



The Role of Green Manures in Sustaining Soil Fertility and Crop Productivity: A Comprehensive Review

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Review Article

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Abstract

Soil degradation driven by intensive monocropping and excessive dependence on synthetic fertilizers has severely compromised soil organic carbon, nutrient balance, and biological activity in major agricultural regions, particularly the Indo-Gangetic Plains. Green manuring has re-emerged as a sustainable strategy to restore soil fertility and enhance crop productivity. It involves the incorporation of fresh green plant biomass into the soil to enhance organic matter content and nutrient availability. Leguminous green manures such as dhaincha (*Sesbania aculeata*) and

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sunhemp (*Crotalaria juncea*) are widely used because of their ability to fix atmospheric nitrogen and improve soil physical, chemical, and biological properties. Numerous studies conducted across different cropping systems and agro-climatic regions have demonstrated that green manuring enhances soil structure, increases microbial activity, improves nutrient cycling, and reduces dependence on chemical fertilizers. In addition, the practice contributes to sustainable crop production by improving soil resilience and maintaining long-term productivity. This review summarizes recent research findings on the effects of green manuring on soil properties and crop performance under diverse cropping systems. The study highlights the importance of integrating green manures into sustainable nutrient management strategies for environmentally sound agriculture.

Keywords: Green Manuring; soil degradation; chemical fertilizers; dhaincha; sunhemp.

1. Introduction

In the current agricultural landscape, sustaining global food security while preserving the ecological integrity of the soil has become a paramount challenge. Decades of intensive monoculture and a heavy reliance on synthetic fertilizers have led to widespread soil degradation, characterized by a loss of soil biodiversity, declining organic carbon levels, and severe structural deterioration. This decline is not merely a loss of nutrients but a fundamental breakdown of the soil's "living" component. Continuous application of high-analysis nitrogenous fertilizers has triggered soil acidification and skewed the N:P:K balance, leading to the "mining" of micro and secondary nutrients like Zinc, Iron, and Sulphur that are rarely replenished in conventional systems (Singh *et al.* 2023). Furthermore, the depletion of Soil Organic Matter (SOM)—the literal backbone of soil fertility—has compromised the soil's buffering capacity and water-retention abilities. In many intensive cropping belts, such as the Indo-Gangetic Plains, the organic carbon content has plummeted below the critical threshold of 0.5%, rendering the soil "biological deserts" where chemical inputs yield diminishing returns. This structural collapse increases vulnerability to compaction, surface crusting, and erosion, which further strips the fertile topsoil of its productive potential (Prajapati *et al.* 2023).

In this context, green manuring—the practice of incorporating undecomposed green plant tissues into the soil—emerges as a critical, eco-friendly strategy for restoring soil health and fertility. By providing a massive influx of fresh biomass, green manuring acts as a biological restorative agent, reversing the damage of chemical intensification by re-coupling the carbon and nitrogen cycles. It serves not only as a localized

nutrient source but as a primary driver for microbial rejuvenation, ensuring that the soil remains a resilient and productive medium for future generations (Kaul *et al.* 2015). The primary strength of green manuring lies in its ability to act as a biological nutrient factory. Unlike chemical fertilizers that provide isolated nutrients, green manures enrich the soil with a complete matrix of organic matter and essential macro and micronutrients. Leguminous green manures, such as Dhaincha (*Sesbania aculeata*) and Sunhemp (*Crotalaria juncea*), are particularly valued for their capacity to fix atmospheric nitrogen (N), contributing between 60 to 90 kg N/ha to the succeeding crop. This biological nitrogen fixation (BNF) significantly reduces the need for synthetic nitrogenous fertilizers by up to 25–50%, thereby lowering both production costs and environmental risks such as nitrate leaching (Naz *et al.* 2023).

Beyond simple nutrient addition, green manuring transforms the soil's physico-chemical and biological properties. The decomposition of added biomass releases organic acids that can lower soil pH in alkaline conditions and solubilize fixed phosphorus (P) and potassium (K), making them more available for plant uptake. Simultaneously, the addition of organic carbon fuels the soil microbial community, enhancing enzymatic activities (such as urease and phosphatase) and improving soil structure through better aggregation and increased water-holding capacity. This review aims to synthesize recent research on the multi-dimensional impacts of green manuring, emphasizing its role as a cornerstone of Integrated Nutrient Management (INM) for sustainable crop production under diverse agro-climatic conditions (Tejada *et al.* 2008; Joshna & Bokado, 2024). Rapid urbanization and industrialization have resulted in the reduction of fertile agricultural land, forcing farmers to cultivate crops on marginal and

degraded soils. These soils are often characterized by low organic matter content, poor nutrient availability, and reduced productivity. Under such conditions, green manuring can play an important role in restoring soil fertility by increasing soil organic carbon, improving nutrient availability, and enhancing microbial activity. Therefore, the integration of green manure crops into farming systems can serve as an effective and sustainable strategy for improving the productivity of marginal lands.

Overall, Green manuring is a sustainable soil fertility management practice that supports the principles of conservation agriculture and sustainable farming. It reduces reliance on chemical fertilizers while enhancing soil resilience and productivity. This makes it a vital strategy for achieving long-term agricultural sustainability in India. Green manuring has been successfully integrated into several cropping systems such as rice–wheat, rice–maize, and rice–pulse systems across different agro-climatic zones. Studies have reported that the incorporation of green manure crops improves soil organic carbon, enhances nutrient availability, and increases crop productivity under both irrigated and rainfed conditions. Therefore, the adoption of green manuring practices can play a crucial role in sustaining soil fertility and

promoting environmentally friendly agricultural production systems.

2. Green Manure Crops

Green manure is defined as plant material incorporated into the soil while still green or at maturity. Specifically, a green manure crop is grown with the purpose of being turned under the soil, either while green or shortly after maturity, to improve soil quality (Soil Science Society of America, 1997). These crops can be either leguminous or non-leguminous and may be grown directly on the site (in situ) or brought in as cuttings from trees and shrubs, the latter practice being known as green leaf manuring (Singh et al., 1991).

A wide variety of legume species have potential as green manures. Although there are several hundred tropical legume species, only a small portion have been studied for their use as green manures. Similarly, temperate regions have numerous legume crops suitable for this purpose. Under ideal growing conditions, annual dry matter accumulation by these legumes ranges from 1 to over 10 Mg per hectare. The amount of nitrogen accumulated in the aboveground dry matter can vary from 20 kg to as much as 300 kg per hectare (Lathwell, 1990).

Table 1. Nutrient content of green manure crops, green leaf manures and weeds (on Dry Basis)

Sr. No.	Plant Name	Botanical Name	N (%)	P (%)	K (%)
I.	Green Manure Crops				
1.	Sunnhemp	<i>Crotalaria juncea</i>	2.30	0.50	1.80
2.	Dhaincha	<i>Sesbania aculeata</i>	3.50	0.60	1.20
3.	Sesbania	<i>Sesbania speciosa</i>	2.71	0.53	2.21
4.	Cowpea	<i>Vigna sinensis</i>	1.70	0.28	1.25
5.	Mungbean	<i>Vigna radiata</i>	2.21	0.26	1.26
II.	Green Leaf Manure				
6.	Gliricidia	<i>Gliricidia sepium</i>	2.76	0.28	4.60
7.	Pongamia	<i>Pongamia pinnata</i>	3.31	0.44	2.39
8.	Neem	<i>Azadirachta indica</i>	2.83	0.28	0.35
9.	Gulmohar	<i>Delonix regia</i>	2.76	0.46	0.50
10.	Peltophorum	<i>Peltophorum pterocarpum</i>	2.63	0.37	0.50
III.	Weeds				
11.	Parthenium	<i>Parthenium hysterophorus</i>	2.68	0.68	1.45
12.	Water hyacinth	<i>Eichhornia crassipes</i>	3.01	0.90	0.15
13.	Trianthema	<i>Trianthema portulacastrum</i>	0.64	0.43	1.30
14.	Ipomoea	<i>Ipomoea carnea</i>	2.01	0.33	0.40
15.	Calotropis	<i>Calotropis gigantea</i>	2.06	0.54	0.31
16.	Cassia	<i>Cassia fistula</i>	1.60	0.24	0.20

Source: Dubey et al. (2015)

For a green manure crop to be agronomically attractive and economically viable, it should possess certain key characteristics. These include being fast-growing for easy integration into cropping systems, producing sufficient dry matter to enhance soil physical, chemical, and biological properties, fixing an adequate amount of nitrogen, and requiring minimal cultural practices during the growth period to remain cost-effective.

The amount of nitrogen (N) fixed symbiotically by legumes depends on several factors, including the plant species and genotype (Unkovich & Pate, 2000), the N-fixation capacity, the biomass produced, the efficiency of the Rhizobia-plant symbiosis (Liu et al., 2011), and environmental conditions (Giller & Cadisch, 1995; Halling et al., 2004). Nitrogen fixation by leguminous crops peaks during the blossoming stage and begins to decline during seed development.

Soil properties also influence legume growth and can determine the proportion of nitrogen derived from atmospheric fixation. This proportion typically decreases as the availability of nitrogen from soil organic matter (SOM) and from organic or mineral fertilizers increases (Riesinger & Herzon, 2010). Additionally, deficiencies in phosphorus (P) and potassium (K) affect the physiological processes of leguminous plants, such as white clover, but do not reduce the proportion of nitrogen fixed from the atmosphere (Høgh-Jensen, 2003).

3. Incorporation of Green Manure Crops

Several methods are used to incorporate green manure crops into the field, including ploughing, harrowing, discing, or tilling the crop into the soil.

Once incorporated, the green manure decomposes, enriching soil fertility, stimulating plant growth, and enhancing nutrient availability through increased soil enzyme activities (Asghar & Kataoka, 2021). The timing of incorporation is critical, as it affects nutrient uptake, helps suppress weed growth, and improves soil quality during decomposition (Sharifi et al., 2016; Kaur et al., 2019; Brito et al., 2019).

Some farmers employ specialized equipment such as flail mowers or roller crimpers to mechanically terminate and incorporate green manure crops. These tools help achieve uniform distribution across the field. Incorporation also aids in controlling insect pests and plant diseases, contributing to healthier crops (Pandey & Srivastava, 2021). However, these methods come with challenges, including establishment and management costs, which may sometimes outweigh the immediate economic benefits for farmers.

Beyond soil enrichment, green manure incorporation helps inhibit weed growth through allelopathic effects or shading, offering a natural weed management approach. It improves soil fertility, increases organic matter, and reduces nutrient leaching. Other benefits include improved soil structure and water retention, leading to better moisture management and decreased soil erosion.

Hence, incorporating green manure crops via ploughing or specialized equipment enhances soil fertility, reduces weed growth, and boosts crop yields by accelerating soil enzyme activities (Kaur et al., 2019). To maximize these benefits and prevent unnecessary reproduction of the green manure crop, incorporation should be completed before the flowering stage.

Table 2. Biomass production and nitrogen contribution of major green manure crops (45–60 Days)

Sr. No.	Common Name	Botanical Name	Growing Season	Green Matter (MT/ha)	Nitrogen Contribution (kg/ha)
1.	Sunnhemp	<i>Crotalaria juncea</i>	Wet	21.2	91
2.	Dhaincha	<i>Sesbania aculeata</i>	Wet	20.2	86
3.	Green gram	<i>Vigna radiata</i>	Wet	8.0	42
4.	Cowpea	<i>Vigna sinensis</i>	Wet	15.0	74
5.	Guar	<i>Cyamopsis tetragonoloba</i>	Wet	20.0	68
6.	Khesari	<i>Lathyrus sativus</i>	Dry	12.3	66
7.	Berseem	<i>Trifolium alexandrinum</i>	Dry	15.5	67

Source: Patra et al. (2023)

4. Improvement in Soil Physical Properties

The decomposition of succulent green biomass releases microbial polysaccharides and fungal hyphae (specifically Glomalin), which bind individual soil particles into stable macro-aggregates. This reduces bulk density and prevents surface crusting (Abid et al. 2009). Green manuring increases the total pore space in the soil profile. The addition of low-density organic matter offsets the weight of mineral particles, making the soil "lighter" and easier for roots to penetrate (Sharma & Mittra, 1988). Organic matter from green manure acts like a sponge. It increases the soil's surface area and number of micropores, allowing it to retain more moisture against gravity, which is crucial for drought resilience. The mitigation of soil compaction and the reduction of Bulk Density (BD) are critical physical improvements facilitated by the regular incorporation of green manure. Longitudinal studies by Chaphale and Badole (1999) initially established that the persistent addition of *Gliricidia sepium* leafy foliage over five years resulted in a notable decrease in BD, enhancing soil porosity. This structural refinement is particularly evident in intensive cereal-based systems; Mandal et al. (2003) observed that incorporating *Sesbania aculeata* (Dhaincha) and green gram in a rice-wheat cropping sequence significantly lowered BD across both the 0–15 cm and 15–30 cm soil profiles. Their findings quantified a reduction of 0.03–0.07 Mg m⁻³ in the surface layer and 0.05–0.09 Mg m⁻³ in the subsurface layer compared to fallow treatments, suggesting that green manuring promotes deeper root proliferation by alleviating subsoil compaction. Recent evaluations further confirm that the integration of green manure with mineral nitrogen (N) can optimize these physical benefits. Islam et al. (2019) reported that the combined application of *Sesbania aculeata* and a subsidized dose of nitrogen (60 Kg N/ha) yielded the lowest BD value (1.11 Mg m⁻³), representing a substantial improvement over the control treatment (1.32 Mg m⁻³). This reduction in bulk density is primarily attributed to the increased Soil Organic Matter (SOM) and the subsequent development of stable macro-aggregates, which create a more favourable, less resistant medium for plant growth. Collectively, these studies indicate that green manuring is a robust tool for enhancing the soil's physical architecture, ensuring better aeration and water infiltration in degraded agricultural lands. Green manure crops are

particularly beneficial in intensive cropping systems where continuous cultivation often leads to soil nutrient depletion and decline in soil organic matter.

The decrease in soil bulk density is attributed to the increase in soil organic carbon, which acts as a binding agent for soil particles and promotes soil aggregation (Kumar et al., 2012). This effect is likely enhanced by the addition of organic matter from incorporated crops like dhaincha and mungbean, which decompose through microbial activity. Green manure can stimulate soil microbial processes involved in organic matter decomposition, leading to improved soil porosity and reduced bulk density (Islam et al., 2019). Similar findings have been reported by Naz et al. (2023), Islam et al. (2019), Carter et al. (2014), and Sultani et al. (2007).

4.1 Chemical Properties

The influence of green manuring (GM) on soil pH is dynamic, acting as a natural regulatory mechanism that varies based on initial soil conditions and the species incorporated. While some studies, such as those by Ganapathi and Ullasa (2019), have noted a slight increase in pH following the incorporation of *Sesbania aculeata* (Dhaincha) in rice-based systems, most research suggests a neutralizing or slightly acidifying trend. Islam et al. (2019) observed that GM incorporation marginally lowered soil pH compared to control plots, although these fluctuations often remained statistically non-significant between different organic treatments.

This acidifying effect is primarily attributed to the release of organic acids and carbon dioxide during the decomposition of succulent biomass. Ma et al. (2021) reported that leguminous green manures exert a more pronounced acidifying impact than non-leguminous species, which is particularly beneficial for the amelioration of alkaline or calcareous soils. Furthermore, the strategic co-incorporation of green manure and rice straw has been shown to act as a buffering agent. As highlighted by Zhou et al. (2020), this integrated approach helps regulate soil reaction, preventing excessive acidity and maintaining an optimal pH range for enhanced microbial activity and nutrient bio-availability. Collectively, these findings indicate that green manuring serves as a vital tool for stabilizing soil pH, ensuring a balanced chemical environment for sustainable crop production.

Table 3. Effect of various Green Manure (GM) treatments on soil available N, P, and K content compared to conventional practices

Sr. No.	GM treatment	Nutrient content in GM treated plots			Nutrient content in comparison				References
		Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	Compared to	Available N (kg ha ⁻¹)	Available P (kg ha ⁻¹)	Available K (kg ha ⁻¹)	
1	Sesbania GM to rice and <i>Leucania</i> GLM to wheat	329.3	37.6	454.1	Control	283.5	30.6	395.0	Das <i>et al.</i> (2024)
2	5 tha ⁻¹ <i>gliricidia</i> foliage	266	18.5	320	NPK (100:50:50)	252	18.1	301	Chaphale and Badole (1999)
3	Cowpea GM	287.7	18.2	116.2	Control	222.7	14.3	93.3	Ansari <i>et al.</i> (2022)
4	<i>Sesbania aculeata</i> + 50% RDN	235.2	16.2	310.3	100% RDN	232.5	14.4	280.6	Kumar <i>et al.</i> (2012)
5	Sunhemp + 75% RDF	208	67	289	100% RDF	175	59	263	Sandhya Rani <i>et al.</i> (2022)
6	Dhaincha + 75% RDF	210	68	291	100% RDF	175	59	263	Sandhya Rani <i>et al.</i> (2022)
7	Green gram + 75% RDF	193	62	272	100% RDF	175	59	263	Sandhya Rani <i>et al.</i> (2022)

*GM- Green Manure

The replenishment of Soil Organic Carbon (SOC) is perhaps the most vital long-term benefit of green manuring, acting as a primary driver for enhanced soil structure and nutrient cycling. Recent evaluations by Rautaray *et al.* (2020) highlight that incorporating *Sesbania aculeata* (Dhaincha) as a dual-purpose green manure-cum-cover crop significantly bolsters SOC levels, thereby revitalizing overall soil health. This carbon enrichment is further amplified when green manures are integrated into residue management systems. For instance, Saikia *et al.* (2020) demonstrated that the combined application of green manure and wheat straw (PTRws25+GM) achieved a remarkable increase in SOC—33% in the surface layer and 31.4% in the subsurface layer—compared to plots without organic amendments. These findings align with those of Zhou *et al.* (2020), who reported that the synergistic incorporation of green manure and rice straw surpassed all other treatments in raising stable SOC concentrations. The magnitude of this carbon surge is highly dependent on the biomass quality and species selected. Irin *et al.* (2021) observed consistently superior organic carbon profiles in plots treated with leguminous biomass; specifically, mungbean (*Vigna radiata*) incorporation resulted in a 32% increase in SOC (1.35%) compared to the control (1.02%). Collectively, these studies suggest that green manuring serves as a biological "carbon pump," effectively reversing the depletion of organic matter caused by intensive chemical farming. By bridging the carbon gap, green manuring not only improves the soil's buffering capacity and water-retention abilities but also creates a more resilient physical environment for sustainable crop production.

The integration of green manures (GM) significantly bolsters the soil's chemical fertility by enhancing the bio-availability of primary macronutrients. Recent research by Zhou *et al.* (2020) underscores a synergistic effect when green manure is co-incorporated with rice straw, achieving a higher total NPK content than single-source organic treatments. The superiority of leguminous species in this regard is well-documented; Irin *et al.* (2021) demonstrated that *Sesbania rostrata* and *Sesbania aculeata* increased available nitrogen by 35–40%, phosphorus by 20–25%, and potassium by 12–16% compared to plots receiving only synthetic fertilizers. These findings are corroborated by Ansari *et al.* (2022), who reported substantial increases in the 0–0.15 m soil layer—ranging from 16.6–29.9% for N, 15.4–31.5% for P, and

16.3–26.0% for K—following the incorporation of *Sesbania*, cowpea, and green gram. Beyond individual crop cycles, the long-term benefits of GM are evident in diverse cropping systems. In a rice-berseem sequence, Naz *et al.* (2023) observed that green manure application, whether applied alone or in conjunction with commercial fertilizers, resulted in significantly higher soil nitrogen concentrations than conventional chemical-only practices. Furthermore, longitudinal evaluations by Das *et al.* (2024) confirm that organic amendments, including green manure, farmyard manure, and compost, facilitate a sustained and significant increase in N, P, and K availability over time. Collectively, these studies highlight that green manuring acts not only as a direct nutrient source but also as a catalyst for improving the Nutrient Use Efficiency (NUE) of mineral fertilizers through enhanced mineralization and reduced nutrient fixation.

4.2 Biological Properties

The biological vitality of soil, often measured through microbial biomass and enzymatic potential, serves as a sensitive indicator of long-term soil health and ecosystem sustainability. Recent research consistently demonstrates that green manuring (GM) acts as a primary substrate for microbial proliferation. Ma *et al.* (2021) observed that green manure application raised the Soil Microbial Biomass Carbon (SMBC) by 28% compared to control plots, while Li *et al.* (2020) confirmed that combining GM with reduced chemical fertilization significantly enhanced organic matter retention and microbial activity in rice ecosystems. The magnitude of this effect is further amplified when GM is integrated with crop residues. In a rice-wheat system in Northwestern India, Saikia *et al.* (2020) reported that the highest SMBC levels (155.7 $\mu\text{g C/mc}$) were achieved under a combination of wheat straw and green manure (PTRw25+GM), nearly doubling the values found in plots without organic amendments (79.07 $\mu\text{g C/mc}$). Furthermore, green manuring significantly stimulates the secretion of extracellular enzymes critical for nutrient cycling. Zhou *et al.* (2020) found that co-incorporating green manure and rice straw maximized the activity of enzymes related to carbon (β -glucosidase), nitrogen (urease), and phosphorus (phosphatase) cycles. Similarly, Ma *et al.* (2021) reported a 14% to 39% increase in phosphatase, urease, catalase, and invertase activities following GM application. These biological improvements are not confined to the surface soil; Ansari *et al.* (2022) demonstrated

that *Sesbania* green manuring (SGM) increased enzymatic activity by 28.3–38.9% in the 0–0.15 m layer and maintained significant increases even in deeper profiles (up to 0.45 m).

Long-term evaluations further underscore the stability of these biological gains. Mishra *et al.* (2023) revealed significantly higher SMBC, microbial biomass nitrogen (SMBN), and dehydrogenase activity (DHA) over a three-year experiment with *Sesbania aculeata*. Most recently, Das *et al.* (2024) observed that long-term organic modules involving Dhaincha and *Leucaena* green leaf manuring resulted in DHA increases of 32.3% to 61.4% across varying soil depths compared to unfertilized controls. Collectively, these studies suggest that green manuring facilitates a robust and diverse soil microbiome, which is essential for efficient nutrient mineralization and the long-term resilience of intensive cropping systems.

4.3 Yield

The ultimate objective of green manuring (GM) is the enhancement of sustainable crop productivity through improved nutrient availability and soil physical health. Recent evidence from Naher *et al.* (2020) demonstrates that leguminous species like *Sesbania aculeata* and *S. rostrata* significantly outperform systems relying solely on synthetic fertilizers in terms of grain yield. This productivity is further maximized through synergistic residue management; Zhou *et al.* (2020) observed that the co-incorporation of green manure with rice straw resulted in the highest yields compared to applying either amendment alone. Quantifying these gains, Irin *et al.* (2021) reported that *S. rostrata* treated

plots achieved an average yield of 4.5 t/ha, representing a 25% increase over chemical-only controls (3.6 t/ha).

The selection of GM species plays a pivotal role in determining yield outcomes, particularly in high-value cropping systems. In the Indo-Gangetic Plains, Singh *et al.* (2021) found that incorporating *S. aculeata* (Dhaincha) into Basmati rice rotations resulted in significantly higher grain and straw yields compared to *Crotalaria juncea* (Sunnhemp) or cowpea. These yield improvements are typically attributed to enhanced growth parameters; Kumar *et al.* (2022) and Naz *et al.* (2023) both noted substantial increases in tiller numbers, grains per spike, and overall harvest index, with rice yields typically rising by 15–30% when GM is integrated with chemical fertilizers.

Long-term sustainability and economic viability are best achieved through Integrated Nutrient Management (INM). A longitudinal study spanning 21 years by Das *et al.* (2024) confirmed that combining organic amendments with inorganic fertilizers (INM) resulted in the highest sustained yields for both rice and wheat. This is supported by recent findings from Kumar and Bordoloi (2024), who demonstrated that incorporating *S. aculeata* or *C. juncea* allows for a 50% reduction in synthetic nitrogen (N) fertilizer without compromising the harvest index or grain yield of wheat. Collectively, these studies highlight that green manuring is not only a biological restorative tool but also a commercially viable strategy for maintaining high-intensity cropping systems with reduced chemical footprints.

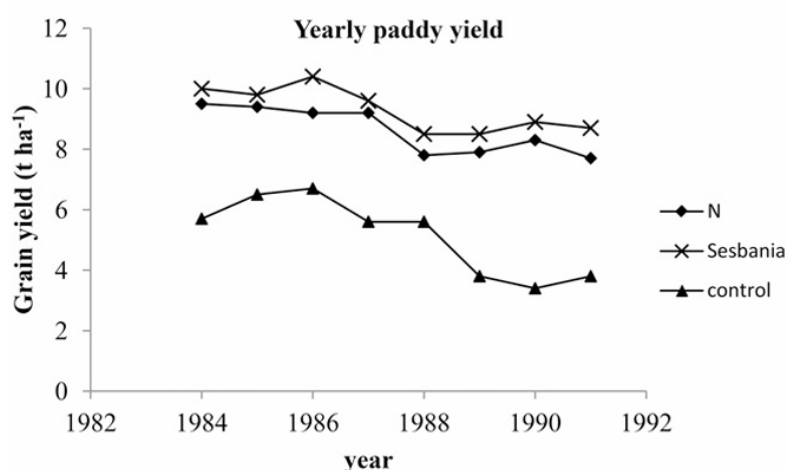


Fig. 1. Long-term (7-year) rice-fallow-rice cropping system

Source: Modified from BRRI (1991) (Naher *et al.*, 2018).

Table 4. Impact of green manure application on the grain yield of major cereal crops

Sr. No.	GM treatment	crop	Yield in GM treatment	Yield in control/RDF	Reference
1.	Sesbania GM to rice and <i>Leucania</i> GLM to wheat	wheat	4.03 t ha ⁻¹	2.63 t ha ⁻¹ (Control)	Das et al. (2024)
2.	Sesbania GM to rice and <i>Leucania</i> GLM to wheat	Rice	3.87 t ha ⁻¹	2.23 t ha ⁻¹ (Control)	Das et al. (2024)
3.	5 tha ⁻¹ <i>gliricidia</i> foliage	Rice	52.08 qha ⁻¹	54.22 qha ⁻¹ NPK (100:50:50)	Chaphale and Badole (1999)
4.	<i>V. unguiculat</i>	Rice	5.13 t ha ⁻¹	3.43 t ha ⁻¹ (Control)	Irin et al. (2021)
5.	<i>Sesbania aculeata</i> +N45	Rice	4.88 t ha ⁻¹	4.51 t ha ⁻¹ (N60)	Islam et al. (2019)
6.	<i>Sesbania aculeata</i> GM, 5 t ha ⁻¹ + 50 % N, 75 kg ha ⁻¹	Wheat	4.81 t ha ⁻¹	4.23 t ha ⁻¹ RDN 150kg ha ⁻¹	Kumar and Bordoloi (2024)
7.	<i>Crotalaria juncea</i> GM, 5 t ha ⁻¹ + 50 % N, 75 kg ha ⁻¹	Wheat	4.58 t ha ⁻¹	4.23 t ha ⁻¹ RDN 150kg ha ⁻¹	Kumar and Bordoloi (2024)
8.	Water hyacinth	Rice	6.53 t ha ⁻¹	5.21 t ha ⁻¹ (Fallow)	Kumar et al. (2022)
9.	<i>Sesbania aculeata</i>	Rice	7.09 t ha ⁻¹	5.21 t ha ⁻¹ (Fallow)	Kumar et al. (2022)
10.	Sudan grass	Rice	5.33 t ha ⁻¹	5.21 t ha ⁻¹ (Fallow)	Kumar et al. (2022)

*GM- Green Manure

In a long-term (7-year) rice-fallow-rice cropping system, paddy dry matter yield was monitored under varying nitrogen regimes: 120 kg ha⁻¹ (irrigated) and 90 kg ha⁻¹ (rainfed) [Fig.1]. For the rainfed crop, soil fertility was augmented annually with 5 t ha⁻¹ of *Sesbania* green manure in addition to standard P and K applications (Naher et al., 2018).

5. Constraints in Adoption of Green Manure Crops

Despite its well-documented ecological benefits, the large-scale adoption of green manuring (GM) remains restricted by significant technological, economic, and operational barriers. Farmers in intensive cropping systems often face a narrow window period between the harvest of one crop and the sowing of the next, making it difficult to allocate the required 6–8 weeks for a non-cash-generating green manure crop. Additionally, the high labour and fuel costs associated with biomass incorporation further discourage its use. In water-scarce or rainfed regions, the unreliability of crop establishment and the risk of nitrogen immobilization due to inadequate moisture for decomposition act as major biophysical deterrents (Mahey et al. 2024). Furthermore, many smallholder farmers remain reluctant to adopt GM due to the absence of immediate economic returns and a lack of technical knowledge regarding location-specific variety selection. Addressing these constraints requires a combination of government seed subsidies, improved extension services, and the development of short-duration varieties that fit seamlessly into existing rotations.

6. Conclusion

Contemporary evidence confirms that green manuring is a key strategy for sustainable intensification and soil restoration. By supplying high-quality organic biomass, green manures improve soil structure, enhance soil organic carbon, reduce bulk density, and strengthen aggregate stability and water-holding capacity. Leguminous green manures provide a substantial nitrogen credit, enabling a 25–50% reduction in synthetic fertilizer use while stimulating microbial biomass and enzymatic activities essential for nutrient cycling. Integrated nutrient management modules that incorporate green manure consistently report 15–30% higher yields in rice–wheat systems than chemical-only practices.

Despite its proven agronomic and ecological benefits, adoption remains constrained by limited cropping windows, seed availability, and labour costs. Future efforts should focus on developing short-duration varieties, improving mechanized incorporation techniques, and introducing policy incentives that recognize soil health services. The adoption of green manuring in different cropping systems and agro-climatic regions can significantly improve soil health, enhance nutrient use efficiency, and reduce reliance on synthetic fertilizers, thereby supporting sustainable agricultural development. Overall, green manuring offers a resilient and scalable pathway to sustain soil fertility, enhance productivity, and promote long-term agricultural sustainability.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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