



REVIEW ARTICLE

# Revitalising soil health through green manuring: A sustainable approach

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Received: 24 February 2026; Accepted: 20 April 2026; Available online: Version 1.0: 01 July 2026

**Cite this article:** Rathika S, Ramesh T, Jeyasrinivas R, Nageswari R, Satheeshkumar N, Sanjaykumar T. Revitalising soil health through green manuring: A sustainable approach. Plant Science Today. 2026; 13(sp5): 1-11. <https://doi.org/10.14719/pst.14220>

## Abstract

The deterioration of soil quality has been a severe problem in recent years. The employment of Green Revolution techniques has raised production to an excessive degree by using a vast quantity of nitrogen (N) fertiliser. However, these techniques have led to soil quality degradation and land deterioration which harms human health and environment. Much of these losses to the environment are nitrate leaching to groundwater and greenhouse gas emissions. As agrochemicals accumulate in the soil, soil quality deteriorates, resulting in lower soil fertility. Green manure refers to crops that are cultivated and incorporated into the soil to improve soil fertility, enhance soil structure, increase water-holding capacity and enrich nutrient content. It can help restore soil fertility, minimise soil erosion and improve soil physico-chemical characteristics. Also, it has the potential to partially substitute the inorganic N fertilisers under specific conditions, thereby reducing the chemical input in agriculture. They are also improving the soil's physical and biological properties. As a result, it also aids in plant protection. Green manuring function in sustainable soil health is examined through several research papers and research initiatives.

**Keywords:** green manure; organic matter; physico-chemical properties; soil fertility

## Introduction

Multiple forms of natural resource degradation threaten the sustained productivity of limited land resources. Soil is the fundamental natural resource for crop production. However, its quality is declining due to the uncontrolled use of agro chemicals to meet the demands of a growing global population, leading to reduced soil fertility and crop yields. Nevertheless, the use of chemicals to improve soil fertility to support effective crop production faces challenges such as the high costs of fertilisers as well as the availability of fertilisers (1). In soil, organic content declines because of continuous cultivation, causing the detachment of nutrients from the plant's rhizosphere. Green manuring is one of the techniques, which involves the use of fertility-building crops, which are used to improve the fertility of soil to boost the development of the subsequent crop by replenishing humus, an essential component for maintaining soil quality by increasing the supply of nitrogen as well as promoting the development of microorganisms (2). Green manure plants are non-polluting, less toxic and biodegradable, which means that they do not leave any residue in the soil, water, or air, nor in the food products that are stored. Hence, green manuring is

considered an essential component of sustainable agricultural systems. Green manuring acts as an organic nutrient source, which provides the nutrients needed by the plants and improves the biological activity of the soil (3). It also helps in the formation of soil aggregates and organo-mineral complexes (4). Rice-growing areas such as Andhra Pradesh, Uttar Pradesh, Karnataka, Punjab and Orissa account for 41 %, 16 %, 11 %, 6 % and 5 % of the total area under green manuring, respectively (5). The productivity of the traditional rice-wheat cropping system in the Indo-Gangetic Plains has declined due to continuous nutrient mining and limited root-zone nutrient replenishment. In these situations, green manuring, which helps soil in the improvement of the health by improving the organic content as well as the nitrogen content, can be a way to solve the problems in fertility of the soil due to various cropping system (6). Unlike synthetic nitrogen (N) fertilisers, leguminous green manure crops offer a promising renewable source of biochemically fixed N as well as the capacity to fix and add large amounts of C to cropping systems. Therefore, green manuring is a highly beneficial practice to enhance soil health. Additionally, it improves soil texture by adding humus or organic matter, which is needed to improve soil productivity (7). Organic matter obtained from green manuring binds loose particles in sandy soils.

Consequently, it improves the soil's ability to hold water. Additionally, it improves conditions to increase the count of soil beneficial microorganisms.

The crops used in green manuring divided into two types depending on the nitrogen fixation ability such as leguminous green manure and non-leguminous green manure.

The former group fixes atmospheric nitrogen and incorporates it into the soil (e.g., sunnhemp, dhaincha, green gram, cowpea, black gram, bean, sweet clover, alfalfa, pea and soybean). The latter group lacks nitrogen-fixing ability and primarily functions as cover crops (such as berseem, buckwheat, chicory, mustard, turnips, ryegrass, oats, barley and rye).

The purpose of the present review is to conduct a critical examination of the impact of green manure on soil health and crop productivity. This review highlights the ways through which green manure crops improve soil fertility in terms of organic matter incorporation, biological nitrogen fixation and physical characteristics of the soil. The scope of the review also includes an assessment of different types of green manure crops and their relevance in various cropping systems.

### Need of green manuring

Due to the need for higher agricultural productivity, farmers are opting for intensive and diversified crops, which have contributed greatly towards soil fertility loss. Soil fertility decreases when there is continuous farming but without sufficient provision of nutrients to soils, causing the depletion of soil fertility. Such a phenomenon affects the chemical composition, organic matter, poor soil structure and nutritional composition of soil (6). Besides the increased cost and unavailability of inorganic fertilisers, especially in developing countries, they can be subjected to adulteration. There is also an increased demand for high-yielding varieties or hybrid crop species, which require higher amounts of nutrients

than other crops. Sole dependence on chemical fertilisers become increasingly difficult, economically unfeasible and environmentally unsound (6). Furthermore, modern agriculture has become highly mechanised, resulting in the reduction of draft animals on farms. Traditionally, farmyard manure was one of the primary sources of organic materials. Shortage of organic amendments to farms has further exacerbated the reduction of soil fertility and microbial population in soil. In this regard, green manuring becomes an important practice in maintaining soil productivity (6).

### Physical properties of soil

Soil physical properties are essential for agricultural production and sustainable soil utilisation and potential indicators for summing up soil quality and productivity. Green manuring and regenerative organic amendments have a deep positive impact on soil physical properties, primarily because of the increased organic input and the biological restructuring of soil aggregates. There is ample evidence to show that the incorporation of green manure crops like *Sesbania rostrata* Bremek. & Oberm, *Crotalaria juncea* L., cowpea and mungbean has been effective in improving soil aggregation, decreasing bulk density and increasing porosity (6–10). The root systems of legume green manure crops are also instrumental in the disruption of compacted layers and the formation of biopores, thus increasing water infiltration and aeration (11, 12).

Addition of *S. rostrata* and *C. juncea* increases the rate of infiltration, prevents run-off and erosion, as well as the removal of surface compaction and hard pan (13). On an average, the green manuring practice reduces the bulk density of soil by 5 %, increases porosity by 8 %, as well as macro and mesopores by 28 % (14). The beneficial effects of green manuring on soil properties are illustrated in Fig. 1 (6). Green manuring with *Sesbania* improves soil structural properties through the production of cementing agents by microbial activity. It also

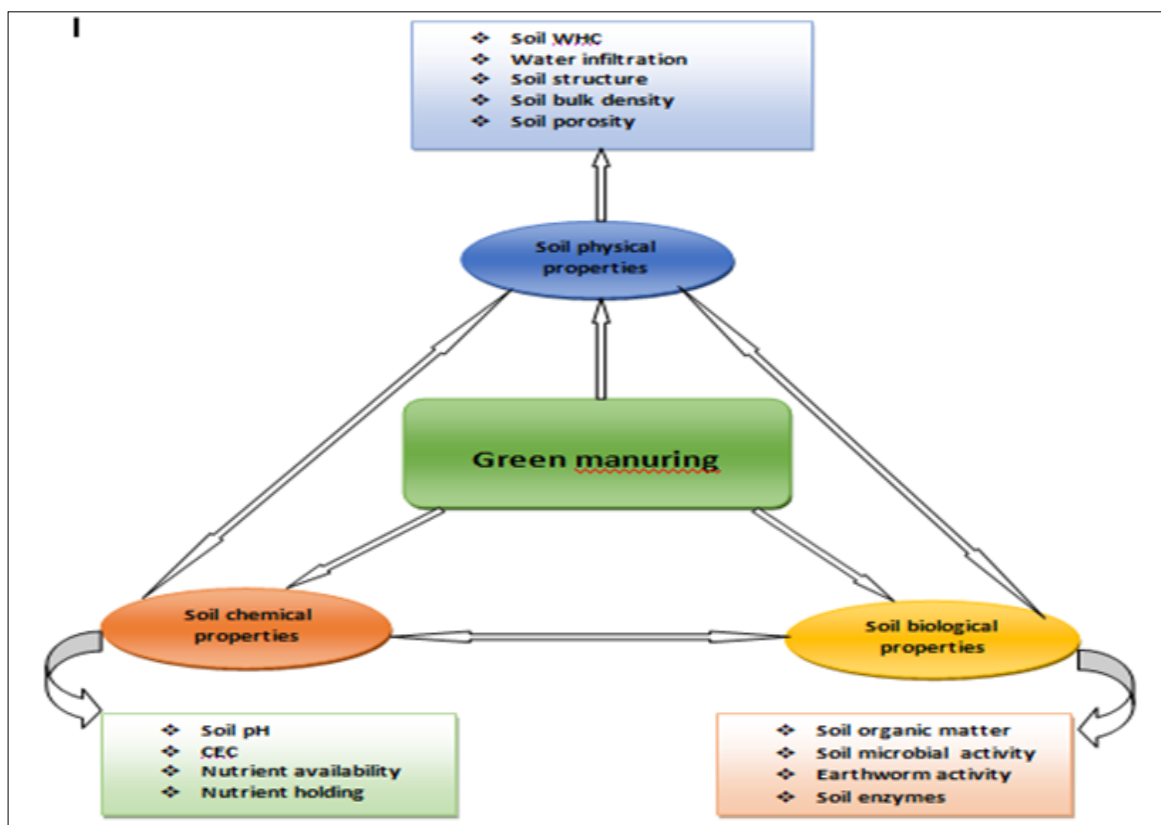


Fig. 1. Effect of leguminous green manuring on soil properties (6).

promotes the aggregation of primary soil particles and micro-aggregates into macro-aggregates through root enmeshment. This effect is attributed to its deep root system, which enhances macrospore formation (15).

Green manuring also improves the structure of the soil, allowing more air to meet the soil, thus improving drainage. Green manuring also helps the sandy soil retain more water, as it does not drain as quickly as before (16). Green manuring reduces soil erosion, both wind and water, as it acts as a cover crop (3). The exudate secreted by the roots of the green manure crop supplies the microorganisms with food, causing them to produce gums that act as an adhesive, sticking the soil together (17). As a result, it reduces the number of cultivations required and improves soil tilth (17).

The green manure biomass is also helpful in the formation of stable macro aggregates as it binds the soil particles through the action of polysaccharides and humic substances released during the decomposition process (18, 19). The improvement in soil structure also makes the soil less prone to crusting and compaction, particularly in intensively cropped or rice-based systems (20, 21). In degraded areas, green manures can be considered as a remedial measure that improves soil friability and tilth (22, 23).

The use of cover crops as green manures can greatly reduce runoff and soil erosion due to their ability to protect the soil and improve aggregate stability (24, 25). Adding green manure residues to the soil also improves saturated hydraulic conductivity (26, 27). In general, green manuring practices promote long-term sustainability through improvements in soil physical properties (28, 29).

Recent breakthroughs further reinforce the importance of micronutrient-enriched organic amendments and nature farming systems in enhancing the physical properties of soil. Micronutrient-enriched organics (30), enhance the formation of stable aggregates through humic-micronutrient interactions, leading to improved structural stability and infiltration. Natural farming practices

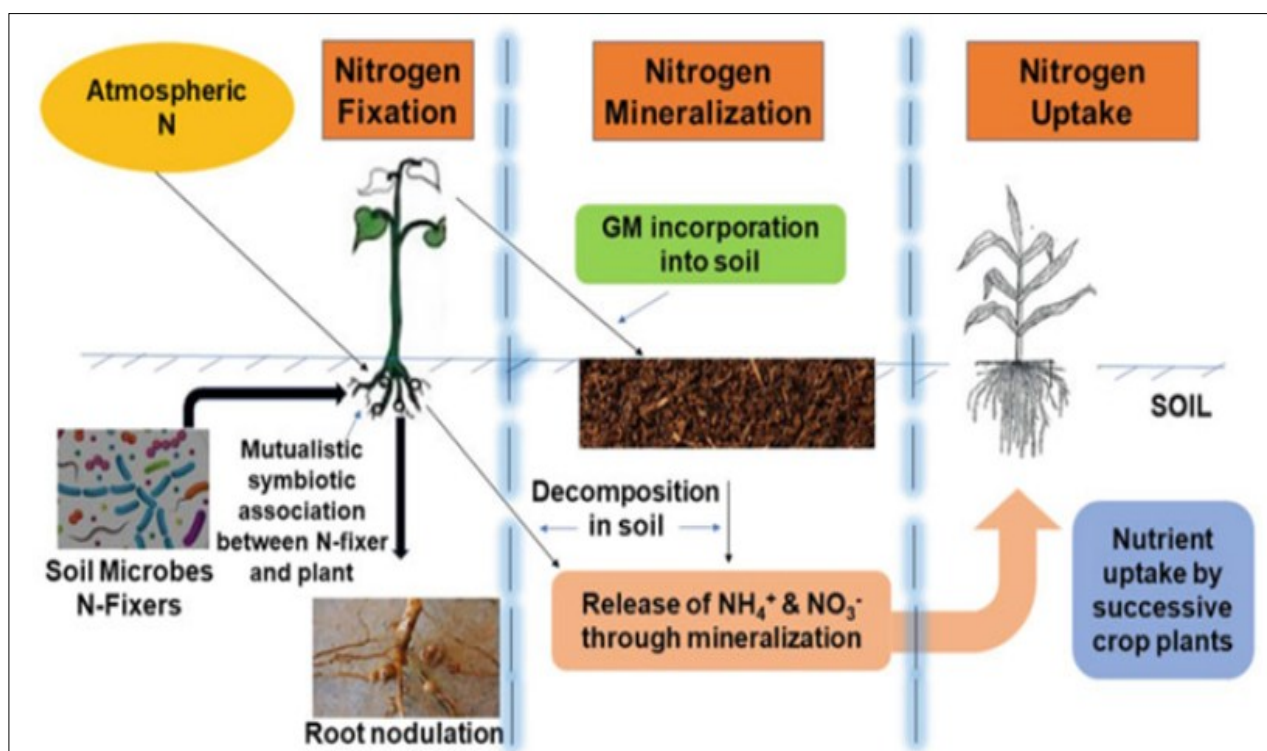
involving fermented liquid manures and biomass mulches also help in minimising soil compaction and improving soil friability (31). In hill and mountain agroecosystems, green manuring and agroecological restoration practices improve soil root depth and erosion risk reduction (32). In addition, eco-friendly fertilisers produced from microbial inoculants improve pore interconnectivity and soil permeability (33), while organic farming systems in temperate and subtropical climates show substantial improvements in water retention capacity due to continuous organic amendment (34).

Zero-landfill approaches involving recycled agricultural residues help in improving soil structure and minimising surface sealing (35). Indigenous agroforestry-green manure systems in the Sikkim Himalayas further illustrate improvements in aggregate formation and soil stability due to continuous organic biomass addition (36). Collectively, these studies emphasise the role of organic and regenerative practices in improving soil physical properties across diverse agroecosystems.

### Chemical properties of soil

Green manuring increases the fertility of the soil through enhanced nutrient pools, solubility and soil chemical reactions. Legume green manure crops can fix atmospheric nitrogen, thus making it available in higher quantities in the soil, but they also can mobilise phosphorus, potassium, calcium, magnesium and micronutrients (9, 37, 38). Green manure addition can act as a soil-acidifying agent by increasing soil organic carbon and microbial activity, which may gradually reduce soil pH. It favours the crop's nutrient availability. Green manure crops have a narrow C:N ratio, favoured by immobilising a higher percentage of applied fertiliser nitrogen and then slowly releasing the same over a period. Nitrogen enrichment in soil by fixation and mineralisation is illustrated in Fig. 2 (39, 40). Sunnhemp appears to be a more efficient green manure crop than other legume crops regarding chemical property improvement and improving soil properties.

In addition to that, carbonic acid, which is a product of the



**Fig. 2.** Nitrogen enrichment in soil by fixation and mineralisation (39, 40).

decomposition of carbon dioxide, which produces the binding material in the soil. However, the effect of other legume species on the soil's chemical properties as green manure may vary. It is attributed to the chemical composition of each legume species (41). The soil binding material results from organic matter decomposition, which produces carbon dioxide that dissolved and formed carbonic acid. The acid consequently reduces the soil's pH, hence increasing calcium carbonate minerals solubility (42). Green manure, especially legume, has N and a low C:N ratio, hence minimising the problem of the immobilised available inorganic N on the steps of decomposition. In addition to that, the biomass produced with the addition of green manure against soil acidification, acts as a buffering agent (3).

This decomposition of green manure residues ends in the formation of organic acids, which in turn helps in the solubilisation of unavailable nutrients such as phosphorus (P), zinc (Zn) and iron (Fe) (10, 43). Organic acids also help in lowering the pH of the soil as well as reducing the sodicity of sodic soils (6, 44). Various studies have proven that green manures increase the soil cation exchange capacity along with improving base saturation as well as the exchangeable calcium (Ca) and magnesium (Mg) content of the soil because of high organic content of green manures (11, 45).

In rice-based systems, the green manures and fertiliser together improves nutrient turnover and maintains soil chemical equilibrium (46, 47). Long-term studies also verify the improvement in buffering capacity and nutrient leaching losses in green manure-treated soils (48). Therefore, green manuring is a reliable method for improving and maintaining soil fertility in crop rotation systems (29, 49).

Micronutrient-fortified organics are also being increasingly acknowledged for their role in improving soil chemical properties. According to previous study, bioactive organics fortified with Fe, Zn, manganese (Mn) and boron (B) work significantly in improving the solubility and chelation of nutrients, thereby improving micronutrient availability (30). Natural and organic farming practices have been found to have lower soil acidity and higher cation exchange capacity because of the continuous accumulation of organic colloids (31, 34). Nature-based restoration in hill ecosystems indicate higher base saturation and improved buffering capacity in degraded acidic soils after the integration of green manure (32).

Eco-friendly microbial fertilisers further accelerate the rates of nutrient transformation and carbonic acid formation, thereby improving Ca and Mg mobilisation (33). Conventional agroforestry-based systems in Himalayan soils also indicate higher mineral weathering and nutrient release with the integration of green manure crops and leaf litter (36). Organic nutrient enrichment methods also indicate higher phosphorus availability and micronutrient solubilisation through organic acid exudation (50). These findings collectively reinforce and expand current understanding of green manure-mediated improvements in soil chemical fertility.

### Biological properties of soil

Biological improvement is one of the most significant and well-documented effects of green manuring. Adding fresh organic matter promotes microbial development, enhances enzyme activity, accelerates nutrient turnover and improves soil biodiversity (9, 18). Green manuring promotes microbial activity by supplying fresh organic carbon that serves as an energy source for soil microflora and supports new microbial biomass

formation (51, 52).

From a microbial perspective, incorporating legume-based green manures offers two key advantages: (i) first, these manures supply microbes with nutrient-dense organic matter, enabling them to break down complex plant residues into forms readily accessible to crops (ii) second, it enriches the diversity of microbes within the soil environment (53). Legume green manures, being high in N and available carbon (C), support the rapid growth of microbes, thereby increasing microbial biomass (both carbon and nitrogen) and enhance enzyme activities like urease, dehydrogenase, phosphatase and  $\beta$ -glucosidase (19, 22). Green manuring with residues of *Trifolium pratense* L. improved the microbial biomass of soil and dehydrogenase, urease,  $\beta$ -glucosidase, phosphatase and arylsulfatase performance in soil (54).

As green manure decomposes, it triggers a series of biochemical reactions that help break down diverse organic compounds (55). Green manures enhance microbial populations and soil enzyme activities through root exudation and improved nutrient transformation processes (56). By supplying carbon-rich organic nutrients, green manures support microbial multiplication and diversify microbial communities, leading to the conversion of locked nutrients in plant residues into forms crops can absorb.

Adding green manure substantially elevates the populations of beneficial soil microbes such as fungi, bacteria and actinomycetes (16), which are responsible for the nutrient cycling processes in soil (57, 58). The enhanced biological nitrogen fixation, both symbiotic and associative, leads to an increase in microbial interactions (37, 59). In addition, green manures reduce soil-borne pathogens due to the increased competition and antagonistic effects of beneficial microbes (60, 61).

The addition of green manures to soil increases the complexity of soil food webs by promoting earthworm populations, which in turn increase nutrient mineralisation and soil structure (45, 62). Therefore, integrating green manures into cropping systems strengthens the biological health of soils, enhancing both sustainability and productivity.

Recent investigations highlight that micronutrient-fortified organic inputs significantly stimulate beneficial microbial communities by supplying bioavailable trace elements essential for enzymatic processes (63). Natural farming systems enhance soil biological health by reducing chemical residues that suppress soil microbiota, leading to increased microbial biomass and enzymatic activities (31, 34). In nature-based restoration frameworks, green manure species enhance soil biodiversity by supporting diverse functional microbial groups, improving biological nitrogen fixation and decomposition pathways (32).

Microbial-based eco-fertilisers enhance population growth-promoting rhizobacteria and mycorrhizal fungi of plant (33). Agroforestry-green manure systems in traditional Himalayan farming create microhabitats rich in fungal hyphae and actinomycetes due to rich litter deposition (36). Studies in African smallholder systems emphasise that legume-based biological nitrogen fixation remains the backbone of sustainable soil bioprocesses (64). Regenerative and permaculture-based systems greatly enrich microbial network complexity, enhancing soil ecological functioning (65). These findings collectively demonstrate that modern organic and regenerative practices further enhance the biological benefits associated with green manuring.

## Nitrogen contribution

Nitrogen is vital for plant development, yet it remains one of the most challenging nutrients to regulate effectively within cropping systems. Leguminous green manure crop generally increases the N level by atmospheric nitrogen fixation. Fertiliser use efficiency is improved by incorporating green manure crops. Nitrogen fixing leguminous crops are preferred as green manure. They reduce external inputs for crops and enhance the soil internal resources availability for the successful cultivation of major crops (66). In addition, it is reported that optimum spacing of 60 x 45 cm in dhaincha improved the plant height, more branches and nodules per plant for nitrogen fixation (67).

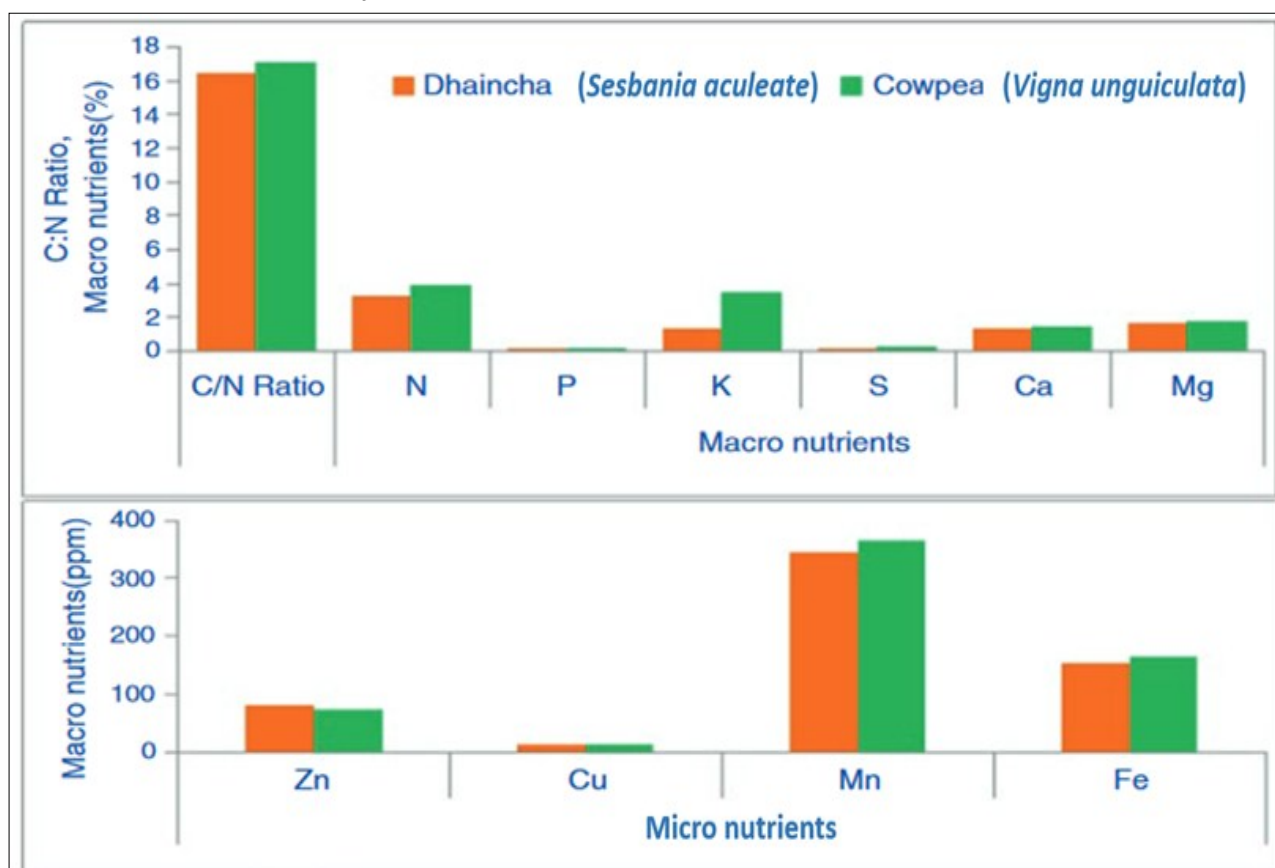
Incorporating dhaincha (*Sesbania aculeata* L.) as green manure can supply between 60 and 90 kg ha<sup>-1</sup> nitrogen to the soil. Leguminous species are highly effective green manures because they convert atmospheric nitrogen into forms that enrich the soil's nitrogen reserves (68). The incorporation of green manure triggers shifts among soil N forms such as microbial biomass dissolved organic N and mineral N resulting in alterations in soil N pools. It is widely acknowledged that maintaining crop cover over the winter is one of the most effective ways of preventing nitrate leaching (4). Nitrogen losses from soil can be minimised by growing cover crop as green manure and it replenish the soil with new nitrogen when incorporate into the soil (69). Enhancement in N use efficiency relies on how well a crop's nitrogen requirements are met by multiple nitrogen sources over the entire growth period (70). Nitrogen release from green manure is gradual and continuous rather than immediate. Since nitrogen is released gradually, losses through leaching, denitrification and ammonia volatilisation are reduced. Soil applied with green manure has no NH<sub>3</sub> volatilisation losses. Deep rooted green manure crops like lucerne, chicory and red clover draw the nutrients from the lower soil layers and make use of it after

decomposition (3). Sunnhemp is widely favoured by farmers because it grows rapidly and fixes atmospheric nitrogen efficiently (53). Green manure crops both fix atmospheric nitrogen and help conserve nitrogen already present in the soil. They provide a large amount of nitrogen for companion as well as subsequent crops (71).

## Carryover of nitrogen to succeeding crops

Incorporation of leguminous green manures, which add nitrogen from biological nitrogen fixation, is a long-established agronomic practice that frequently promotes significant increases in crop growth and yield. As indicated in Fig. 3, green manure crops involved in mineralisation process thus supply nutrients to crops (72, 73). The carryover effect depends on how much biologically fixed nitrogen the legume contributes to the soil system. It is also influenced by the remaining nitrogen available for the next crop and how effectively that crop uses it. Green manure incorporation adds substantial nitrogen to soil; however, nutrient release is gradual and biologically fixed nitrogen becomes available to plants over an extended period. Together, these processes ensure a continuous nitrogen supply for subsequent crops (74). The recovery of N provided by green manure by crops is below 30 %, leaving significant amounts of residual nitrogen in the soil (75). Green manure crops can capture and utilise leftover nutrients remaining in the soil from the previous crop cycle (42). Green manuring of dhaincha supplies 10 to 15 t ha<sup>-1</sup> of fresh biomass and 40 to 50 kg ha<sup>-1</sup> of nitrogen to succeeding crops (76).

Nevertheless, carry-over effects vary across different agroecosystems due to soil variation, climate, cropping sequences and management practices that influence the availability and uptake of nitrogen. Mineralisation and immobilisation processes may cause nitrogen unavailability for subsequent crops where the proportion of C:N in the soil becomes extremely high, hence creating sub-optimal conditions for nitrogen availability.



**Fig. 3.** Nutrient composition and supply of nutrient by 8-week-old green manuring crops (72, 73).

A knowledge gap lies between the process of nitrogen mineralisation of green manure residues and their need by the subsequent crops. Appropriate methods of residue management through improved timing of incorporation and selection of green manure are essential in ensuring effective recycling of nitrogen. Future studies need to be focused on the use of advanced technologies such as isotope tracing for measuring nitrogen dynamics and evaluating long-term impacts on soil nitrogen balance under diverse cropping systems.

#### Availability of other nutrients

Soil fertility, a critical determinant of crop productivity, can be enhanced through green manure incorporation, which releases macro- and micronutrients during decomposition. The breakdown of green manure and the nutrient release largely depend on physical factors of soil (like moisture, temperature and texture), its chemical (such as C:N ratio, pH and nutrients status) and microbial activity. Applying green manure can enhance phosphorus availability for the following crop through multiple soil-improving processes (77). Green manuring in sodic soil, improves organic carbon of soil, available nitrogen, phosphorus and potassium (78).

During decomposition, green manure releases organic acids that help dissolve native phosphorus in the soil and keep it available for longer time. Furthermore, dhaincha extracts phosphorus from subsurface soil layers in a cost-effective manner, making it available to subsequent crops (39). Green manuring has been shown to improve phosphorus release from rock phosphate in paddy fields (79). Incorporating green manure and green gram residue into the soil improved N, P and potassium (K) absorption by rice and wheat crops (80).

As they decompose, green manure crops release nutrients and help recycle key elements like nitrogen, phosphorus and potassium within the integrated system of plant nutrients. According to previous studies, after decomposition of green manure the organic P and K might easily be accessible by succeeding crops in available form (81). Green manure incorporation decreases the soil pH and phosphate fixation with Fe and Al, increasing availability of P. Green gram and velvet bean increased available P in soil by 0.03 and 0.37 mg kg<sup>-1</sup>, respectively. Increases in Mn and Fe concentration were observed under conditions of submergence (82). Green manure crops such as *S. aculeata*, *Mimosa invisa* Mart. ex Colla and *Vigna radiata* (L.). Wilczek contributed significant source of absolute N, P, K, S and various micronutrients to next crops grown (5). Incorporation of green manure under submerged condition increases the concentration of Fe and Mn (41). Utilisation of P and K to the extent of 10 to 12 % was reported under field conditions because of the application of green manures (3).

Incorporation of green manure enriches the availability of macro and micronutrients, except for nitrogen. Acids in organic form produced at decomposition improve the solubility of phosphorus, zinc and iron (9, 44). Deep-rooted cover crops bring nutrients from lower soil depths, increasing the nutrient concentration in surface soil (11, 49).

Increased microbial activity increases the mineralisation of K, Ca, Mg, S and micronutrients due to enzyme-mediated reactions (19, 57). Legume green manure incorporation increases available P due to phosphatase enzyme action, while increasing exchangeable K due to organic complexation (38, 83).

In integrated approaches involving green manure, mulching and organic fertiliser application, the efficiency of nutrient cycling is

significantly improved (58, 84). Green manures, therefore, improve the multi-nutrient supply needed for sustainable balanced nutrition and high yield.

Micronutrient-fortified organics significantly improve the bioavailability of Fe, Zn, Mn, Cu and B by facilitating chelation and solubilisation during decomposition (30). Organic farming practices increase the cycling of multi-nutrients because of the varied organic materials and lower chemical antagonism (31, 34). Nature-based restoration methods demonstrate substantial mobilisation of P, Ca, Mg and micronutrients in hill soils where organic materials are added to accelerate mineral weathering (32).

Eco-microbial fertilisers help in solubilising P and K by secreting organic acids and phosphatases (33). Zero-waste organic practices using recycled residues increase the long-term nutrient pool (35). Legume-based agroforestry practices improve nutrient extraction from deeper soil horizons (85).

#### Soil organic matter and water holding capacity of soil

Contemporary agricultural systems incorporate crop rotation and the green manures use serves as an effective approach for attaining sustainable and efficient crop production. Soil organic matter is widely acknowledged as a critical component that underpins true soil fertility. While green manure typically enriches organic matter and microbial biomass, the improvement varies with management practices, environmental conditions and the amount of biomass incorporated.

The soil moisture retention capacity and consistency are all influenced by green manure incorporation. Soil structural modifications brought about by green manure also impact porosity, aeration, infiltration rate and hydraulic conductivity (85). Variations in pore size distribution have been observed in soils treated with different green manures. In this scenario using *Sesbania* as a green manure steadily expanded the macro- and mesopores while leaving micropores unaltered, increasing plant available water holding capacity. Fields amended with *Sesbania* recorded upto a 17 % rise in available soil moisture (86). Dhaincha > cluster bean > rice bean was the most effective in improving the water holding capacity of green manure incorporation and dhaincha outperformed with more macro and larger mesopores than the untreated soil, next by cluster bean and rice bean (14). In sandy soils, the additional organic matter from green manure improves aggregate stability and porosity, enabling the soil to retain moisture for longer periods (5).

Soil organic matter (SOM) is the core of the ecological significance of green manuring. Regular addition of fresh organic matter enhances the labile and stable pools of SOM, thereby improving carbon sequestration and soil resilience (9, 19). Enhanced water-holding capacity is achieved through enhanced SOM and improved soil aggregation (6, 22). Green manure-treated soils have improved moisture retention, lower evaporation rates and higher infiltration rates (12, 26). The SOM also improves hydraulic conductivity and protects soils against drought and irregular rainfall events (27, 28).

Micronutrient-supplemented organics can further improve the quality of SOM by increasing the humic and fulvic acid components, thus improving water retention capacity and structural properties (58). Natural farming practices show a rapid accumulation of SOM due to regular mulching and addition of biomass (31, 34). In hill and mountainous regions, green manuring along with agroforestry practices can increase soil carbon and improve water dynamics, which are essential for rainfed agriculture (32, 36).

Eco-fertilisers can alter the decomposition rates of organic matter, thus increasing the accumulation of SOM (33). Nutrient cycling methods with zero landfilling practices can improve SOM in degraded areas by recycling agricultural waste (35). These additional results clearly show that modern regenerative practices can significantly enhance the SOM and water retention capacity of green manures.

### Reclamation of salt affected soil

High salt levels in the soil hinder plant development by creating osmotic stress around the root zone. Applying green manure considerably enhances nitrogen, organic carbon and total carbohydrate content in saline soils. Green manuring is widely used in sodic soils to restore soil health and boost fertility. These practices help reduce the elevated soil pH by introducing organic acids that promote the replacement of sodium ions with beneficial ions like calcium (87). Sodic soils typically contain little organic matter because sodium carbonate and bicarbonate dissolve humus, especially fulvic and humic fractions. Therefore, incorporating green manure into sodic soils increases organic matter levels, which in turn improves structure and physical conditions of the soil. Moreover, green manures facilitate the substitution of sodium ions at exchange sites with calcium ions (88). *Sesbania aculeata*, containing about 34 % Calcium on dry-weight basis, is effective in displacing sodium from sodic soils (89). As green manure decomposes, it releases CO<sub>2</sub> and increase soluble calcium in the soil solution, which replaces sodium at exchange sites, ultimately aiding sodic soil reclamation (90).

Green manures are very efficient in the reclamation of sodic and saline soils through the modification of soil chemistry and improvement of physical and biological properties. Legumes like *S. aculeata* and *S. rostrata* can produce a substantial amount of biomass with high organic acid content, which can lower soil pH and alkalinity (6, 9). Organic acids like humic, fulvic and acetic acids can solubilise CaCO<sub>3</sub>, releasing Ca<sup>2+</sup> ions that can displace Na<sup>+</sup> ions from the exchange sites (44). Green manuring can increase salt leaching by improving soil physical properties like structure, permeability and infiltration rate (12, 22). Green manure crops that are salt-tolerant, such as dhaincha (*Sesbania* spp.) and *Tephrosia* spp., are very efficient in the reclamation of highly degraded soils (49). Long-term use can result in the improvement of soil structure, reduction of ESP and improvement of nutrient availability.

Recent studies show that organic amendments rich in micronutrients can greatly accelerate the process of sodic soil reclamation by increasing Ca-Na exchange and pH reduction (30). Ecological farming practices help in desodification by encouraging steady organic acid production (31). Hill region ecological restoration studies have shown improvement in both acidic and salt-affected soils through green manure biomass addition, which helps in improving Ca mobilisation (32). Eco-friendly microbial fertilisers help in improving ionic balance and detoxifying sodium-affected soils (33). These findings further support the role of green manures in sodic soil reclamation.

### Nitrogen addition by different green manure crops

Nitrogen addition by different green manure crops is presented in Table 1.

### Limitations of green manuring

- Cultivation of green manure crops needs both time and space, thereby reducing the available area and period for planting main crops (91, 93).
- The efficiency of green manuring depends on the yields of biomass and the decomposition time that in turn are influenced by the environment, moisture content and crops grown (72, 74).
- Nitrogen mineralisation may occur at inappropriate times in relation to nutrient needs of the growing plants, thereby reducing utilisation efficiency (72, 74).
- Under certain environmental conditions (high C:N ratio of residues, lack of nutrients), immobilisation of mineralised nitrogen by microorganisms will make the mineralisation of the element ineffective for crops (39, 40).
- Residual nitrogen is likely to be lost in cases where there are excess rains and irrigation due to leaching and volatilisation (70).
- Reclaiming poor soils such as sodic soils via green manures may require more time compared to methods such as application of gypsum (42, 44).
- Labor input, lack of seeds and management demands could restrict its use by the farmers (85).

**Table 1.** Nitrogen addition by different green manure crops

| Crop         | Incorporation rate (t ha <sup>-1</sup> ) | N addition (kg ha <sup>-1</sup> ) | Reference |
|--------------|------------------------------------------|-----------------------------------|-----------|
| Sunnhemp     | 0.9–2.9 (DWB)                            | 23–82                             | (91)      |
|              | 9.0 (DWB)                                | 20.1                              | (92)      |
|              | 20–30 (FWB)                              | 84–129                            | (53)      |
|              | 13.6 (FWB)                               | 302                               | (66)      |
|              | 11.2 (DWB)                               | 195.1                             | (93)      |
| Red clover   | 8.7 (DWB)                                | 217                               | (94)      |
|              | 15 (FWB)                                 | 40.8                              | (95)      |
|              | 4.52 (DWB)                               | 40                                | (96)      |
| Dhaincha     | 24.5–34.8 (FWB)                          | 90.3                              | (97)      |
|              | 23.2 (FWB)                               | 77.1–105                          | (53)      |
|              | 3.02 (DWB)                               | 83.1                              | (98)      |
| Cluster bean | 18–30 (FWB)                              | 61–85                             | (53)      |
| Berseem      | 16–18 (FWB)                              | 60                                | (53)      |
| Cowpea       | 4.0 (DWB)                                | 168                               | (66)      |
|              | 1.65 (DWB)                               | 46.2                              | (99)      |
| Common vetch | 2.42 (DWB)                               | 51.2                              | (100)     |
|              | 0.4 (DWB)                                | 10.2                              | (99)      |
| Faba bean    | 2.87 (DWB)                               | 63.3                              | (100)     |
| Lablab       | 3.25 (DWB)                               | 111.05                            | (100)     |

FWB: fresh weight basis; DWB: dry weight basis.

## Conclusion

Incorporating green manures into soil is regarded as a sound agronomic practice across farming systems due to the various benefits they provide. This approach enhances the sustainability of cropping systems by minimising erosion and improving soil structure and physical quality. Green manuring boosts soil organic matter and fertility, strengthens nutrient- holding capacity and lowers the soil's contribution to greenhouse gas emissions. As an economical and efficient method, green manuring helps cut down on chemical fertiliser expenses while maintaining soil productivity and strengthening long-term sustainability. Adding green manure crops to the soil helps reduce nitrogen losses and improve nitrogen use efficiency. Most green manure species are legumes that fix atmospheric nitrogen through *Rhizobium* activity. Therefore, green manuring represents an environmentally friendly and economically viable alternative under increasing fertiliser costs. It has proven to be an effective technology while ensuring soil productivity without causing environmental degradation. However, the effectiveness of green manuring depends on parameters like biomass production, rate of decomposition and synchronisation of nutrient release with crop demand. Variations in such parameters can make it less effective, indicating that green manuring is not always universally beneficial but can be context specific. From the application point of view, green manuring could be considered as a part of sustainable agriculture. Future research should focus on species selection, nutrient release synchronisation and long-term effects on diverse agroecosystems. As a result, green manuring remains a promising strategy for enhancing soil health, ensuring environmental sustainability and supporting resilient agricultural systems.

## Acknowledgements

The authors gratefully acknowledge Tamil Nadu Agricultural University, Coimbatore, India, for providing the necessary facilities to carry out this research.

## Authors' contributions

SR and TR collected the literature. SR and TR reviewed the literature and prepared the first draft of the manuscript. SR, TR, RJ, RN, NS and TS edited the manuscript. SR and TR performed the second revision of the manuscript. SR, TR, RJ, RN, NS and TS carried out the final revision of the manuscript. All authors have read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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