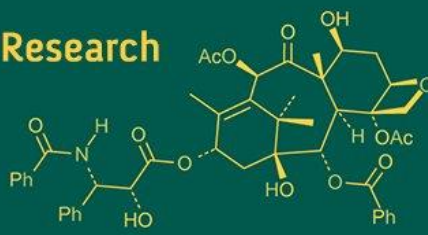


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1711-1714
www.biochemjournal.com
Received: 02-04-2026
Accepted: 07-05-2026

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Multi-dimensional role of green manuring crops in enhancing soil health and ecosystem functions: A comprehensive review

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6St.9250>

Abstract

Modern agricultural systems face the dual challenge of maximizing crop productivity while reversing soil resource depletion. Continuous intensive cultivation using synthetic chemicals has caused widespread soil degradation, loss of organic matter, and structural compaction. Green manuring-the intentional cultivation and subsequent incorporation of fresh, un-decomposed plant biomass into the soil matrix-serves as an ecological restoration strategy. This review synthesises the multi-dimensional impacts of green manuring on soil physicochemical and biological properties. By introducing labile organic carbon and fixing atmospheric nitrogen, green manuring alters rhizosphere dynamics, enhances microbial enzymatic activities, improves macro-aggregate stability, and optimizes nutrient cycling efficiency. Ultimately, this comprehensive synthesis establishes green manuring as an indispensable, scale-neutral methodology for mitigating agroecosystem degradation and fostering long-term global food security.

Keywords: Green manuring, rhizosphere dynamics, macro-aggregate stability, soil matrix

Introduction

Modern intensive agriculture and heavy reliance on synthetic fertilizers have led to severe soil health degradation, particularly in heavily cropped regions like the Indo-Gangetic plains (Mandal et al., 2003) ^[12]. Green manuring is a core management strategy in conservation agriculture. The system involves growing specialized cover crops-primarily fast-growing legumes or deep-rooted crucifers and incorporating their succulent green biomass directly into the soil plough layer during the pre-flowering stage. This technique restores soil fertility, recaptures deep-seated nutrients, stimulates multi-trophic biological webs, and builds resilient physical soil structures without relying on synthetic inputs. The soil rhizosphere-the narrow zone of soil directly influenced by root secretions and associated microorganisms is the primary hot spot for nutrient transformation and uptake in agricultural systems (Richardson et al., 2009) ^[17]. Traditional intensive cropping often depletes rhizosphere organic substrates, resulting in degraded biological activity. Green manuring bridges the gap between biological activity and chemical nutrient availability within the rhizosphere (Fageria, 2007) ^[3].

Importance of green manuring in enhancing soil health and ecosystem functions:

1. Physical properties of soil

1.1 Soil Aggregation and Structure

The addition of green manure biomass contributes readily decomposable organic carbon to the soil matrix (Sahil et al., 2026) ^[5]. As soil microbes decompose this fresh material, they exude polysaccharides, mucilages, and other microbial binding agents that glue individual soil particles together into structural units (MacRae & Mehuys, 1988) ^[11]. This process significantly enhances water-stable soil aggregation and improves overall structural stability (Dabney et al., 2001) ^[2]. Stable aggregates prevent the formation of hard surface crusts, which otherwise impede seedling emergence and restrict rainfall intake (Mavi & Singh, 2007) ^[13].

1.2 Reduction of Soil Bulk Density

High soil bulk density restricts root proliferation and limits fluid movement through the soil profile (Shukla et al., 2004)^[18]. Green manuring consistently decreases soil bulk density by increasing the volume of total pore space (Mandal et al., 2003)^[12]. The rapid accumulation and sub-surface incorporation of high-volume organic biomass lower the soil's compacted state (Rathika et al., 2026)^[16]. This results in a looser, more friable soil tilth that reduces mechanical impedance for subsequent cash crops (Mavi & Singh, 2007)^[13].

1.3 Moisture Retention and Water Dynamics

Improving soil organic matter (SOM) fractions directly influences the soil-water relationship (Dabney et al., 2001)^[2]. Green-manured soils exhibit an increased water-holding capacity, which provides distinct physical benefits for both light-textured sandy soils and heavy clay soils (MacRae & Mehuys, 1988)^[11]. In sandy soils, the added organic matter acts like a sponge to retain water against gravity, while in clay soils, improved aggregation increases the number of transmissions macropores for better drainage (Shukla et al., 2004)^[18]. Additionally, increased infiltration rates minimize surface runoff and drastically decrease topsoil erosion risks (Dabney et al., 2001)^[2].

1.4 Aeration and Thermal Regulation

Root systems of green manure crops, particularly deep-rooted legumes, play a vital biological role in disrupting compacted subsurface hardpans by creating extensive bio pores (Rathika et al., 2026)^[16]. This enhances soil macroporosity and improves aeration, allowing necessary gas exchange (O₂ and CO₂) between the root zone and the atmosphere (Mandal et al., 2003)^[12]. Furthermore, maintaining a green manure canopy cover prior to incorporation buffers extreme soil temperature fluctuations, which protects the soil's microbial populations and minimizes evaporative water loss from the surface layer (Sahil et al., 2026)^[5].

2. Chemical properties of soil and nutrient cycling

The incorporation of green manures triggers an immediate shift in rhizosphere chemistry, primarily driven by microbial stimulation (Tejada et al., 2011)^[19].

2.1 Organic Acid Exudation: Decomposing green manures release low-molecular-weight organic acids, such as citric, oxalic, and malic acids, which temporarily lower rhizosphere pH and chelate metal cations (Richardson et al., 2009)^[17].

2.2 Enzymatic Amplification: The influx of easily degradable substrates stimulates microbial synthesis of critical extracellular enzymes, including phosphatases, glucosidases, and ureases (Tejada et al., 2011, Kusum, A. 2023)^[19, 6].

2.3 Siderophore Production: Enhanced microbial activity promotes the secretion of iron-chelating siderophores, making trace elements more bioavailable to subsequent crops (Richardson et al., 2009)^[17].

2.4 Nitrogen Cycling and Biological Nitrogen Fixation (BNF)

Leguminous green manures introduce atmospheric nitrogen into the system via symbiotic fixation, dramatically altering nitrogen availability (Fageria, 2007)^[3].

- **Mineralisation and Immobilisation:** Fresh biomass with a low carbon-to-nitrogen (C:N) ratio (typically below 20:1) undergoes rapid mineralisation, converting organic nitrogen into plant-available ammonium (NH₄⁺) and nitrate (NO₃⁻) (Fageria, 2007)^[3].
- **Nitrogen Priming Effect:** The supply of labile carbon stimulates indigenous soil microbes to decompose older, recalcitrant soil organic matter, unlocking further nitrogen stores through a process known as the priming effect (Kuzyakov, 2010)^[10].
- **Leaching Mitigation:** Deep-rooted non-leguminous green manures act as "catch crops," absorbing residual profile nitrates and storing them in organic form to prevent groundwater leaching (Tiemann et al., 2015)^[20].

2.5 Phosphorus Solubilization and Mobilization

Phosphorus (P) is highly prone to fixation as insoluble complexes in both acidic and alkaline soils, but green manuring acts as a key biochemical driver for its mobilization (Bünemann et al., 2011)^[1].

- **Competitive Adsorption:** Organic anions released during decomposition compete with phosphate ions for binding sites on soil minerals, releasing bound P into the soil solution (Richardson et al., 2009, Kusum et al., 2020)^[17, 7].
- **Phosphatase Activity:** Microbial proliferation boosts acid and alkaline phosphatase activity, hydrolysing organic phosphorus forms into orthophosphates (Bünemann et al., 2011)^[1].
- **Mycorrhizal Symbiosis:** Green manure crops support a robust network of Arbuscular Mycorrhizal Fungi (AMF) that extend the root surface area for active phosphorus mining (Richardson et al., 2009)^[17].

2.6 Potassium and Micronutrient Dynamics

Beyond N and P, green manures actively redistribute potassium (K) and micro-elements within the root zone through enhanced crop diversity (Tiemann et al., 2015)^[20].

- **K Bio-accumulation:** Green manures act as potassium pumps, taking up K from deeper soil layers and depositing it into the topsoil upon incorporation (Fageria, 2007)^[3].
- **Micronutrient Complexation:** The breakdown products of green manures form stable, soluble organo-metal complexes with zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn), preventing their fixation into unavailable mineral phases (Richardson et al., 2009, Kusum et al., 2020 and Kusum et al., 2025)^[17, 9, 10].

3. Biological properties of soil

3.1 Augmentation of Microbial Biomass Carbon and Nitrogen

The absolute size of the soil microbial pool is a sensitive indicator of overall soil quality and fertility.

3.2 Labile Carbon Substrates: Freshly incorporated green manures bypass the slower breakdown pathways of woody residues. They provide an immediate supply of water-soluble carbohydrates, amino acids, and organic acids that fuel rapid microbial reproduction (Tejada et al., 2011)^[19].

3.3 Elevated Biomass Indices: This resource influx triggers a sharp increase in Soil Microbial Biomass Carbon (SMBC)

and Microbial Biomass Nitrogen (SMBN), creating a larger biological nutrient reservoir that prevents nutrient leaching (Frasier et al., 2016)^[4].

3.4 The "Priming Effect": The sudden rise in active microbial populations temporarily accelerates the decomposition of native, recalcitrant soil organic matter, releasing trapped elements back into the biological cycle (Kuz'yakov, 2010)^[10].

4. Structural Shifts in Soil Microbial Communities

Green manuring does not just increase microbial numbers; it alters the taxonomic and functional composition of the entire soil microbiome.

- **Bacterial vs. Fungal Succession:** The early phases of green manure decomposition favour fast-growing, copiotrophic bacteria (like *Proteobacteria* and *Bacteroidetes*). As the remaining residues become tougher and more fibrous, the succession shifts to saprophytic fungi and actinobacteria capable of degrading lignin and cellulose (Tiemann et al., 2015)^[20].
- **Mycorrhizal Support:** Crops utilized as green manures (e.g., specific clovers and legumes) serve as host plants that maintain and build up indigenous populations of Arbuscular Mycorrhizal Fungi (AMF).
- **Functional Diversity:** High-throughput DNA sequencing confirms that green manure rotations significantly increase alpha diversity indices, indicating a more stable, resilient, and redundant microbial network (Zander et al., 2016)^[22].

5. Amplification of Soil Enzyme Activities

Soil enzymes, secreted primarily by active microbes and plant roots, are the catalysts for almost all biochemical processes in the soil matrix.

- **Hydrolases and Oxidoreductases:** Green manured soils consistently display elevated activities of dehydrogenases, which serve as direct indicators of overall microbial metabolic activity (Tejada et al., 2011)^[19].
- **Nutrient Target Enzymes:** The application of green biomass stimulates the production of specific extracellular enzymes targeting key nutrient pools: β -glucosidase for carbon cycling, urease and proteases for nitrogen release, and alkaline/acid phosphatases for unlocking fixed phosphorus (Bünemann et al., 2011)^[1].

4. Biological Disease Suppression and Biotherapeutics

Incorporating cover crops and green manures changes the biological equilibrium, transforming the rhizosphere into a hostile environment for soil-borne pathogens.

- **Competitive Exclusion:** The massive surge in beneficial saprophytic bacteria physically outcompetes pathogens for space, nutrients, and root attachment sites (Mazzola, 2002).
- **Biofumigation Pathways:** Specific green manures release natural chemical compounds upon breakdown. For example, cruciferous green manures (like *Brassica juncea*) release glucosinolates. When chopped and incorporated, these compounds break down into volatile isothiocyanates, which naturally suppress destructive nematodes, fungi, and weeds (Vandermeer, 1992).

5. Some common Green Manure crops applied in soil

Botanical Name	Common Name	Biomass to Incorporate (t/ha)	Nutrient Released (N Fixed kg/ha)	Primary Soil Health Mechanism	Reference
<i>Sesbania aculeata</i>	Dhaincha	20.0 – 25.0	80 – 120	Rapid biomass mineralization & nodulation in waterlogged/saline soils	Fageria (2007) ^[3]
<i>Crotalaria juncea</i>	Sunnhemp	22.0 – 30.0	90 – 150	Deep taproot for hardpan shattering & robust nematostatic properties	Dabney et al. (2001) ^[2]
<i>Vigna unguiculata</i>	Cowpea	15.0 – 20.0	60 – 100	Rapid, dense canopy closure maximizing weed suppression	Mandal et al. (2003) ^[12]
<i>Cyamopsis tetragonoloba</i>	Guar / Cluster bean	15.0 – 18.0	50 – 80	Drought-tolerant root systems improving soil structural stability in arid zones	Sahil et al. (2026) ^[5]
<i>Trifolium alexandrinum</i>	Berseem clover	18.0 – 22.0	100 – 130	High root exudation stimulating AMF	Richardson et al. (2009) ^[17]
<i>Phaseolus trilobus</i>	Pillipesera	10.0 – 12.0	40 – 60	Excellent short-term cover against soil erosion	Mavi & Singh (2007) ^[13]

6. Conclusion

Green manuring is an essential nature-based solution, cost-effective and ecologically sound strategy for improving soil properties. It helps in continuously building soil organic matter, improving aggregation, decreasing bulk density and regulating soil moisture dynamics. Green manures create a robust, resilient soil environment that sustains long-term crop yields. By integrating root dynamics and fresh plant biomass into the plough layer, this practice recaptures deep-lying nutrients and drives critical microbial cycles. Integrating specific green manures into crop rotations is vital for minimizing synthetic fertilizer inputs and fostering resilient, low-emission agricultural ecosystems.

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