International Journal of Plant & Soil Science

Volume 38, Issue 2, Page 427-439, 2026; Article no.IJPSS.154403
ISSN: 2320-7035

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

Sahil [a], R S Garhwal [b*], Sumit [c], Ankush Kamboj [d] and Satender Kumar [e]

[a] Department of Soil Science, CCS Haryana Agricultural University, Hisar, Haryana, India.
[b] College of Agriculture (Kaul), CCS Haryana Agricultural University, Hisar, Haryana, India.
[c] Department of Agricultural Economics, CCS Haryana Agricultural University, Hisar, Haryana, India.
[d] Department of Forestry, CCS Haryana Agricultural University, Hisar, Haryana, India.
[e] Division of Crop Improvement, ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i25995

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/154403

Review Article

Received: 18/12/2025
Published: 11/03/2026

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

---

**Corresponding author: E-mail: Rsg.rca2011@gmail.com;*

Cite as: *Sahil, Garhwal, R. S., Sumit, Kamboj, A., & Kumar, S. (2026). The Role of Green Manures in Sustaining Soil Fertility and Crop Productivity: A Comprehensive Review. International Journal of Plant & Soil Science, 38(2), 427–439. https://doi.org/10.9734/ijpss/2026/v38i25995*

sunnhemp (*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 Sunnhemp (*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	*Crotalaria juncea*	2.30	0.50	1.80
2.	Dhaincha	*Sesbania aculeata*	3.50	0.60	1.20
3.	Sesbania	*Sesbania speciosa*	2.71	0.53	2.21
4.	Cowpea	*Vigna sinensis*	1.70	0.28	1.25
5.	Mungbean	*Vigna radiata*	2.21	0.26	1.26
II.	**Green Leaf Manure**				
6.	Gliricidia	*Gliricidia sepium*	2.76	0.28	4.60
7.	Pongamia	*Pongamia pinnata*	3.31	0.44	2.39
8.	Neem	*Azadirachta indica*	2.83	0.28	0.35
9.	Gulmohar	*Delonix regia*	2.76	0.46	0.50
10.	Peltophorum	*Peltophorum pterocarpum*	2.63	0.37	0.50
III.	**Weeds**				
11.	Parthenium	*Parthenium hysterophorus*	2.68	0.68	1.45
12.	Water hyacinth	*Eichhornia crassipes*	3.01	0.90	0.15
13.	Trianthema	*Trianthema portulacastrum*	0.64	0.43	1.30
14.	Ipomoea	*Ipomoea carnea*	2.01	0.33	0.40
15.	Calotropis	*Calotropis gigantea*	2.06	0.54	0.31
16.	Cassia	*Cassia fistula*	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 allopathic 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	*Crotalaria juncea*	Wet	21.2	91
2.	Dhaincha	*Sesbania aculeata*	Wet	20.2	86
3.	Green gram	*Vigna radiata*	Wet	8.0	42
4.	Cowpea	*Vigna sinensis*	Wet	15.0	74
5.	Guar	*Cyamopsis tetragonoloba*	Wet	20.0	68
6.	Khesari	*Lathyrus sativus*	Dry	12.3	66
7.	Berseem	*Trifolium alexandrinum*	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 *Leucania* GLM to wheat	329.3	37.6	454.1	Control	283.5	30.6	395.0	Das *et al*. (2024)
2	5 tha^{-1} *gliricidia* 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 *et al*. (2022)
4	*Sesbania aculeata* + 50% RDN	235.2	16.2	310.3	100% RDN	232.5	14.4	280.6	Kumar *et al*. (2012)
5	Sunhemp + 75% RDF	208	67	289	100% RDF	175	59	263	Sandhya Rani *et al*. (2022)
6	Dhaincha + 75% RDF	210	68	291	100% RDF	175	59	263	Sandhya Rani *et al*. (2022)
7	Green gram + 75% RDF	193	62	272	100% RDF	175	59	263	Sandhya Rani *et al*. (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 μg Cmic) 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 μg Cmic). 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.

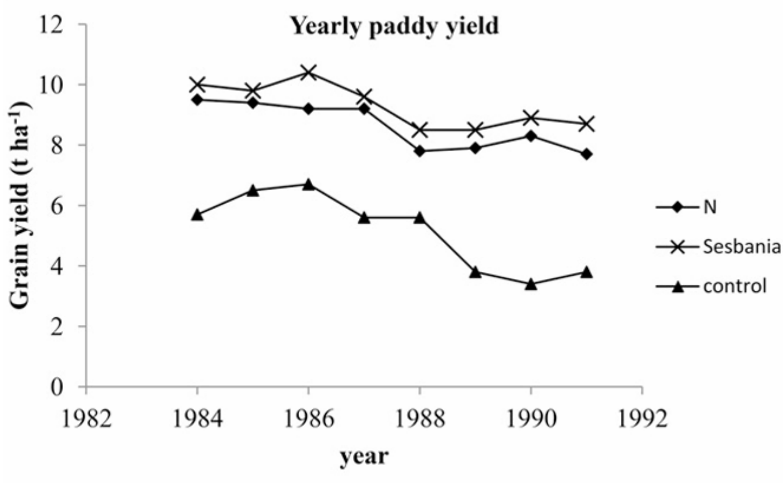

Fig. 1. Long-term (7-year) rice-fallow-rice cropping system
Source: Modified from BRRI (1991) (Naher et al., 2018).

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 *Leucania* 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 *Leucania* GLM to wheat	Rice	3.87 t ha^{-1}	2.23 t ha^{-1} (Control)	Das *et al*. (2024)
3.	5 tha^{-1} *gliricidia* foliage	Rice	52.08 qha^{-1}	54.22 qha^{-1} NPK (100:50:50)	Chaphale and Badole (1999)
4.	*V. unguiculat*	Rice	5.13 t ha^{-1}	3.43 t ha^{-1} (Control)	Irin *et al*. (2021)
5.	*Sesbania aculeata*+N45	Rice	4.88 t ha^{-1}	4.51 t ha^{-1} (N60)	Islam *et al*. (2019)
6.	*Sesbania aculeata* 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.	*Crotalaria juncea* 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.	*Sesbania aculeata*	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.

References

Abid, M., & Lal, R. (2009). Tillage and drainage impact on soil quality: II. Tensile strength of aggregates, moisture retention and water infiltration. *Soil and Tillage Research*, 103(2), 364–372. https://doi.org/10.1016/j.still.2008.11.004

Ansari, M. A., Choudhury, B. U., Layek, J., Das, A., Lal, R., & Mishra, V. K. (2022). Green manuring and crop residue management: Effect on soil organic carbon stock, aggregation, and system productivity in the foothills of Eastern Himalaya (India). *Soil and Tillage Research*, 218, 305–318. https://doi.org/10.1016/j.still.2022.105318

Asghar, W., & Kataoka, R. (2021). Green manure incorporation accelerates enzyme activity, plant growth, and changes in the fungal community of soil. *Archives of Microbiology*, 204(1). https://doi.org/10.1016/j.still.2022.105318

Brito, L. F., Galvão, J. C. C., Giehl, J., Coellho, S. P., Campos, S. d. A., Barrella, T. P., Santos, T. R. d., Mendonça, B. F., & Jesus, É. V. d. (2019). Decomposition of cover crop mulch and weed control under a no-till system for organic maize. *Bioscience Journal*, 35(5), 1339–1348. https://doi.org/10.14393/BJ-v35n5a2019-41836

BRRI (Bangladesh Rice Research Institute). (1991). *Annual internal review report 1991: Soil and fertilizer management*. Gazipur, Bangladesh: Bangladesh Rice Research Institute.

Carter, M. S., Sorensen, P., Petersen, S. O., Ma, X., & Ambus, P. (2014). Effects of green manure storage and incorporation methods on nitrogen release and N_2O emissions after soil application. *Biology and Fertility of Soils*, 50, 1233–1246. https://doi.org/10.1007/s00374-014-0936-5

Chaphale, S. D., & Badole, W. P. (1999). Effect of green manuring and NPK combinations on soil health and yield of rice (*Oryza sativa*). *Indian Journal of Agronomy*, 44(3), 443–449. https://doi.org/10.59797/ija.v44i3.3532

Das, B., Pooniya, V., Shivay, Y. S., Zhiipao, R. R., Biswakarma, N., Kumar, D., & Critykar, J. (2024). Twenty-one years' impact of using organic amendments on the productivity of rice–wheat rotation and soil properties. *Field Crops Research*, 309, 109–118. https://doi.org/10.1016/j.fcr.2024.109311

Dubey, L., Dubey, M., & Jain, P. (2015). Role of green manuring in organic farming. *Plant Archives*, 15(1), 23–26. https://www.plantarchives.org

Ganapathi, & Ullasa, M. Y. (2019). Effect of insitu green manuring on soil fertility, growth and yield of rice under organic farming. *The Journal of Research ANGRAU*, 47(1), 28–39. https://www.jorangrau.org/index.php/jorangrau/article/view/103

Giller, K. E., & Cadisch, G. (1995). Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil*, 174, 255–277. https://doi.org/10.1007/BF00032251

Halling, M. A., Topp, C. F. E., & Doyle, C. J. (2004). Aspects of the productivity of forage legumes. *Grass and Forage Science*, 59, 331–344. https://doi.org/10.1111/j.1365-2494.2004.00435.x

Høgh-Jensen, H. (2003). The effect of potassium deficiency on growth and N_2 fixation in *Trifolium repens*. *Physiologia Plantarum*, 119, 440–449. https://doi.org/10.1034/j.1399-3054.2003.00189.x

Irin, I. J., Biswas, P. K., & Khan, M. A. (2021). Efficacy of different green manuring crops to soil fertility, yield and seed quality of T. aman rice. *Asian Journal of Medical and Biological Research*, 7(4), 298–311. https://doi.org/10.3329/ajmbr.v7i4.57610

Islam, M. M., Urmi, T. A., Rana, M. S., Alam, M. S., & Haque, M. M. (2019). Green manuring effects on crop morpho-physiological characters, rice yield and soil properties. *Physiology and Molecular Biology of Plants*, 25, 303–312. https://doi.org/10.1007/s12298-018-0624-2

Joshna, A., Bokado, K., & Barkha. (2024). Green manure for sustainable crop production: A review. International Journal of Environment and Climate Change, 14(5), 147–156. https://doi.org/10.9734/ijecc/2024/v14i54177

Kaul, A., Kaur, R., Choudhary, A. K., Sepat, S., Dass, A., & Scientists, S. (2015). Importance of green manuring in sustainable agriculture. *Popular Kheti*, 2(2).

Kaur, H., Brar, G. S., & Shete, P. (2019). A review on different weed management approaches. *International Journal of Current Microbiology and Applied Sciences*, 8(08), 2854–2859. https://doi.org/10.20546/ijcmas.2019.808.328

Kumar, R., & Bordoloi, N. (2024). Combined impact of reduced N fertilizer and green manure on wheat yield, nitrogen use efficiency and nitrous oxide (N_2O) emissions reduction in Jharkhand, eastern India. *Field Crops Research*, 318, 109591. https://www.sciencedirect.com/science/article/pii/S0378429024003447

Kumar, S., Dahiya, R., Kumar, P., Jhorar, B. S., & Phogat, V. K. (2012). Long-term effect of organic materials and fertilizers on soil properties in pearl millet–wheat cropping system. *Indian Journal of Agricultural Research*, 46(2), 161–166. https://arccjournals.com/journal/indian-journal-of-agricultural-research

Kumar, V., Singh, M. K., Raghuvanshi, N., & Sahoo, M. (2022). Rice (*Oryza sativa* L.)–baby corn (*Zea mays* L.) cropping system response to different summer green manuring and nutrient management. *Agronomy*, 12(9), 2105–2112. https://doi.org/10.3390/agronomy12092105

Lathwell, D. J. (1990). *Legume green manures*. TropSoils Bulletin Number 90–01, Soil Management Collaborative Research Support Program, North Carolina State University, Raleigh, North Carolina.

Li, Z., Zhang, X., Xu, J., Cao, K., Wang, J., Xu, C., & Cao, W. (2020). Green manure incorporation with reductions in chemical fertilizer inputs improves rice yield and soil organic matter accumulation. *Journal of Soils and Sediments*, 20, 2784–2793. https://doi.org/10.3390/agronomy12092105

Liu, Y. Y., Wu, L. H., Baddeley, J. A., & Watson, C. A. (2011). Models of biological nitrogen fixation of legumes: A review. Agronomy for Sustainable Development. https://doi.org/10.1051/agro/2010008

Ma, D., Yin, L., Ju, W., Li, X., Liu, X., Deng, X., & Wang, S. (2021). Meta-analysis of green manure effects on soil properties and crop yield in northern China. *Field Crops Research*, 266, 108–146. https://doi.org/10.1016/j.fcr.2021.108146

Mahey, H. K., Sharma, K., Singh, A., Rampal, V. K., & Kaushik, P. (2024). Green manuring crop plants: Harnessing natural processes to enhance soil health and promote sustainable agricultural practices. *Preprints*.https://doi.org/10.20944/preprints202406.0340.v1

Mandal, U. K., Singh, G., Victor, U. S., & Sharma, K. L. (2003). Green manuring: Its effect on soil properties and crop growth under rice–wheat cropping system. *European Journal of Agronomy*, 19(2), 225–237. https://doi.org/10.1016/S1161-0301(02)00037-0

Mishra, J., Biswal, S., Pattnaik, S., Sahoo, S., Mohapatra, S., Pradhan, J., & Swain, S. (2023). Soil organic and enzymatic properties as influenced by green manuring and establishment methods in rice-rice system. *International Journal of Plant and Soil Science*, 35(2), 108–113. https://doi.org/10.9734/IJPSS/2023/v35i22920

Naher, U. A., Choudhury, A. T., Biswas, J. C., Panhwar, Q. A., & Kennedy, I. R. (2020). Prospects of using leguminous green manuring crop *Sesbania rostrata* for supplementing fertilizer nitrogen in rice production and control of environmental pollution. *Journal of Plant Nutrition*, 43(2), 285–296. https://doi.org/10.1080/01904167.2019.1671012

Naz, A., Rebi, A., Naz, R., Akbar, M. U., Aslam, A., Kalsom, A., & Zhou, J. (2023). Impact of green manuring on health of low fertility calcareous soils. *Land*, 12(3), 546. https://doi.org/10.3390/land12030546

Pandey, V., & Srivastava, A. (2021). Effect of integrated use of organic manures and chemical fertilizers under soil test crop response approach on soil properties and yield of maize (*Zea mays* L.). *International Journal of Plant & Soil Science*, 33(10), 40–47. https://doi.org/10.9734/ijpss/2021/v33i1030471

Patra, A., Singh, R. P., Kundu, M. S., Kumar, G., Malkani, P., Singh, B. K., ... & Mukherjee, S. (2023). Green manuring: A sustainable approach for soil health improvement. *Agriculture & Food E-Newsletter*, 5(04), 198–201.

Prajapati, S. K., Dayal, P., Kumar, V., & Gairola, A. (2023). Green manuring: A sustainable path to improve soil health and fertility. *Int. J*, 1, 24–33. https://doi.org/10.5281/zenodo.10049824

Rautaray, S. K., Pradhan, S., Mohanty, S., Dubey, R., Raychaudhuri, S., Mohanty, R. K., & Ambast, S. K. (2020). Energy efficiency, productivity and profitability of rice farming using *Sesbania* as green manure-cum-cover crop. *Nutrient Cycling in Agroecosystems*, 116, 83–101. https://doi.org/10.5281/zenodo.10049824

Riesinger, P., & Herzon, I. (2010). Symbiotic nitrogen fixation in organically managed red clover-grass leys under farming conditions. *Acta Agriculturae Scandinavica - Soil and Plant Science*, 60, 517–528. https://doi.org/10.1080/09064710903233870

Saikia, R., Sharma, S., Thind, H. S., & Singh, Y. (2020). Tillage and residue management practices affect soil biological indicators in a rice–wheat cropping system in north-western India. *Soil Use and Management*, 36(1), 157–172. https://bsssjournals.onlinelibrary.wiley.com/doi/abs/10.1111/sum.12544

Sandhya Rani, Y., Jamuna, P., Triveni, U., Patro, T. S. S. K., & Anuradha, N. (2022). Effect of in situ incorporation of legume green manure crops on nutrient bioavailability, productivity and uptake of maize. *Journal of Plant Nutrition*, 45(7), 1004–1016. https://doi.org/10.1080/01904167.2021.2005802

Sharifi, M., Julia, R., Hammermeister, A. M., Alam, M. Z., & Mackey, T. (2016). Effect of cover crops on yield and leaf nutrient concentrations in an organic Honeycrisp apple (*Malus domestica* 'Honeycrisp') orchard in Nova Scotia, Canada. *HortScience*, 51(11), 1378–1383. https://doi.org/10.21273/HORTSCI.51.11.1378

Sharma, A. R., & Mittra, B. N. (1988). Effect of green manuring and mineral fertilizer on growth and yield of crops in rice-based cropping on acid lateritic soil. *The Journal of Agricultural Science*, 110(3), 605–608. https://www.cambridge.org/core/journals/the-journal-of-agricultural-science/article/effect-of-green-manuring-and-mineral-fertilizer-on-growth-and-yield-of-crops-in-ricebased-cropping-on-acid-lateritic-soil/

Singh, A., Shivay, Y. S., Prasanna, R., & Kumar, A. (2021). Basmati rice quality enhancement by zinc fertilization and green manuring on a sub-tropical inceptisol in Indo-Gangetic plains of India. *Indian Journal of Agriculture Sciences*, 13(125), 105–113. https://doi.org/10.5539/jas.v13n5p125

Singh, P., Singh, A., Singh, V. K., & Singh, O. (2023). Green manuring for sustainable agriculture. In *Encyclopedia of Green Materials* (pp. 1–6). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-16-4921-9_261-1

Singh, Y., Khind, C. S., & Singh, B. (1991). Efficient management of leguminous green manures in wetland rice. *Advances in Agronomy*, 45, 135–189. https://doi.org/10.1016/S0065-2113(08)60040-1

Soil Science Society of America. (1997). *Glossary of soil science terms*. SSSA, Wisconsin DC.

Sultani, M. I., Gill, M. A., Anwar, M. M., & Athar, M. (2007). Evaluation of soil physical properties as influenced by various green manuring legumes and phosphorus fertilization under rain fed conditions. *International Journal of Environmental Science & Technology*, 4, 109–118. https://doi.org/10.1007/BF03325968

Tejada, M., Gonzalez, J. L., García-Martínez, A. M., & Parrado, J. (2008). Effects of different green manures on soil biological properties and maize yield. *Bioresource Technology*, 99(6), 1758–1767. https://doi.org/10.1016/j.biortech.2007.03.052

Unkovich, M. J., & Pate, J. S. (2000). An appraisal of recent field measurements of symbiotic N_2 fixation by annual legumes. *Field Crops Research*, 65, 211–228. https://doi.org/10.1016/S0378-4290(99)00088-X

Zhou, G., Gao, S., Lu, Y., Liao, Y., Nie, J., & Cao, W. (2020). Co-incorporation of green manure and rice straw improves rice production, soil chemical, biochemical and microbiological properties in a typical paddy field in southern China. *Soil and Tillage Research*, 197, 104–128. https://doi.org/10.1016/j.still.2019.104499

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/154403