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Review

Green Manuring Crop Plants: Harnessing Natural Processes to Enhance Soil Health and Promote Sustainable Agricultural Practices

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Abstract: The intensification of modern farming methods in developed nations has exacerbated the issue of soil degradation and over-utilization of naturally available resources, hence, tinkering negatively with the health and productive capacity of soil. Chemical fertilizers, while increasing crop yields, have resulted in environmental pollution and health hazards. Green manuring presents a sustainable alternative by enriching soil fertility and reducing reliance on chemical fertilizers. This paper reviews the impact of green manuring on soil properties, crop yield, and farm economies. In-situ green manuring involves growing and incorporating the crops within the field, while ex-situ green manuring incorporates plant material from external sources. Leguminous green manures are particularly effective owing to nitrogen fixation capability and rapid decomposition. The inclusion of green manure improves the availability of nutrients, microbial count and carbon content of the soil, thereby, enhancing the overall health of soil and crop productivity. Additionally, green manures reduce pests and diseases, suppress weeds, and provide supplementary forage. Despite the benefits, challenges such as limited water resources, seed availability, and farmer reluctance hinder widespread adoption. Future research should focus on raising awareness, quantifying benefits, and developing location-specific cropping systems to optimize green manuring practices.

Keywords: soil degradation; green manuring; crop yield; soil health and sustainability

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India is projected to surpass its present population count of 1.38 billion by 2030, necessitating additional food production to meet nutritional demands. Consequently, farmers in developed countries have embraced modern agricultural practices, including the cultivation of high-yielding varieties and the intensive use of agrochemicals, to meet the escalating demand for food grains. These intensive practices of crop production have resulted in the degradation of soil and excessive use of precious natural resources. As a result, soil health declines, characterized by a decrease in soil water retention capacity and deficiencies in various macronutrients and micronutrients, leading to groundwater pollution (Gill et al., 2008; Meena, 2013). Unrecovered fertilizers from crops are released into the environment, predominantly entering surface water or groundwater. Chemical fertilizers often contain harmful elements such as cadmium, chromium, mercury, lead, nickel, among others. The application of fertilizers also results in residual toxic effects like salinity, acidity and alkalization of soil, besides, leaching of nitrate fertilizers in groundwater water is widespread and it results in blue baby syndrome disease among the children. Therefore, the need for chemical fertilizers can be cut down by green manuring, application of farm yard manure (FYM) and crop residue recycling. Green manure is classified as organic nutrition which involves the incorporation and slight

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mixing of entire fresh plant or plant part into the soil as manure without any prior decomposition or composting. Green manures consist of annual or perennial leguminous plants, cultivated either individually or more commonly in crop mixtures, typically for several months or even up to multiple years, interspersed between regular periods of crop cultivation. These are grown in between the trees and vines in orchards and vineyards when trees are under dormant conditions. As these plant parts are not nutrient-concentrated, so they are added in bulk quantities. These crops help in building and maintaining soil fertility while providing other secondary advantages viz., soil organic matter and structure building, prevention of nutrient leaching, smothering weed growth, etc. The practice of green manuring, though, indirectly by knowing the fertilizing value of grass or weeds as manure, was initiated for the first time in China around 1134 B.C. and then later on spread to North America through Europe where rye, buckwheat and oats were cultivated as green manure crops (Pieters 2006). Since the development of scientific research many years back, soil rejuvenation through green manuring as part of crop rotation has been recognized well. In India, about 35 years ago (1988-89), 6.2 million ha of the area was reported to be under green manuring with more than 60% area located over six states of the Indian subcontinent i.e., Andhra Pradesh, Uttar Pradesh, Madhya Pradesh, Karnataka, Orissa and Punjab. Green manuring can accumulate 80-100 kg ha^{-1} nitrogen during crop growth of 45–60 days. The utilization of green manures enhances soil health and microbial populations, leading to increased nutrient availability and uptake by plants. Incorporating green manure into agricultural practices has the potential to suppress weeds, control soil-borne diseases, and disrupt the life cycles of pests (Kumar et al., 2014; Varma et al., 2017). Particularly for small-scale farmers facing challenges in purchasing expensive mineral fertilizers, green manure holds significant importance (Meena et al., 2014). Hence, these crops present promising opportunities for food grain production while maintaining the sustainability of the system. With these considerations, this review aims to offer insights into the utilization of green manures for sustainable soil management and crop production.

1. Classification of Green Manure

There are broadly two types of green manuring:

In-situ Green Manuring**:** *In-situ* green manuring is cultivating desired green manure crops in the field itself and its incorporation into the soil 45-60 days after sowing. An ideal green manure crop should be a fast-growing and high bio-mass producer with minimum nutrient and water requirements. Nitrogen-fixing legumes that have heavy tender growth early in their life cycle are most suitable for green manuring (Table 1).

Table 1. Crops commonly used for in-situ green manuring (Source: Bahadur *et al* 2022).

Name of plant	Scientific name (S.N)	Name of plant	S.N
Dhaincha	*Sesbania aculeate* and *Sesbania rostrata* (stem nodulating crop)	Black lentil	*Lens culinaris*
Lablab	*Lablab purpureus*	Purple vetch	*Vicia benghalensis*
Cluster bean	*Cyamopsis tetragonoloba*	Adzuki bean	*Vigna angularis*
Sunnhemp	*Crotalaria breviflora*	Red clover	*Trifolium pratense*
Cowpea	*Vigna unguiculata*	Alfalfa	*Medicago sativa*
Green gram	*Vigna radiate*	Common vetch	*Vicia sativa*

Ex-situ Green Manuring**:** It is also known as green leaf manuring. It involves the growing of leguminous or non-leguminous shrubs/trees in the field and then incorporation of their leaves and tender green twigs into the field or green biomass collected from the nearby forest is incorporated into the soil of some other field. The species generally used for green leaf manuring are given in Table 2. Nevertheless, the choice of green manure crop is contingent upon various factors, including the prevailing climatic conditions, cropping system utilized, seed availability, and other considerations such as local preferences. The nutrient content in these green leaf manures varies with species which is depicted in Table 3.

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Table 2. Shrubs/trees commonly used for ex-situ green manuring (Source: Bahadur *et al* 2022).

Name of shrub/ tree	S.N	Name of shrub/ tree	S.N
Subabul	*Leucaena leucocephala*	Neem	*Azadirachta indica*
Karanj	*Pongamia glabra*	Gulmohur	*Delonix regia*
Milkweed	*Calotropis gigantean*	Gliricidia	*Gliricidia sepium*
Water hyacinth	*Eichhornia crassipes*	Cassia	*Cassia fistula*

Table 3. Nutrient content of important green manures (Source: TNAU Agri tech portal).

Name of plant	S.N	(%) Nutrient content on air dry basis		
		Nitrogen	Phosphorus	Potassium
Green manures				
Sunhemp	*Crotalaria juncea*	2.3	0.5	1.8
Dhaincha	*Sesbania aculeata*	3.5	0.6	1.2
Sesbania	*Sesbania speciosa*	2.7	0.5	2.2
Green leaf manures				
Neem	*Azadirachta indica*	2.8	0.3	0.3
Pongania	*Pongamia glabra*	3.3	0.4	2.4
Gliricidia	*Gliricidia sepium*	2.8	0.3	4.6
Peltophorum	*Peltophorum ferrugenum*	2.6	0.4	0.5
Gulmohur	*Delonix regia*	2.8	0.5	0.5

2. Need for Green Manuring

The intensification of traditional farming practices has resulted in widespread reliance on agrochemicals, agricultural machinery, and high-yielding crop varieties. However, this intensification has led to detrimental effects on the environment, including groundwater and air pollution, exacerbating the greenhouse effect (Mylonas et al., 2020). In the recent past, chemical fertilizer usage has increased to achieve higher crop productivity. Their use apart from being a costly affair, also leads to the degradation of the environment, soil health and quality of the produce. In India, about 70 percent of total fertilizer applied accounts for meeting nitrogen requirements and its fertilizer use efficiency is only 30 to 50 percent (Anonymous 2018). Fertilizer use efficiency of other essential nutrients is also very low viz., 15-20%, 60-70%, 8-10% and 1-5 % for P, K, S and micronutrients, respectively (Anonymous 2019). Detrimental health impacts, for instance, hormonal disruptions, neurological, reproductive and immune systems malfunctioning have been noticed in the human body owing to the consumption of plant materials having high residual chemical concentrations (Paroda 2017). Nitrate contamination of drinking water is responsible for many diseases in humans and animals such as blue baby syndrome, gastric cancer, goiter, birth defects, and heart diseases. Leaching of higher concentrations of nitrate and phosphorus along with soil water leads to the eutrophication of water bodies that threaten aquatic life. Continuous usage of chemical fertilizers results in sub-optimal and supra-optimal availability of some major and minor essential nutrients (Verma *et al* 2020). Moreover, decreasing soil organic matter content, limited use of bio and organic manures, and poor management lead to declining agricultural productivity per unit of cultivated area (Reddy *et al* 2022). To reverse the trend of declining agricultural productivity and to achieve sustainability it is necessary to include green organic manures for providing balanced nutrition to crops along with sustaining soil health (Fudzagbo and Abdulraheem, 2020). Due to increased environmental awareness and the need to minimize the expenditures on inputs, the usage of organic fertilizers, such as green manure crops, has significantly increased, recently (Pappa *et al* 2006). As a source of organic materials and nutrients, animal dung and green manure have historically played a significant role in organic farming (Ciaccia *et al* 2017). Sustainable soil productivity is crucial, and most nations are in the post-green revolution phase with stagnant or declining crop yields as a major challenge. Hence, to enhance future grain production while safeguarding soil health, farmers and researchers have embraced resource conservation practices and

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the incorporation of green manuring into farming systems (Meena and Majumdar, 2016; Meena et al., 2016). Green manuring involves the incorporation of green parts of plants into the soil, by cultivating these either in the same field or grown elsewhere but incorporated in another field before they flower. It is essential to incorporate them before flowering to prevent a wider C:N ratio, which slows down decomposition and leads to temporary nutrient immobilization. Green manure crops, often high in biomass production (Table 4), harness solar energy to supply macro and micronutrients to soil microbes through carbon flux. Leguminous green manures, in particular, possess atmospheric nitrogen fixation capacity and make it available to plants, contributing significantly to soil fertility preservation (Table 5, Figure 1) (Meena et al., 2018). While both legumes and non-legumes can serve as green manures, but, highly preferred are legumes due to their superior nitrogen-fixing capacity and symbiotic relationships with beneficial soil microorganisms (Lin et al., 2019).

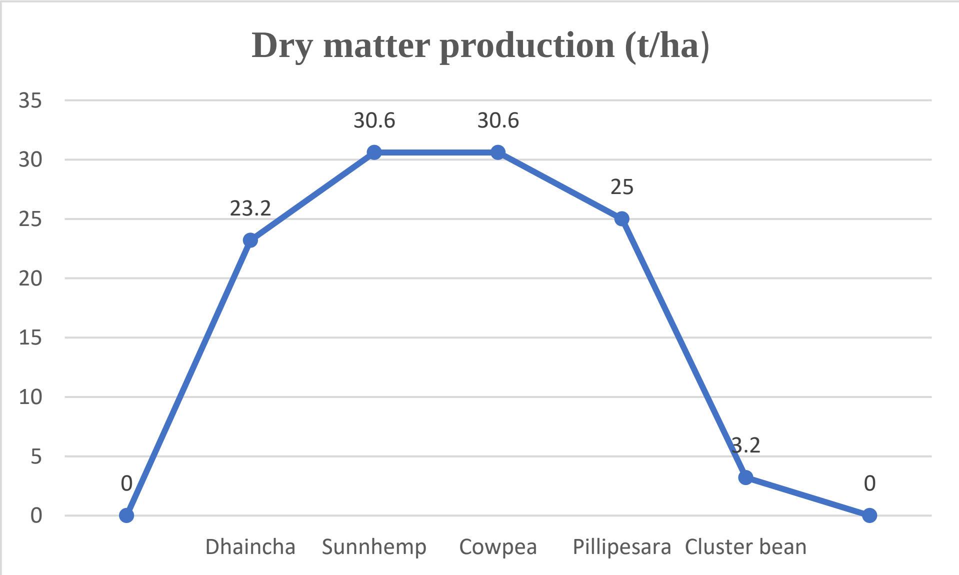

Figure 1. Biomass production of green manure crops (Source: TNAU Agri tech portal).

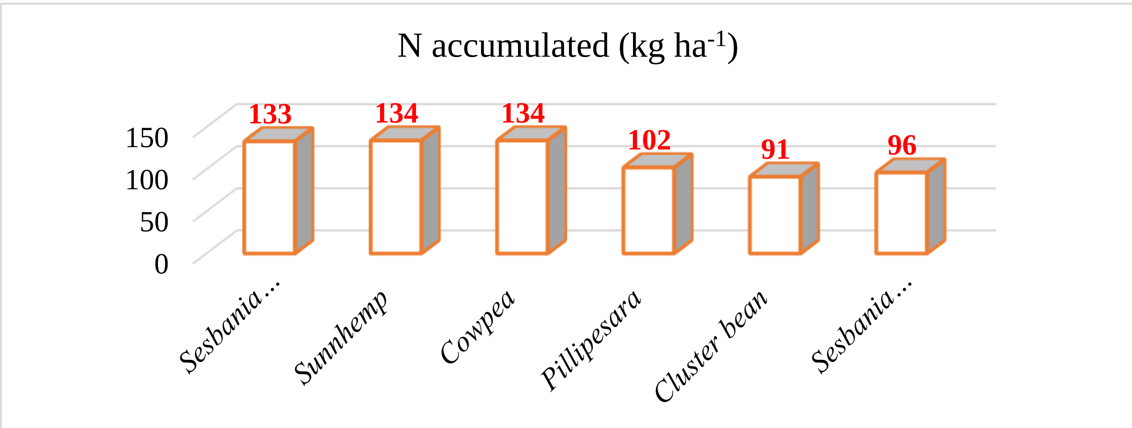

Figure 2. Nitrogen accumulated by green manure crops (kg ha-1) (Source: TNAU Agri tech portal).

Table 4. Increase in economic yield due to green manuring over control (non-manured).

Crop	% increase	Source
Grain yield of wheat (t ha^{-1})	47.39	Muhammad *et al* (2022)
Grain yield of rice (t ha^{-1})	53.59	Islam *et al* (2018)
Grain yield of rice (t ha^{-1})	26.51	Kumar *et al* (2022)
Grain yield of rice (t ha^{-1})	49.18	Naz *et al* (2023)
Sunflower seed yield (Mg ha^{-1}).	45.17	Thind *et al* (2007)

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Chickpea seed yield (kg ha^{-1})	31.28	Goddumarri *et al* (2022)
Grain yield of maize (kg ha^{-1})	14.41	Rani *et al* (2022)
Green cob yield of sweet corn (t ha^{-1})	51.18	Nikita *et al* (2015)

Table 5. Some examples of associations between rhizobia and legumes (Source: Rascio and Rocca 2008).

Rhizobia	Host plants
Azorhizobium caulinodans	*Sesbania*
Mesorhizobium loti	*Lotus, Lupinus, Anthillis*
Rhizobium leguminosarum biovar. viciae	*Vicia, Pisum, Cicer*
Sinorhizobium meliloti	*Medicago, Trigonella, Melilotus*
Bradyrizobium japonicum	*Glycine, Vigna*
Rhizobium leguminosarum biovar. trifolii	*Trifolium*
Rhizobium leguminosarum biovar. phaseoli	*Phaseolus*

3. Impact of Green Manuring on Soil Properties

Green manures act as reservoirs and suppliers of various nutrients released during decomposition, contributing to soil organic carbon content and boosting microbial populations. Incorporating green manures into cropping systems increases soil organic matter and nutrient levels, thereby enhancing the physical, chemical, and biological properties of the soil. This augmentation ultimately improves soil productivity and erosion susceptibility decreases over time (Rayns et al., 2010).

4.1. Impact on Soil Physical Properties

Green manuring enhances various soil physical properties such as soil structure, bulk density, water retention capacity and soil texture. It also modifies the pore proportion of soil by reducing micropores while increasing macropores (Kumar, 2019). Soil properties improved with the incorporation of crop residues and green manuring (Pawar *et al* 2018). Continuous legume-based green manuring results in a build-up of the microbial population in the soil which improves the physical condition of the soil (Shukla *et al* 2011) Various types of organic substances are produced when incorporated green manure decomposes and these substances aggregate the dispersed soil particles that result in better soil aggregation which in turn improves hydraulic conductivity and drainage by enhancing percolation and infiltration rate (MacRae and Mehuys 1985). Total porosity measures the amount of pore space in the soil for air and water and it increases with the addition of green manure and it is inversely proportional to bulk density (Min *et al* 2003; Tester 1990). Salahin *et al* (2013) found that the green manuring with dhaincha recorded significantly lowest bulk density (1.44 g cm^{-3}) and particle density (2.48 g cm^{-3}) which was followed by green manuring with mimosa and *Vigna radiata* whereas the non-green manuring had the significantly highest bulk (1.55 cm^{-3}) and particle density (2.54 cm^{-3}). The order of effectiveness of green manuring crops in improving the total porosity of soil was *Sesbania aculeata* > *Mimoisica invisa* > *Vigna radiata* > non-green manuring (Sultani *et al* 2007 and Sultani *et al* 2007). Naz *et al* (2023) revealed that the significantly lowest bulk density (1.46 g cm^{-3}) and the highest porosity (44.7%) were recorded with green manuring of *Sesbania* along with recommended chemical fertilizers application for three consecutive years. The organic matter addition results in the loosening of the soil and increases the capacity of the soil to hold water in contrast to the application of sole fertilizer. Rani *et al* (2022) investigated the impact of the continuous incorporation of green manure and concluded that the soil infiltration rate and water-stable aggregates were positively influenced which ultimately resulted in an increment in crop yield. Green manures are quickly decomposable and have a significantly quicker impact on aggregate stability (Ansari *et al* 2022). Sultani et al. (2007) infer that incorporating green manures led to a 5% reduction in soil bulk density, an 8% improvement in total porosity, and a 28% increase in the proportion of macropores and large mesopores. Additionally, green manuring significantly enhanced available

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water for plants by 17% compared to non-green manuring practices. Schumann et al. (2000) found that green manuring with *Sesbania rostrata* and *Crotalaria juncea* notably increased water holding capacity, reduced soil erosion, prevented runoff, alleviated surface compaction, and mitigated hardpan formation, resulting in improved soil physical conditions. Moreover, green manures act as cover crops, minimizing soil erosion due to splashing and surface runoff, thus reducing water erosion by increasing surface roughness and decreasing wind speed near the soil surface. Souza and Santosh (2018) and Melo et al. (2019) reported that green manure incorporation into the soil plow layer improved organic carbon sequestration and nitrate-N content, while also benefiting soil physical characteristics.

4.2. Impact on Soil Chemical Properties:

Green manuring improves nutrient uptake efficiency, microbial biomass and water retention in the soil. High-quality green manure crops, such as legumes with low lignin content and C:N ratio, can be particularly effective (Gill et al., 2020). Green manure incorporation reduces soil pH and exchangeable sodium percentage in alkali soils. This reduction is due to increased organic acid production during green manure decomposition, which increases the availability of Ca2+ ions that exchange with Na+ ions in the clay complex (Rao and Pathak, 1996). Soil pH considerably decreased after leguminous manure incorporation into the soil in comparison to the initial soil pH, as manuring produces more anions during the decomposition by liberating hydrogen ions into the soil (Girma *et al* 2012). Legume crops have a symbiotic relationship with bacteria having the capacity to fix nitrogen, such as *Rhizobium*, allowing them to fix atmospheric nitrogen (Kumar et al., 2018). Roots are the main site of the symbiosis process to begins after the root nodule formation (Kumar and Hemantaranjan, 2017). Salahin *et al* (2013) found that the mixture of leguminous crops consisting of *Sesbania aculeata*, *Mimosa invisa*, and *Vigna radiata* supplied a significant amount of macro and micronutrients to the subsequent crops. When organic phosphorus (P) in green admixture tissues decomposes, it provides a labile form of P to the crop to be grown in sequence, providing more organic mineralized P to the soil to replace already existing organic P pools (Tiessen *et al* 1994). Green manure when decomposed, releases certain organic acids that aid in the solubilization of phosphate present in insoluble form. This process makes phosphate readily available to plants, thereby reducing the need for additional phosphorus fertilizer application to crops (Singh 1984; Hundal *et al* 1987). Significantly higher soil organic matter (SOM) and organic carbon content were recorded in the green-manured plots with Egyptian clover whereas the minimum was under where no green manuring was done. Similarly, Shabir et al. (2020) found that green-manured plots exhibited the highest availability of NPK, whereas plots where no green manuring was performed showed the lowest values for these nutrients. Singh *et al* (2009) outlined that the organic carbon and available macronutrients were significantly higher in *Sesbania* green manured plots at 60 days after sowing (DAS) followed by *Crotalaria* green manuring at 60 DAS whereas summer fallow recorded the lowest values of OC and available NPK, which might be due to mineralization of nutrients present in the green manures by the soil microbes. It also raises the humus content along with essential nutrient availability (Bindra and Thakur 1994). The incorporation of leguminous plants resulted in significantly higher total N, available P, exchangeable K, and OC (Abera and Gerkabo 2020). Idham *et al* (2021) concluded that with the application of *C. pubescent* at 10 t ha^{-1} resulted in the significantly highest nutrient uptake of nutrient due to its quick decomposition and mineralization by the soil microorganisms. Moreover, the soil pH and cation exchange capacity were found to be slightly declined with the incorporation of green manure which liberates organic acids during their decomposition into the soil and increases the number of anions in the soil. Application of partially dried tamarind (*Tamarindus indicus*) leaves resulted in the affirmation of soil salinity and its leaves create a favorable environment for the proliferation of soil microbes. Green manures such as *Pavetta indica*, *Thespesia*, *Azadirachta indica*, and sun hemp were capable of growing under saline conditions as well (Vakeesan *et al* 2008). Similar results were recorded by other scientists, that green manuring improved the availability of potassium, calcium and manganese (Katyal, 1977 and Nagarajah *et al* 1989). Figures 3 and 4 presents the effect of green manuring on the chemical properties of the soil under different crops.

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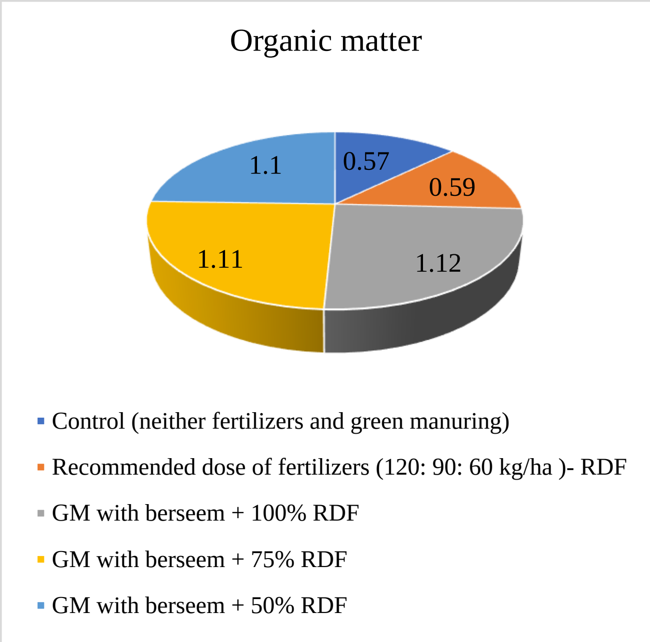

Figure 3. Impact of green manuring with berseem and fertilizer on soil organic matter content (average of three years) (Source: Naz *et al* 2023).

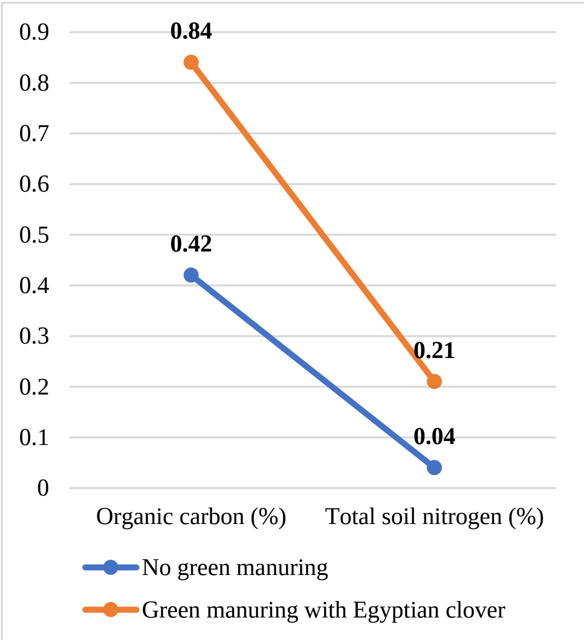

Figure 4. Impact of green manuring on organic carbon and total nitrogen content in the soil at the harvest of spring maize (Source: Shabir *et al* 2020).

4.3. Impact on Soil Biological Properties:

Organic matter serves as a habitat for numerous microorganisms, including bacteria, fungi, algae, protozoa, insects, and earthworms. Each of these organisms operates according to its unique set of rules and influences soil nutrient content (Pieters, 2006). In soil, after the decomposition of crop residues, simple carbohydrates are produced, which bacteria readily consume and multiply rapidly in the soil. However, fungi, being fast-growing and saprophytic, compete with actinomycetes for organic substrates during the initial phase. As the soil's easily utilizable carbon substrates become depleted in the later stages, actinomycetes thrive due to their capability to decompose and utilize relatively resistant organic compounds (Mukherjee *et al* 1990). Green manuring increased the

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availability of carbon substrates which in turn increased the microbial population of soil. In addition, legume-based green manures, are a significant source of nitrogen in crop production (Kataokaet *et al* 2017). The C: N ratio serves as the most reliable predictor for the maximum amount of nitrogen mineralized from crop residue. Green manure, characterized by a low C/N ratio and high nitrogen concentrations, undergoes rapid decomposition. As a result, the soil experiences maximum net nitrogen mineral accumulation within 2-4 weeks after its incorporation (Zhou et al., 2019). In this regard, Maiksteniene and Arlauskiene (2004) reported that the clover and lucerne green manuring resulted in higher mineralization rates owing to narrow C/N ratio. Enzymes play a vital role in natural nutrient cycling, a process influenced by agricultural practices (Yao et al., 2006). Enzymes often respond more rapidly to the alterations in methods of soil management than other factors, making their activity valuable as early indicators of biological alterations (Bandick and Dick, 1999; Masciandaro et al., 2004). Consequently, monitoring activities of enzymes and microbial biomass provides a proper indication of organic biomass turnover. Kautz et al. (2004) observed an increase in enzymatic activities following the incorporation of green manures. The decomposition of green manures are source of carbon and energy required for the growth and formation of new cell material, leading to the proliferation of colonies saprophytically on decomposing organic matter and conversion of unavailable nutrients into an available form (Ye et al., 2014). Dehydrogenase, an intracellular enzyme involved in oxidative phosphorylation processes (Trevors, 1984), has been noted by Garcia et al. (1997) as an indicator of soil microbial biomass. Dehydrogenase enzyme oxidizes soil organic matter through proton and electron transfer from substrates to acceptors. Dehydrogenase activity can be used as a high-quality indicator of overall microbiological activity because this indicator indicates the full spectrum of oxidative activity of soil microflora (Kzlkaya and Hepşen 2007). Higher dehydrogenase activity was observed where high doses of green manures were applied and did not include any type of toxic compounds to microorganisms (Tejada and Gonzalez 2006). Tejada *et al* (2008) revealed that when the soil was fertilized with 15 t ha^{-1} of T. *pratense*, a significantly higher activity of dehydrogenase was observed in the soil portion. Urease is a nickel-dependent enzyme that catalyzes the hydrolysis of urea to produce ammonium carbamate, which then readily gets hydrolyzed to produce carbonic acid and an additional molecule of ammonia (Andrews *et al* 1984). Surucu *et al* (2014) found that the green manuring of fababean leads to an increase in urease enzymatic activity. Green manuring enhanced the soil urease and dehydrogenase activities in comparison to conventional fertilization. When all of the fababean's components were used as green manure instead of beneath-the-ground stubbles, the increase in enzymatic activities was higher. Figures 4–6 depict the impact of green manuring on the biological properties of the soil under different cropping situations.

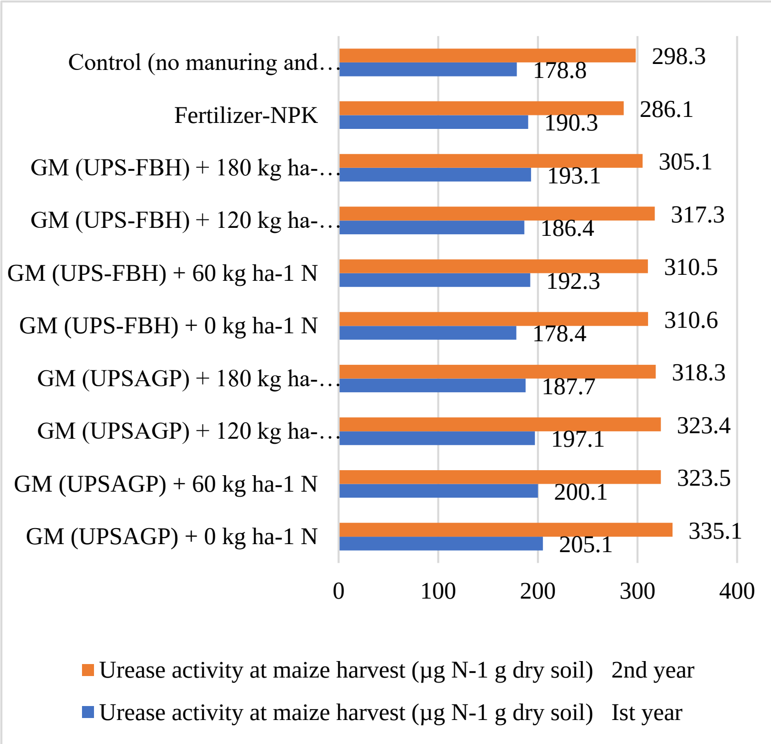

Figure 5. Impact of green manuring with Underground parts-stubble-above ground parts (UPSAGP) and Underground parts-stubble-Faba bean harvested (UPS-FBH) on urease activity in the soil at the harvest of maize under green manuring-maize-wheat cropping system (Source: Surucu *et al* 2014).

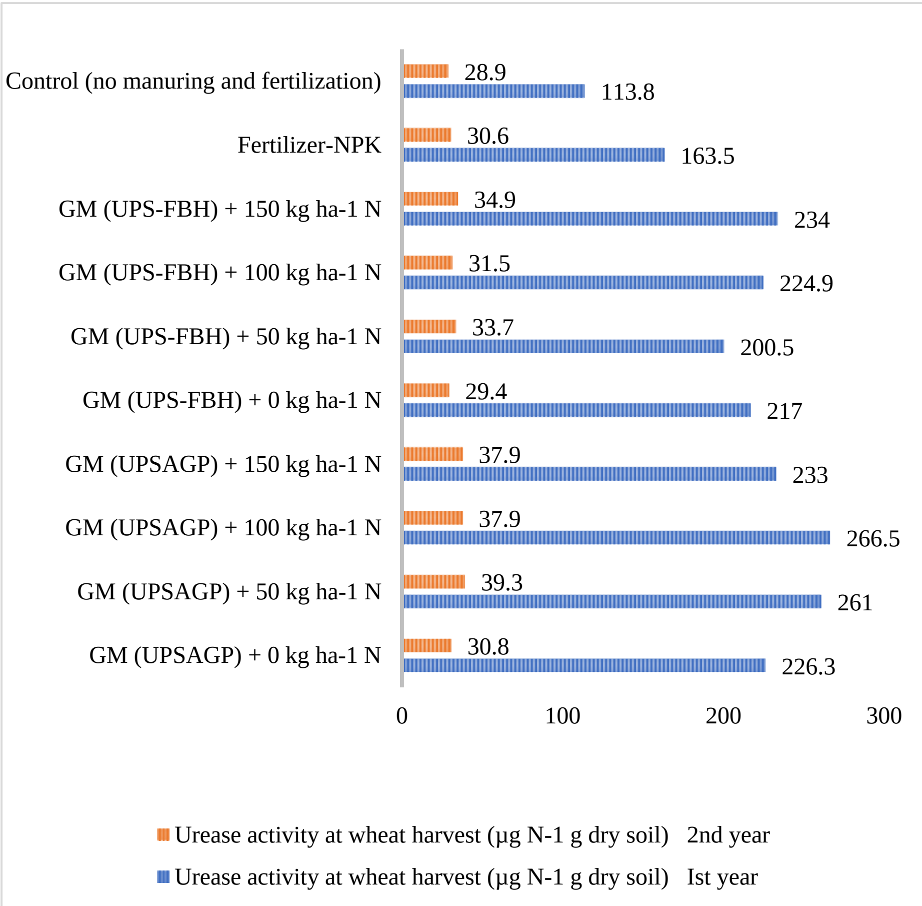

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Figure 6. Effect of green manuring (GM) with Underground parts-stubble-above ground parts (UPSAGP) and Underground parts-stubble-Faba bean harvested (UPS-FBH) on urease activity in the soil at the harvest of wheat under green manuring-maize-wheat cropping system (Source: Surucu *et al* 2014).

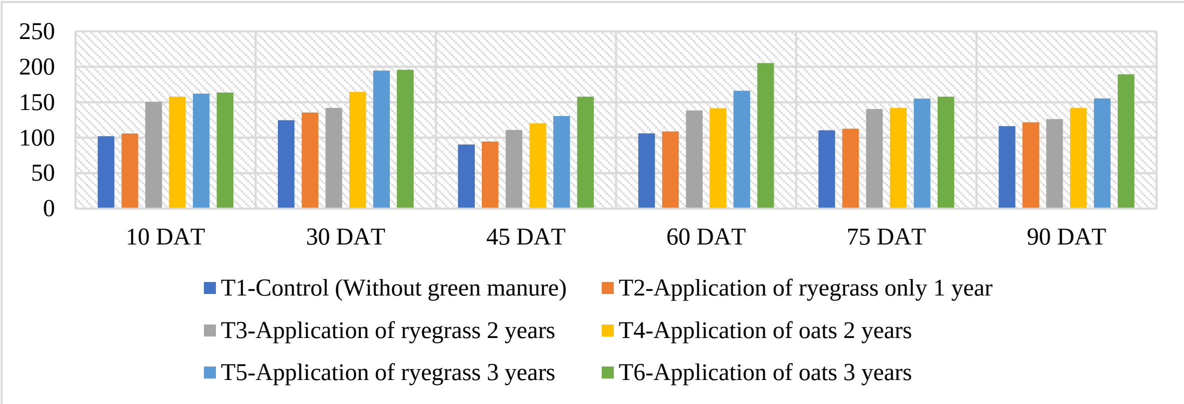

Figure 7. Impact of green manure on soil microbial biomass carbon (mg kg^{-1}) (Source: Ye *et al* 2014).

4. Role of Green Manuring on Crop Production

5.1. Impact of Green Manuring on the Productivity of Cereals

Leguminous crops are extremely efficient in binding nitrogen, reaching a peak during blooming and beginning to decline during seed development (Leinonen 2000). These crops play a dual role in soil enrichment, they not only contribute to soil nutrient status but also possess deep, well-developed root system that helps in the uptake of less accessible, deeply placed nutrients in different layers of soil. (Noordwijk *et al* 2015), enhancing the number of plant nutrients in the surface soil and decreasing the need for fertilization (especially N). Consequently, green manure crops can minimize the hazards of NO^{3-} leaching. In South Asia, dhaincha (*Sesbania aculeata*) and sun hemp are popular due to their ability to develop nodules that fix atmospheric nitrogen and add a sufficient amount of organic matter into the soil (Panneerselvam and Manuel 2004). Green manuring with dhaincha can be the substitute for meeting the 20 percent nitrogen requirement in rice (Qaswar *et al* 2019). The combination of Chinese milk vetch as green manure along with fertilizer (nitrogen) significantly improved the chlorophyll content in contrast to applying a single application of nitrogen fertilizer in rice (Xie *et al* 2017). Islam *et al* (2018) observed that green manuring with the *Crotalaria juncea* + 60 kg nitrogen fertilizer resulted in significantly higher panicle length, effective tillers, 1000 grain weight and grain yield of the desired crop. Behera *et al* (2022) revealed that the application of 75 percent soil test-based recommendation of nitrogen (STBNR) + *dhaincha* (GM) recorded a significantly higher crop growth rate.

The inclusion of peas and green manure crops following grain harvests notably enhanced wheat productivity (Sultani et al., 2004). Furthermore, Yadav et al. (2020) discovered that the residual impact of in-situ green manuring using sesbania in rice, coupled with foliar application of 0.5% chelated Zn-EDTA at 20, 40, 60, and 80 DAS, significantly improved yield attributes and grain yield of wheat compared to in-situ green manuring of rice bean, ex-situ green manuring using subabul, and summer fallow. Soil application of gypsum at one tone ha^{-1} along with in-situ green manuring with guar (40 days old) significantly increased the wheat grain yield (up to 38 percent) and soil moisture contents as compared to non-green manuring and farmer practice (traditional) due to organic matter addition which had a positive effect on the soil health (Kausar *et al* 2020). Muhammad *et al* (2022) recorded that the *Sesbania aculeata* (60 days old) + 75% N (90 kg N ha^{-1}) improved the SOM and nitrogen content that helped in the better establishment of succeeding crop i.e. significantly greater grain yield of wheat whereas sole green manuring can't ensure sustainable crop production as grain yield recorded

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was lower under the sole application. Green manuring with *Leucaena leucocephala* (subabul) as the green manure crop significantly increased wheat production by 11.7% (Palled *et al* 2000).

Makinde (2009) determined that combining the application of well-balanced high doses of nutrients with green manuring significantly influences the growth and development of maize. The findings of Bayer *et al* (2000), showed that legume cover crops, such as common vetch, can provide almost all of the N needed for the greatest possible maize production. In-situ incorporation of dhaincha along with the fertilizer. The addition of legumes as green manure in combination with 60 kg N ha^{-1} resulted in an increment in the recorded maize plant height, number of leaves per plant, and stem girth (Ibrahim *et al*2022). This study additionally revealed that legume incorporation may reduce the dose of N fertilizer applied to maize by 60 kg N ha^{-1}. Similarly, Hiremath *et al* (2020) found that significantly higher maize equivalent yield and system productivity were recorded under maize + sunhemp as green manure (43.82 q ha^{-1}) than the other treatments. Kumar *et al* (2019) concluded that the Zero tillage in maize and green manuring with *Sesbania* recorded significantly higher yield-attributing characteristics, grain yield, and net returns in maize.

5.2. Impact of Green Manuring on the Productivity of Oilseeds

A field experiment was conducted by Xu *et al* (2023), revealing the improvement in peanut pod yield and quality of the soil through the manipulation of microbial population in the rhizosphere and regulation of soil metabolites. Green manuring led to an increase in the population of carbon and nitrogen cycle-related bacteria, which consists of Acidobacteria, Actinobacteria and Sphingomonas, as well as carbon or nitrogen-related soil metabolites such as betaine, stachyose, raffinose, melibiose, trimethyl selenonium and 3-dehydrosphinganine. This, in turn, contributed to the augmentation of available carbon and nitrogen in the soil for plant uptake. Consequently, green manuring emerges as an effective strategy for overcoming continuous cropping challenges in peanut production systems by increasing nutrient cycling, soil metabolites, and the population of beneficial microbes in the rhizospheric region. Intercropping of legume green manure (Labadou) in between the rows of maize and its incorporation into the field before the sowing of rapeseed reduced the nitrogen fertilizer addition in rapeseed (Gu *et al* 2021). Over two consecutive years of field experiments, it was observed that incorporating 19–24 tons per hectare of legume green manure could substitute for 25-35% of nitrogen fertilizers. Due to this practice, the content of soil organic matter increased which resulted in a significant increase in the seed yield of mustard. This approach proves to be a promising, sustainable, and cost-effective method for enhancing soil fertility (Gu *et al* 2021). Conjugated application of manure at 20 t ha^{-1} derived from animals along with fenugreek green manure significantly improved the seed yield of sesame. With the addition of animal manure, phosphorus and potassium availability increased by 15%, respectively (Jalilian *et al* 2022). Ghalavand et al (2009) revealed that the combined application of green manure and mycorrhiza practices boosted sunflower yield and nutrient content, with mycorrhizae enhancing phosphorus and another nutrient uptake. Thind *et al* (2007) reported the residual effect of green manuring with *sesbania* under a potato-sunflower cropping system and found significantly higher LAI, growth parameters and seed productivity of sunflowers due to higher availability of nutrients.

5.3. Impact of Green Manuring on the Yield of Fiber Crops

Blaise *et al* (2005) found that the upland hybrid cotton productivity was significantly influenced by in situ green manure in comparison to conventional tillage. Green manuring with (*Crotalaria juncea*) improved the physical as well as chemical properties of the soil resulting in better plant growth and an increased plant height, main stem number per node, dry matter accumulation, and seed cotton yield. Improvement in grain yield was due to increased organic carbon content and better nutrient availability (Blaise 2011; Figure 8). Green leaf manuring with 75% RDF + *gliricidia* resulted in a significant increase in soil organic carbon content, microbial biomass carbon and higher availability of micro and macro nutrient in contrast to chemical fertilizers alone this might be due to G*liricidia* is effective in substituting the fertilizer requirement of rainfed cotton and thus, improves the yield attributes and seed cotton yield (Gabhane *et al* 2023). Pawar *et al* (2020) stated a significant increase

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in the yield of cotton (12.26 q ha^{-1}) in salt-affected under in-situ green manuring of dhaincha and sunhemp. Though, cotton yield under dhaincha and sunhemp in-situ green manuring was statistically at par with the application of gypsum at 2.5 t ha^{-1}, it indicates that green manures have the same potential to increase the crop yield as chemical fertilizers in sodic soils. Conjugated application of chemical fertilizer along (*Gliricidia sepium*) resulted in significantly higher nutrient uptake by cotton in vertisols and higher cotton stalk yield (3067.2 kg ha^{-1}). Praharaj *et al* (2009) worked on sustaining soil fertility and cotton productivity via in-situ incorporation of green manure and it was found that the simultaneous sowing of cotton and sunhemp under ridge furrow system, followed by the incorporation of sunhemp at 2.5 t ha^{-1}, improved cotton productivity significantly (1.70 t ha^{-1}). Saha et al. (2008) documented a notable rise in mesta fiber yield resulting from the integrated application of inorganic fertilizer and green manures. Application of inorganic fertilizers with 50% N requirement through green manure dhaincha + 50% N requirement through urea significantly enhanced the availability and uptake of nutrients and minimized the dose of inorganic fertilizers. Hence, resulted in a significantly higher fiber yield of jute as compared to the control (non-manured) due to the synchronized and quick release of nutrients from the inorganic as well as green manures (Mitra *et al* 2010).

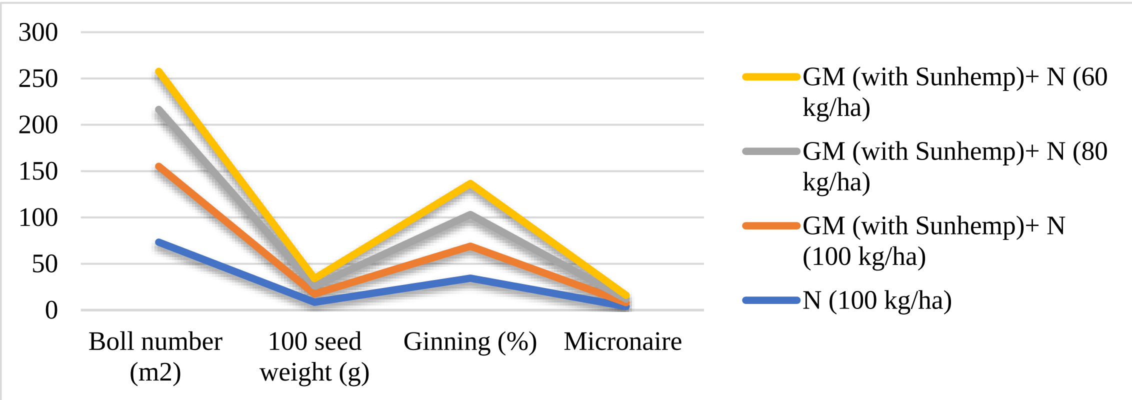

Figure 8. Influence of green manuring with sunhemp (*Crotalaria juncea*) on the number of bolls (m^{-2}) and fiber qualities of cotton (Source: Blaise 2011).

5.5. Impact of Green Manuring on the Yield of Sugar Crops

Combined application of biofertilizer (*Azotobacter* at 10 kg ha^{-1}) and green manuring with *Crotalaria juncea* along with RDF twice (one and three months after planting) showed significantly higher uptake of nitrogen, length of the stalk of sugarcane and cane yield of sugarcane (Djajadi *et al* 2020). A study conducted by, Bokhtiar *et al* (2003) noted that combining chemical fertilizer and green manuring with S. aculeata 45 days after sowing (DAS) led to a marked increase in the growth, yield attributes such as the number of millable cane stalks, total number of tillers, and cane yield. The elevated cane yield was attributed to the mineralization of green manure, subsequently enhancing nitrogen availability for plant uptake and thereby promoting better cane growth. Application of nitrogenous fertilizers at 180 kg ha^{-1} and green manuring with sunhemp recorded a significant increase in the total number of millable canes, number of tillers, stem girth, plant height, stalk weight, cane yield of sugarcane and brix percentage (19.70 (Kabiraj *et al* 2017). A significantly higher tiller count was obtained with sugarcane + sunhemp (as green manure crop) over the sole crop (sugarcane) (Roodagi *et al* 2000). Similarly, Jayapal *et al* (2000) also found that the sowing of two rows of *Sesbania aculeata* in between rows of sugarcane along with the application of 75 percent of the recommended nitrogen dose produced a higher number of millable canes, tiller count, economic cane yield and juice quality. They also found that green manuring with *Sesbania* alone produced cane yield (60–80 t ha^{-1}), which was significantly higher than the control.

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5. Increase in Economic Yield under Green Manuring

Green manuring results in improved soil environment and properties which in turn improve the nutrient availability, hence, absorption and assimilation in the plant. Higher grain yield, thus, obtained helps in achieving higher farm economies. Table 4 presents the improvement recorded in the economic yield of different crops due to green manuring compared to the non-manured fields.

6. Residual Effect of Green Manuring:

Pre-*kharif* green manuring with blackgram under a rice-wheat cropping system resulted in significantly higher yield attributes and yield of rice (5.87 t ha^{-1}). Building upon that, wheat planted following rice cultivation demanded fewer nutrients. The findings indicated that plots treated with green manure yielded significantly higher wheat crops compared to plots solely fertilized with chemicals. (Gautam *et al* 2021). Application of *Sesbania aculeata* before the transplantation of wetland rice resulted in increased water-stable aggregates of size 0.1-0.5 mm, reduced soil bulk density, higher organic matter content and increased infiltration rate in comparison to un-manured plots. Improved wheat yield was recorded due to better wheat root development as green manuring decreased the bulk density of the soil in the upper soil layer and improved other soil physio-chemical and biological conditions of soil (Boparai *et al* 1992) than un-manured plots. During *pre-kharif*, brown manuring with sunnhemp sown in 1:2 row (Sunhemp: Maize), recorded significantly higher yield attributes and grain yield of maize (55.35 q ha^{-1}) as compared to sole maize (43.85 q ha^{-1}) without brown manuring. It also showed a positive residual effect on succeeding wheat crops and significantly higher straw and grain yields of wheat (Hiremath *et al* 2020). Mandal et al. (2003) discovered that incorporating green manures like Sesbania and green gram led to a noteworthy enhancement in yield attributes and rice yield, while also contributing to the overall improvement of soil health. Furthermore, besides the positive impacts on rice, the adoption of green manuring practices in the rice-wheat cropping system notably improved the growth and yield of the subsequent wheat crop.

7. Biological Nitrogen Fixation by Green Manuring (Mechanism)

It has been estimated that biological nitrogen fixation accounts for 80–90% of the nitrogen available to plants in natural ecosystems. This process, performed by prokaryotes, involves the reduction of molecular nitrogen to ammonia, which is subsequently assimilated by plants in the form of amino acids (Figure 9). This is a crucial event as it allows for the recovery of nitrogen that is irreversibly lost in ecosystems due to bacterial activities. Nitrogen fixation contributes approximately 200 million tons of nitrogen per year to the Earth's ecosystem (Meena *et al* 2018). Various nitrogen-fixing prokaryotes, occurring either as free-living organisms or in symbiosis with plants, are detailed in Table 5.

The symbiotic associations mentioned above hold significant importance:

1. Symbiosis occurs between aerobic bacteria (rhizobia) and the roots of Leguminosae plants. This association leads to the formation of root nodules, facilitating nitrogen fixation. Leguminous plants produce flavonoid compounds that interact with nitrogen-fixing bacteria, triggering nodule formation on the roots. Consequently, leguminous waste can serve as raw material for composting, providing the added benefit of containing nitrogen-fixing bacteria (Corti et al., 2012).
2. Another essential symbiosis involves aerobic diazotrophic actinomycetes of the genus Frankia and the roots of actinorhizal plants. In this case, root nodule formation occurs, along with mechanisms for nitrogen fixation.

Additionally, among free-living organisms, oxygenic photosynthetic cyanobacteria play a crucial role. They engage in photosynthesis, combining with atmospheric oxygen (O_2). The incorporation of organic nitrogen into natural ecosystem food chains primarily stems from the activity of photoautotrophic organisms such as cyanobacteria, algae, and terrestrial plants. These primary producers absorb nitrogen from the environment, primarily in the form of nitrate, reducing it to ammonia, which is then assimilated into organic compounds to form amino acids.

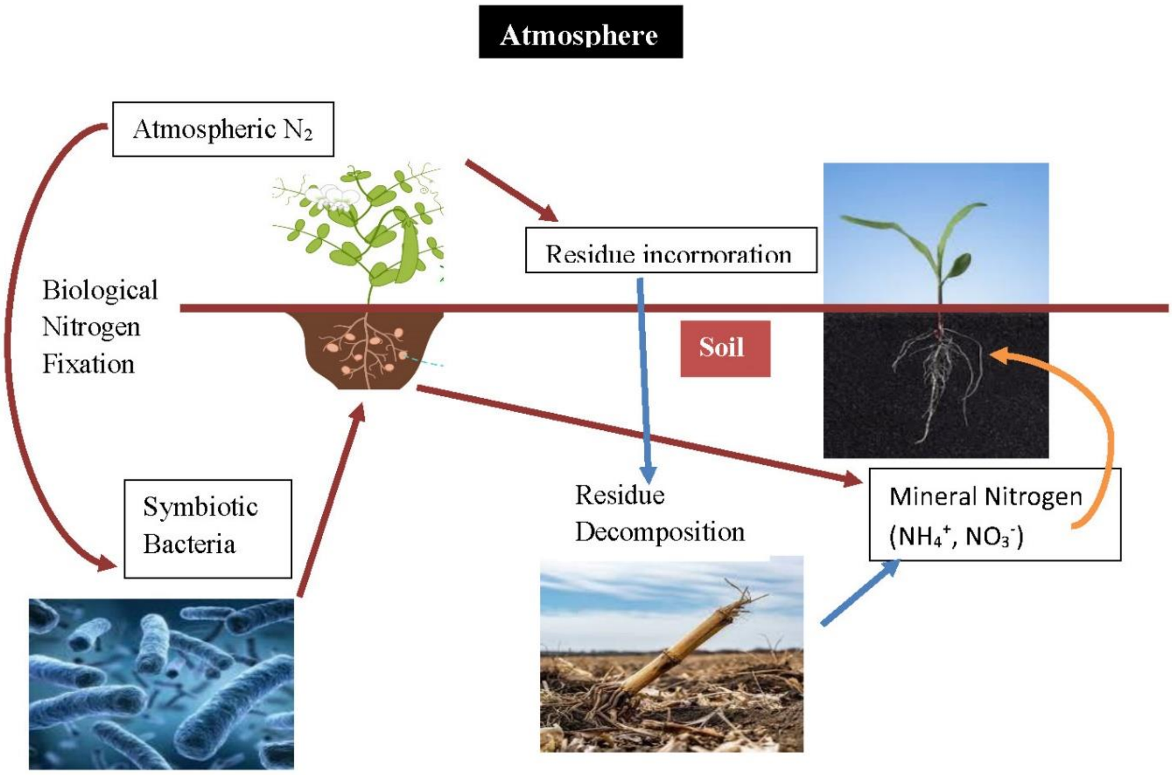

Figure 9. Nitrogen fixation and mineralization of legumes green manure in the soil. (Source: Meena *et al* 2018).

3. Role of Green Manuring in Organic Farming

One of the most crucial problems associated with organic farming is the management of soil fertility. In this agricultural method, fertilization with organic and natural materials is required. Leguminous crops grown as green manures aid in boosting water holding capacity, soil organic matter, microbial biomass, and nutrient use efficiency. Additionally, it results in a decrease in soil erosion as they act as cover crops. Macro, as well as micronutrients to the plant, can be delivered more effectively by applying high-quality leguminous green manure crops because legumes have a low C:N ratio and low lignin content. Legumes are commonly chosen as green manure crops due to their ability to fix atmospheric nitrogen symbiotically with Rhizobium bacteria in root nodules, leaving a portion available for use by companion or subsequent crops (Iderawumi and Kamal, 2022). Dhaincha, sunhemp, mung bean, and guar cultivated as green manure crops during the Kharif season have been found to contribute between (8-21 tons/ha) of green matter and (42-95 kg/ha) of nitrogen. Similarly, khesari, cowpea, and berseem grown as green manure crops during the rabi season can add 12 to 29 tons of green matter and 67 to 68 kg of nitrogen per hectare (Mishra and Nayak, 2004). There are two primary sources of nutrients the decomposition of organic matter and the breakdown of soil minerals. The release of nutrients from organic materials through microbial decomposition can start within a few days and last for many years and centuries (Saskatchewan Agriculture and Food, 2006). In contrast to this, the release of nutrients from soil minerals through their breakdown is a much slower process in comparison to decomposition and may take centuries for a reasonable amount of nutrients to be released. Carbon, nitrogen, zinc, and other plant nutrients from organic inputs are retained depending on the population of microorganisms in the surrounding soil environment (Dannehl *et al* 2017; Costerousse *et al* 2021 and Kassio *et al* 2017). Soil microorganisms convert nitrogenous and carbon molecules present in green manures into nutrients that plants can receive easily (Leonard, 2021). In the plants, the roots absorbed a higher concentration of nutrients than the shoots (Zandvakili *et al* 2017). When compared to controlled fields, the green-manured plots increased organic matter reserves significantly and improved the overall cycle of nitrogen fixation

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and organic matter due to the addition of green manure legume crops. Enhanced soil attributes resulting from the positive impact of green manuring lead to increased agricultural yields (Egodawatta *et al* 2011). Therefore, green manures play a vital role in the nutritional point of view of organic farming.

4. Potential of Green Manuring in Integrated Nutrient Management (INM)

Integrated use of both organic and inorganic nutrient sources i.e. nutrient management involves the coordinated utilization of organic and inorganic fertilizers, green manuring, crop residues, and soil amendments to uphold the soil physico-chemical and biological properties which in turn enhances the nutrient use efficiency. Key components of integrated nutrient management include soil testing, organic amendments, inorganic fertilizers, crop rotation, and green manuring. Organic inputs such as green manures, compost, farmyard manure (FYM), vermicompost, crop residues, and bio-fertilizers play pivotal roles in maintaining soil fertility and ensuring stable yields (Lamessa, 2016). The basal application of chemical fertilizer in conjunction with in-situ green manuring using cowpea has been shown to result in significantly taller plants, increased leaf number, greater total dry matter accumulation, higher leaf area index and enhanced tuber yield of potatoes compared to other treatments (Prabhudeva et al., 2018).The complete decomposition and mineralization of nutrients, through green manure, supply the nutrients to the plants and solubilizes the insoluble nutrients into available form for plant uptake. These findings are in alignment with the findings of Sepehya *et al* (2012) and Majumdar *et al* (2007), who have also concluded that integrated application of green manures along with inorganic fertilizers sustained the productivity of crops as well as maintained soil fertility. The conjugated use of green manures and chemical fertilizers also decreased the overall losses of nitrogen such as volatilization, denitrification, leaching, etc. Boosting the nitrogen (N) dosage has been shown to elevate volatilization losses, whereas incorporating green manure at lower N levels (up to 40 kg ha^{-1}) has been observed to reduce these losses (Sommer, 2004). Moreover, the integrated application of Sesbania green manure and $(NH_4)_2SO_4$ has demonstrated increased overall nitrogen utilization compared to separate applications (Huang and Liao, 1992). Split applications of green manure and urea (prilled) have resulted in notably higher grain yields with relatively minimal N losses through volatilization and leaching (Selvi and Kalpana, 2009).

Green manure as pest management

On average, it is estimated that diseases contribute to one-third of the total losses incurred through various factors such as attack of insects, weed infestation and rodents, etc. While for the management of pests and diseases chemical pesticides, insecticides, and seed treatments play a vital role, there is a growing preference for environmentally friendly, integrated and sustainable pest management techniques (Rani et al., 2022). Research has shown that employing green manure aids in the management of various types of agricultural pests and diseases, decreases soil erosion, controls weeds, and acts as a substrate for the proliferation of beneficial microbes, alongside enhancing soil health and fertility (Table 6). Green manuring enhances soil microbial activity, promotes microbial diversity, and increases microbial density in the soil. Once the beneficial microbial population is established, the pathogens are suppressed through phenomena such as competition, predation, parasitism and antibiosis etc (Davis *et al* 1994). Green manures contribute to the enhancement of microbial communities, including bacteria, non-pathogenic Fusarium species, Streptomyces, and other Actinomycetes. Rhizobacteria through the production of antibiotics plays a key role in disease suppression. There are six classes of antibiotic compounds associated with the bio-control of root diseases, namely, pyoluteorin phloroglucinols, pyrrolnitrin, hydrogen cyanide, and phenazines cyclic lipopeptides (Haas and Defago, 2005). The use of brassica crops such as mustard, rapeseed, turnip etc., as green manures has been shown to reduce the attack of diseases, nematodes and weeds, along with the improvement of soil characteristics and economic yield as *brassica* species produce glucosinolates and its break down to produces isothiocyanates, which are volatile toxins similar to those produced by the commercial fumigant that acts as bio-fumigants that suppresses the disease (Guire, 2003). Green manuring with *S. aculeata* reduced mycelial growth and sclerotia production significantly (Kumar 2010). Cruciferous plants containing glucosinolates inhibit fungal growth,

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particularly that of Pythium spp. (Lazzeri and Manici, 2001). Green manures have proven effective against various vegetable diseases. For instance, the application of lucerne hay was successful against Sclerotinia sclerotiorum in lettuce, while lucerne residues were effective against root rot in peas caused by *Aphanomyces outreaches* (Williams-Woodward et al., 1997). Additionally, the use of buckwheat in potatoes helped control common scab and verticillium wilt (Wiggins and Kinkel, 2005). Manure also serves as a habitat for certain predators such as carabid and staphylinid beetles (Collins et al., 2006). Likewise, green manure crops that flower like crimson clover and buckwheat attract insects such as ladybirds, hoverflies, lacewings, and predatory and parasitic wasps.

Certain green manure crops like *S. rostrata* and *Aeschynomene afraspera* have been effective in controlling harmful nematodes in rice, such as *Hirschmanniella mucronata* and *H. oryzae*, (Prot et al., 1992). Green leaves incorporation of *Thespesia spp.*, *Calotropis gigantea*, *Azadirachta indica*, *Gliricidia maculata* and *Glycosmis spp.* has been shown to reduce *Meloidogyne incognita* infestations in the Amazon (Pakeerathan et al., 2009; Wang et al., 2002). Furthermore, *Crotalaria* spp. assists in managing infestations of *Meloidogyne javanica* and *M. incognita* (Germani and Plenchette, 2004).

Table 6. Examples of the diseases suppressed by green manures.

Name of the Disease	Suppressed by green manure	Source
Common scab (*Streptomyces scabies*) in buckwheat	*Sesbania aculeata*	Wiggins and Kinkel (2005)
Verticillium wilt (*Verticilium spp.*) in potatoes	*Sesbania aculeata*	
Common root rot of pea	Lucerne	Williams-Woodward *et al* (1997)
Tomato southern blight (*Sclerotium rolfsii*)	Rye-vetch	Bulluck *et al* (2002)
Nematodes *Hirschmanniella mucronata* and *H. oryzae* in rice	*Sesbania rostrata* and *Aeschynomene afraspera*	Germani and Plenchette (2004).
Nematodes *Meloidogyne incognita* and *M. javanica*	Rapeseed and hairy vetch grown together and *Crotalaria* spp.	Germani and Plenchette (2005)
Soil-borne fungi *Sclerotinia* spp.	Brassica green admixture	Pung *et al* (2004)
Soil borne fungi viz., *Rhizoctonia solani, Sclerotinia sclerotiorum and Sclerotium rolfsii*	Green manuring with *Sesbania aculeata*	Kumar (2010)
Leaf spot and leaf blight in maize	Calopogonium-Pueraria mixture	Saquee *et al* (2023)
Pythium spp.	Cruciferous crops exhibit the capacity to generate various types of isothiocyanates (ITCs), which are recognized biofumigant chemicals. Squee discovered that these crops are linked to decreases in soil levels of borne pathogens and diseases affecting potatoes at varying degrees.	Lazzeri and Manici (2001)
Black scurf and scab disease in pot	Mustard green manuring	Sexton *et al* (2007)
Downy mildew (*Peronospora parasitica*) on brown mustard	*Brassica carinata*	Michel *et al* (2014)

and powdery mildew (*Erysiphe graminis*) on rye	

5. Constraints in Green Manure Production

Several challenges are hindering the widespread adoption of green manuring practices among farmers in intensive cropping systems. These difficulties encompass the hesitancy to dedicate six to eight weeks solely for cultivating green manure crops, frequently stemming from constraints like limited water supplies and the absence of high-quality seeds. Additionally, the sensitivity to photoperiodism during peak summer months, particularly in regions where rice follows a wheat crop, poses difficulties for farmers working in the fields. Moreover, farmers may be dissuaded by the less immediate impacts of green manuring compared to inorganic fertilizers, as well as the relatively high sowing and then incorporation costs. (Iderawumi and Kamal 2022). The narrow window period between crops further complicates the timing of growing and incorporating green manure. If these crops are not incorporated at the proper growth phase and time, there is a risk of temporary immobilization of nitrogen due to their higher lignin content and carbon-to-nitrogen ratio. Additionally, green manuring may not be suitable for water-intensive crops under dryland agriculture (Gill et al 2008 and Meena 2013). Difficulties with decomposition may emerge when sowing the subsequent crop if adequate moisture is not present, particularly in semi-arid areas. Moreover, the absence of immediate economic gains during the initial phases of green legume manuring, along with the convenience of accessing and using mineral fertilizers, adds to farmers' reluctance to embrace green manuring methods. Additionally, the comparatively lower costs of mineral fertilizers in contrast to the high expenses associated with land and labor also reinforce the inclination towards conventional fertilization approaches (Aase et al., 1996).

6. Future Concerns

The degradation of land caused by human activities is concerning, particularly as improper agricultural practices lead to soil fertility decline. Green manures are pivotal in addressing this issue, influencing the physicochemical and biological attributes of soil positively, thereby enhancing its fertility. Through intensification of crop rotations with legumes, it facilitates the fixation of atmospheric nitrogen in the soil, alongside mitigating soil erosion and nutrient depletion. Incorporating green plant matter into the soil effectively ameliorates problematic soils. Additionally, green manuring aids in weed, disease, and pest management. In summary, to achieve enhanced soil health and agricultural sustainability, green manuring emerges as a viable option for tropical and subtropical climates.

Future research focusing on legumes as green manures should prioritize the following areas:

(a) Numerous research findings worldwide have underscored the advantages of green manures in enhancing soil physical, chemical and biological health. However, the application of these findings on farms remains limited due to a lack of awareness.

(b) It is essential to quantify the advantages of green manuring w.r.t. fertilizer and water savings, increased crop productivity, and soil health enhancement.

(c) Developing location-specific cropping systems is imperative, incorporating compatible legume green manure crops either partially or during the interim period between two crops.

(d) Innovative techniques, such as brown manuring of legume crops grown as intercrops, need to be devised to save time and eliminate the need for incorporation.

Conclusion

Implementing green manuring techniques presents a hopeful remedy for the obstacles encountered in contemporary agriculture. By reducing reliance on chemical fertilizers and improving soil health, green manuring promotes sustainable crop production while mitigating environmental impacts. Leguminous green manures, in particular, contribute significantly to nitrogen fixation and soil fertility enhancement. Despite challenges such as water scarcity and farmer reluctance, the potential benefits of green manuring underscore its importance in achieving agricultural sustainability. Future research should focus on addressing these challenges and optimizing green manuring practices to ensure its widespread adoption and long-term benefits for soil health and food security.

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