water conditions. The incorporated biomass was allowed to decompose for five days prior to transplanting rice.

2.3 | Crop Establishment and Nutrient Management

Rice seedlings (21–23 days old) of the variety 'Swarna' (MTU 7029; parentage: Vasista × Mahsuri; medium duration of 145 days with short, bold grains) were transplanted in the second week of July. The recommended fertilizer dose of 80-100 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 40 kg K_2O ha^{-1} was applied. The entire phosphorus dose and three-fourths of the potassium were applied as basal at transplanting. Nitrogen was applied in three split doses at establishment, maximum tillering, and panicle initiation stages. In plots without *S. aculeata*, nitrogen was applied at 30, 40, and 30 kg ha^{-1}, whereas in *S. aculeata* incorporated plots, reduced nitrogen doses of 25, 30, and 25 kg ha^{-1} were applied at the respective stages. The remaining one-fourth of potassium was applied along with nitrogen at the panicle initiation stage. All other agronomic and crop management practices were followed as per regional recommendations (Choudhary & Dixit, 2024).

2.4 | Weed Observations

Weed density and biomass of grasses, broad-leaved weeds, and sedges were recorded at 60 days after transplanting (DAT). Observations were made using a quadrat of 0.5 m × 0.5 m placed at ten randomly selected locations in each plot. To assess natural weed infestation, three permanent weed-infested strips (5 m wide) were maintained in each field without any weed control measures, and samples were drawn from these strips. Weeds were categorized by functional groups, oven-dried at 65 ± 2 °C for 48 h, and weighed using an electronic balance to determine dry biomass.

2.5 | Crop Growth and Yield Attributes

Crop growth parameters, including plant height, aboveground biomass, and leaf area, were recorded from three randomly selected locations within each plot, and mean values were used for analysis. Leaf area index (LAI) was computed using the following equation 1:

$$LAI = \text{Leaf area } (cm^2)/\text{Ground area } (cm^2) \qquad \text{eq (1)}$$

Yield attributes such as number of tillers per hill, panicles per m^2, panicle length and weight, and number of filled and unfilled grains per panicle were recorded at maturity.

2.6 | Soil Water Dynamics

Perforated polyvinyl chloride (PVC) pipes were installed in each plot to monitor standing water depth. At the booting stage, 5 cm of irrigation water was applied, and daily water depletion was recorded for 15 consecutive days during a rain-free period to assess soil water retention.

2.7 | Yield and Economic Analysis

Grain and straw yields were harvested from three randomly selected areas of 25 m^2 (5 m × 5 m) in each plot for more precision, and mean values were used for interpretation. Harvest index was calculated as the ratio of grain yield to total aboveground biomass (grain + straw).

Economic parameters, including cost of cultivation, gross returns, net returns, and benefit–cost (B: C), were computed. In *S. aculeata* incorporated plots, the cost incurred for raising *S. aculeata* was included in the total production cost of rice. Gross returns were calculated using prevailing market prices for grain and straw, while net returns and B:C were estimated using standard procedures described by Choudhary and Kumar (2013).

2.8 | Soil Analysis and Carbon Estimation

Soil bulk density (ρb) was determined using the core method with a core sampler of 5.8 cm height and 5.4 cm diameter. Soil organic carbon, available nitrogen, and phosphorus were analyzed using standard laboratory procedures. Soil carbon stock was calculated using equations 2 and 3 proposed by Lee *et al.* (2009):

$$\text{C stock } (Mg\ ha^{-1}\ year^{-1}) = \text{Concentration } (\%)/100 \times \text{Depth } (m)/100 \times \rho b\ (Mg\ m^{-3}) \times \text{Area } (10000\ m^2)/ha \qquad \text{eq (2)}$$

Carbon addition through *S. aculeata* biomass was estimated as:

$$\text{C added } (kg\ ha^{-1}\ year^{-1}) = \text{Dry biomass of } S.\ aculeata \text{ (sum of three years)} \times 40/100 \qquad \text{eq (3)}$$

assuming that plant biomass contains approximately 40% carbon. Carbon stabilization was calculated as the difference between the final and initial SOC values, and annual carbon stock change (kg ha^{-1} $year^{-1}$) was estimated by dividing this difference by the study duration.

2.9 | Statistical Analysis

Data on all measured parameters were subjected to analysis of variance (ANOVA) using the F-test as described by Gomez and Gomez (1984). Treatment means were compared using the least significant difference (LSD) test at the 5% probability level (p = 0.05). Standard deviation values were computed within plots to assess variability.

3 | RESULTS AND DISCUSSIONS

3.1 | Weed Flora

The experimental rice fields were infested with a diverse weed flora comprising grasses, broad-leaved weeds, and sedges. Dominant grassy weeds included jungle rice [*Echinochloa colona* (L.) Link], barnyardgrass [*E. crus-galli* (L.) P. Beauv.], crabgrass [*Digitaria sanguinalis* (L.) Scop.], and knotgrass (*Paspalum distichum* L.). The major broad-leaved weeds were water clover (*Marsilea quadrifolia* L.), water primrose (*Ludwigia prostrata* Roxb.), sessile joyweed (*Alternanthera sessilis* (L.)). R. Br.], joyweed (*Alternanthera paronychioides* Forssk.), pink node flower (*Caesulia axillaris* Roxb.), creeping cradle plant [*Cyanotis axillaris* (L.) D. Don], false daisy (*Eclipta alba* L.), and benghal dayflower (*Commelina benghalensis* L.). The sedge population was mainly represented by smallflower umbrella sedge (*Cyperus difformis* L.), rice flat sedge (*C. iria* L.), and pipewort (*Eriocaulon sieboldianum* L.).

3.2 | Weed Prevalence and Suppression Mechanisms

Incorporation of *Sesbania aculeata* markedly reduced the density and biomass of different weed groups as well as total weed infestation compared with plots without green manuring (Table 1). Grassy weeds were significantly suppressed under *S. aculeata* incorporation, with densities ranging from 3.8 to 9.2 plants m^{-2}, representing a reduction of 36.1–58.2% relative to non-incorporated plots (8.9–14.4 plants m^{-2}). Similarly, densities of broad-leaved weeds and sedges were substantially lower in *S. aculeate* incorporated plots, with reductions of 20.8–60.0% and 26.1–51.7%, respectively. Consequently, total weed density was reduced to 13.1–28.2 plants m^{-2} under *S. aculeata* incorporation, compared with 30.7–48.4 plants m^{-2} in plots without incorporation. A parallel trend was observed for weed biomass. Total weed biomass in *S. aculeate* incorporated plots ranged from 12.2 to 17.7 g m^{-2} and consistently declined over the years, whereas substantially higher biomass (19.8–27.9 g m^{-2}) was recorded in plots without green manuring. Overall, incorporation of *S. aculeata* resulted in a reduction of 41.7–57.3% in total weed density and 36.6–38.4% in total weed biomass across the study period (Table 1).

The pronounced weed suppression can be attributed to several interacting mechanisms. Establishment of *S. aculeata* during the pre-monsoon period promoted synchronized germination of weed seeds, which were subsequently destroyed upon incorporation of the green manure before flowering, thereby depleting the soil weed seed bank. In addition, decomposition of *S. aculeata* biomass generates heat and gaseous by-products that can reduce weed seed viability (Dahlquist *et al.,* 2006). Enhanced soil organic matter following green manuring stimulates microbial activity and diversity, which may further suppress weeds through competitive and allelopathic effects. Broad-leaved weeds, in particular, were more sensitive to *Sesbania* incorporation, corroborating earlier findings that early-stage incorporation or intercropping of *Sesbania* effectively controls broad-leaved weed flora in rice systems (Singh *et al.,* 2007).

TABLE 1 Effect of *S. aculeata* incorporation on group-wise and total weed density and total weed biomass on puddled transplanted rice

Weed parameters	Treatment	2014	2015	2016
Grasses (no. m^{-2})	Without	14.4a±2.1	8.9a±2.4	9.1a±2.0
	With	9.2b±1.0	3.9b±0.9	3.8b±1.2
Broadleaf weeds (no. m^{-2})	Without	24.8a±3.8	16.0a±1.5	16.6a±1.8
	With	12.2b±1.6	6.4b±1.1	6.8b±1.6
Sedges (no. m^{-2})	Without	9.2a±2.4	5.8a±1.3	5.4a±1.3
	With	6.8b±0.6	2.8b±0.8	3.0b±0.9
Total weed density (no. m^{-2})	Without	48.4a±4.0	30.7a±5.2	31.1a±5.1
	With	28.2b±2.3	13.1b±2.9	13.6b±3.6
Total weed biomass (no. m^{-2})	Without	27.9a±2.9	21.6a±3.6	19.8a±3.3
	With	17.7b±0.6	13.6b±1.7	12.2b±1.6

3.3 | Growth and Yield Attributes

Incorporation of *S. aculeata* significantly improved rice growth parameters, including plant height, total aboveground biomass, and LAI (Table 2). Plant height ranged from 108.0 to 116.1 cm under *S. aculeata* incorporation, compared with 100.6–112.8 cm in non-incorporated plots. Total plant biomass (17.6–18.6 g hill^{-1}) and LAI (2.70–2.74) were 17.0–25.7% and 10.0–14.0% higher, respectively, than those recorded without incorporation. The enhanced growth may be attributed to the release of phytohormones and improved nutrient availability following *Sesbania* decomposition (Naher *et al.,* 2013), which promoted taller plants with larger and more numerous leaves. Increased LAI enhanced interception of solar radiation and photosynthetic efficiency, resulting in greater biomass production and improved assimilate translocation to reproductive organs.

Improved vegetative growth translated into superior yield attributes under *S. aculeata* incorporation. The number of tillers (7–8 hill^{-1}), panicles (300–315.7 m^{-2}), panicle length (23.2–23.7 cm), panicle weight (2.70–3.59 g), and number of filled grains per panicle (114–121) were significantly higher, while the number of unfilled grains (10–29 panicle^{-1}) was markedly lower than in non-incorporated plots. Compared with the control, *S. aculeata* incorporation increased tillers per hill by 21.2–31.0%, panicles per m^2 by 10.7–17.7%, panicle length by 3.1–4.9%, panicle weight by 7.6–17.4%, and filled grains per panicle by 8.1–14.8%, while reducing unfilled grains by 19.5–25.0%. These findings are consistent with earlier reports demonstrating improved growth and yield attributes in rice-based systems following green manuring with *Sesbania* (Paul *et al.,* 2014).

TABLE 2 Effect of *S. aculeata* incorporation on growth and yield attributes and yield of puddled transplanted rice

Parameters	Treatment	2014	2015	2016
Growth parameters				
Plant height (cm)	Without	100.6b±4.04	112.5a±4.51	112.8b±2.65
	With	108.0a±2.74	116.5a±5.11	116.1a±2.91
Total plant biomass (g hill^{-1})	Without	14.0b±2.35	15.9b±2.33	15.2b±2.1
	With	17.6a±0.95	18.6a±0.83	18.1a±0.8
Leaf area index	Without	2.39b±0.04	2.49b±0.09	2.42b±0.04
	With	2.70a±0.09	2.74a±0.1	2.76a±0.09
Yield attributes				
Tillers (no. hill^{-1})	Without	5.7b±1.04	5.8b±0.29	6.6b±1.14
	With	7.0a±1.22	7.6a±0.31	8.0a±0.71
Panicle (no. m^{-2})	Without	267.4b±9.40	271.0b±9.31	276.7b±9.07
	With	314.6a±6.91	300.0a±55.70	315.7a±25.32
Panicle length (cm)	Without	22.9b±0.44	22.5a±0.93	22.6a±0.70
	With	23.8a±0.28	23.2a±0.55	23.7a±0.78
Panicle weight (g panicle^{-1})	Without	2.3b±0.12	3.29b±0.13	3.32b±0.13
	With	2.7a±0.11	3.54a±0.25	3.59a±0.23
Sound grain (no. panicle^{-1})	Without	105.8b±5.12	100.4b±11.29	105.7b±8.33
	With	114.4a±5.13	115.3a±3.51	120.7a±3.21
Unfilled grain (no. panicle^{-1})	Without	10.4a±1.82	29.0a±2.51	26.6a±2.51
	With	7.8b±1.92	22.9b±4.35	21.4b±4.09

3.4 | Grain and Straw Yield and Harvest Index

Enhanced growth and yield attributes under *S. aculeata* incorporation culminated in significantly higher rice yields (Table 3). Grain yield increased by 11.6–20.3% compared with non-incorporated plots, with yield gains becoming more pronounced over successive years. Straw yield also increased by 5.0–7.1%, while harvest index improved by 2.2–7.0% under *S. aculeata* incorporation. The sustained yield advantage reflects improved nutrient recycling, enhanced SOC, and better soil physical conditions resulting from repeated green manuring. Green manuring with *S. aculeata* has been shown to exert residual benefits on succeeding crops and can partially substitute synthetic nitrogen fertilizers, thereby enhancing system sustainability (Wabi *et al.,* 2016). The addition of *S. aculeata* biomass to the plow layer increased nutrient availability and SOC content, which are critical determinants of rice productivity in intensively cultivated systems. Previous studies have similarly reported improved rice grain yield, nutrient-use efficiency, and long-term sustainability with integrated use of *Sesbania* green manuring and inorganic fertilizers (Kannan *et al.,* 2025). Long-term experiments in South Asia have demonstrated yield increases of 9–11% with continuous green manuring, along with improved soil carbon status compared with sole reliance on chemical fertilizers (Shah *et al.,* 2011).

3.5 | Economic Performance

Economic analysis indicated that *S. aculeata* incorporation marginally increased the cost of cultivation by ₹4.11–4.25 × 10^3 ha^{-1} compared with non-incorporated plots (Table 3). However, the higher grain yield obtained under *S. aculeata* incorporation substantially increased gross returns (by 11.2–19.3%) and net returns (by ₹4.6–15.0 × 10^3 ha^{-1}), resulting in 8.3–20.0% higher net profitability. The B: C remained comparable between treatments, indicating that the additional investment in green manuring was economically justified.

TABLE 3 Effect of *S. aculeata* incorporation on yield and economic parameters on puddled transplanted rice

Parameters	Treatment	2014	2015	2016
Yield parameters				
Grain yield (kg ha^{-1})	Without	5228b ±63.9	6344b±712.8	6250.0b±809.6
	With	5836a±100.7	7383a±337.1	7521.1a±445.1
Straw yield (kg ha^{-1})	Without	6428b±83.2	8234b±489.48	8073.3b±636.8
	With	6843a±82.6	8647a±568.0	8647.2a±600.0
Harvest index	Without	0.45a±0.002	0.43b±0.04	0.44b±0.04
	With	0.46a±0.005	0.46a±0.01	0.47a±0.02
Economic parameters				
Cost of production (x 10^3 ₹ ha^{-1})	Without	22.69	23.89	25.04
	With	26.84	28.04	29.29
Net returns (x 10^3 ₹ ha^{-1})	Without	55.36±0.94	73.81±12.62	74.91±11.19
	With	59.96±1.40	84.71±12.97	89.92±6.77
Benefit-cost ratio	Without	3.44±0.04	4.09±0.53	3.99±0.47
	With	3.23±0.05	4.02±0.46	4.07±0.23

Seed price of Sesbania ₹50 kg^{-1}; each irrigation charges, ₹500 ha^{-1}; price of rice, ₹14.7 kg^{-1}; straw price, ₹1 kg^{-1}

3.6 | Soil Water Dynamics

Soil water depletion patterns differed markedly between treatments and across years (Fig. 1). In the initial year, differences between treatments were minimal; however, with continued *S. aculeata* incorporation, the gap widened progressively in subsequent years. Plots without *S. aculeata* lost water more rapidly after soil saturation, whereas *S. aculeata*–incorporated plots retained higher moisture levels throughout the observation period. Improved soil aggregation, porosity, and structural stability following green manuring enhanced soil water-holding capacity. In addition, *S. aculeata* incorporation reduced soil compaction, erosion, and surface runoff, thereby improving moisture retention within the soil profile (Sahoo *et al.,* 2023).

3.7 | Soil Physical and Chemical Properties

After three years, incorporation of *S. aculeata* significantly improved soil physical properties. Bulk density decreased by 2.7% in the 0–5 cm layer and by 1.9% and 1.8% in the 5–10 and 10–15 cm layers, respectively, compared with non-incorporated plots (Fig. 2a). Soil organic carbon content increased substantially with *S. aculeata* incorporation, particularly in surface soil layers. SOC increased by 29.4% at 0–5 cm depth, followed by 20.8% and 10.8% increases at 5–10 and 10–15 cm depths, respectively, relative to the control (Fig. 2b). On average, *S. aculeata* incorporation contributed approximately 1982.8 kg C ha^{-1} $year^{-1}$ through biomass addition. Continuous incorporation resulted in higher carbon stocks in the upper 0–15 cm soil profile, whereas plots without green manuring exhibited a decline in SOC, especially in surface layers. Shallow incorporation using rotavators facilitated SOC accumulation, enhanced carbon stability, and promoted carbon sequestration (Table 4), in agreement with earlier findings (Choudhary *et al.,* 2020), (Meena *et al.,* 2021, Singh *et al*., 2021) .

3.8 | Carbon Dynamics and Sequestration

Annual production of aboveground *S. aculeata* biomass ranged from 4729 to 5029 kg ha^{-1}, contributing 1939.2–2011.6 kg C ha^{-1} $year^{-1}$ (Table 4). After three years, carbon stocks increased by 0.26, 0.16, and 0.07 Mg ha^{-1} $year^{-1}$ at 0–5, 5–10, and 10–15 cm depths, respectively. Carbon stabilization was highest in surface soils (780.3 kg ha^{-1} $year^{-1}$ at 0–5 cm) and declined with depth. Similarly, carbon sequestration rates were significantly higher under *S. aculeata* incorporation, with gains of 260.1, 157.0, and 67.4 kg ha^{-1} $year^{-1}$ at respective depths compared with non-incorporated plots. These results underscore the role of green manuring in enhancing soil carbon storage and mitigating carbon losses in intensively cultivated rice systems.

3.9 | Available Nitrogen and Phosphorus

Incorporation of *S. aculeata* significantly improved soil available nitrogen and phosphorus across soil depths (Fig. 2c, d). Available N increased by 18.6%, 20.4%, and 17.2% at 0–5, 5–10, and 10–15 cm depths, respectively, compared with non-incorporated plots. Similarly, available P increased by 11.6%, 9.3%, and 14.8% at corresponding depths. The improvement in nutrient availability reflects enhanced mineralization of *Sesbania* biomass, increased microbial activity, and improved nutrient retention in soils with higher SOC. The sustained addition of *S. aculeata* biomass replenished nutrients removed by successive crops, reduced reliance on synthetic fertilizers, and minimized environmental contamination. Approximately

25% of the crop nitrogen requirement could be met through *S. aculeata* incorporation, allowing a reduction of about 20 kg N ha⁻¹ year⁻¹ without compromising grain yield (Wang *et al.,* 2009).

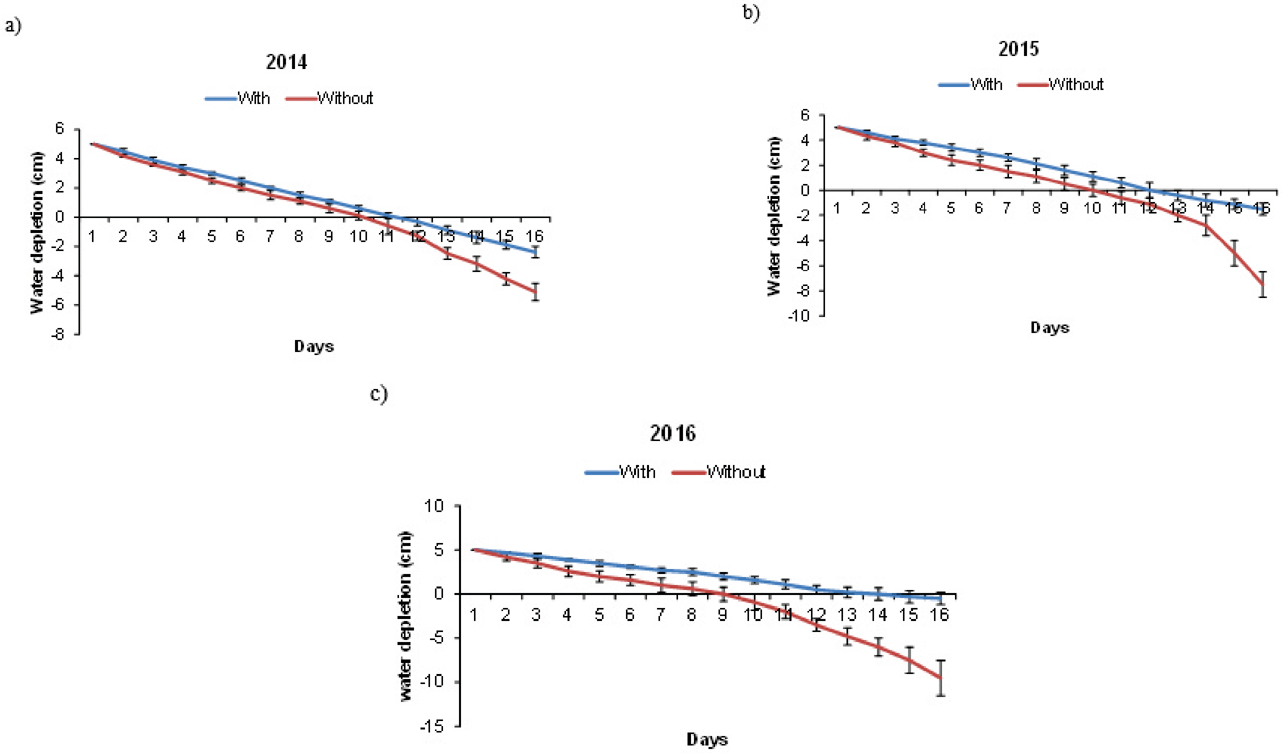

FIGURE 1 Effect of with and without *S. aculeata* incorporation on water depletion pattern on rice field during panicle initiation stage during a) 2014, b) 2015 and c) 2016.

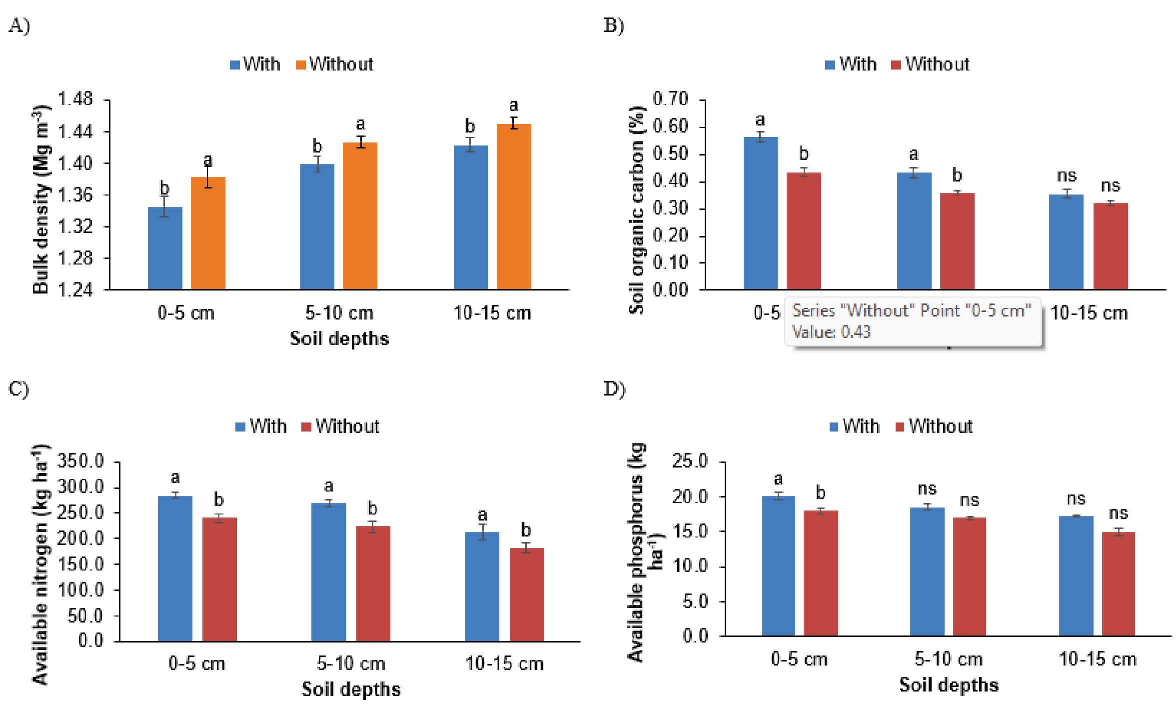

FIGURE 2 Effect of incorporation of *S. aculeata* on A) bulk density, B) soil organic carbon, C) available nitrogen and D) available phosphorus (three years after study).

TABLE 4 Carbon stabilization and carbon sequestration under *S. aculeata* incorporated plots without incorporation

Parameter	2014	2015	2016
Biomass of *S. aculeata* (kg ha^{-1})	4729.0±121.0	4994.0±260.1	5029.0±158.1
Carbon input (kg ha^{-1})	1939.2±64.19	1997.6±109.66	2011.6±63.23
	0-5 cm	5-10 cm	10-15 cm
Carbon stock (Mg ha^{-1}year^{-1})	0.26±0.04	0.16±0.04	0.07±0.04
Carbon stabilization (kg ha^{-1}year^{-1})	780.3±112.47	470.9±105.65	202.2±129.44
C sequestration ((kg ha^{-1}year^{-1})	260.1±37.49	157.0±35.22	67.4±43.15

4 | CONCLUSIONS

The present study demonstrates that incorporation of *Sesbania aculeata* is an effective and sustainable approach for enhancing weed control, rice productivity, and soil health in transplanted rice systems. Incorporation of *S. aculeata* reduced total weed density by 41.7–57.3% and weed biomass by 36.6–38.4% compared with non-incorporated plots, indicating strong biological weed suppression and depletion of the weed seed bank. These effects resulted in improved crop performance, with rice grain yield increasing by 11.6–20.3% and greater soil water retention due to improved soil physical properties. The practice also contributed substantially to soil carbon dynamics and fertility. Incorporation of *S. aculeata* added 1,982.8 kg C ha^{-1} yr^{-1}, increased soil porosity by 2.14%, and enhanced soil organic carbon by 21.3% in the 0–15 cm soil layer. Carbon sequestration and stabilization were estimated at 161.5 and 484.5 kg C ha^{-1} yr^{-1}, respectively. Additionally, soil nitrogen and phosphorus contents increased by 18.8% and 11.8%, allowing a reduction of at least 20% in synthetic nitrogen fertilizer use. Overall, *S. aculeata* incorporation offers a viable, climate-smart strategy to improve productivity, profitability, and environmental sustainability in rice-based systems.

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CONFLICT OF INTEREST

The author has no conflict of interest.

DATA AVAILABILITY STATEMENT

The corresponding author is liable to make the data available on request.

AUTHOR CONTRIBUTION

VKC: Conducted the experiment, data recording, statistical analysis, prepared the original manuscript.

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