Potential Impacts of Green Manure Incorporation on Soil Fertility Enhancement and Rice yield

Abstract

Soil green manure amendment is a potential agricultural practice for soil fertility management and conservation of ecosystem. Common green manure plants such as sunn hemp, dhaincha and pulses have different nature and ability to contribute essential nutrients for plant growth and carbon sequestration. Those plants are ultimately serving as a supplement or replacement for chemical fertilizers. Producing of nutrients from green manure amendment by decomposition and mineralization processes is influenced by quantity & quality of green manure and soil properties. Therefore, management of green manure to be efficient and synchronize crop demands is essential. Management on days to harvest, incorporation days into soil and amount of green manure is based on its C/N ratio and biomass obtained which are changing with the age. Rice is major crop and ultimately producing in topical Asia and the it is increasing to meet the demands of increasing population. The study focused on green manure amendment and its impact on rice yield. Incorporation of green manure enhances nitrogen and carbon balance in the soil while decreasing the need for chemical fertilizer applications, ensuring to improve rice yields. Rice yield by the application of only green manure 20 ton/ha application was 90% higher than that without nutrient application. Then, combine application of sunn hemp and chemical nitrogen fertilizer increases rice yield 8-17% than the only chemical nitrogen fertilizer. By combination of green manure 20 ton/ha and chemical N fertilizer 60 kg/ha produced higher yield than only double chemical N fertilizer rate of 120 kg/ha. Similarly, the synergistic effect of organic compost and green manure significantly increased the benefits of green manure alone. In terms of soil fertility, green manure amendment provides plant essential nutrients and improve physical and biological properties as well. Therefore, the practice of green manuring shows promising potential for positively influencing soil health, thereby contributing to the sustainability of crop yields.

Key words: green manure; nitrogen; carbon; rice yield.

1. Introduction

Effective soil management practices enhance soil organic carbon, thereby increase sustainability in crop production. At the same time, it can safeguard the environment by reduction of greenhouse gas (GHG) emission which contribute significantly to global warming. Proper rational contribution of chemical fertilizers and organic matter will improve soil physical, chemical and biological properties thereby improve soil health. Currently, agricultural sector faces the challenges of limited nitrogen use efficiency and escalating cost of fertilizers, at the same time deficient soil fertility is demanding more nutrients. Enhancing efficiency and the judicious use of chemical and organic fertilizers can mitigate these challenges and benefit the environment.

Utilizing leguminous green manure crops is particularly beneficial as they have the ability to fix atmospheric nitrogen, thereby reducing the fertilizer requirements for subsequent crops. Recently, alternatives such as green manure, compost, and farmyard manure have been recognized as sustainable sources of nutrients, promoting soil fertility while also reducing fertilizer costs and ensuring ecological stability. In fact, the availability of farmyard manure and compost can be limited, especially for field crops requiring substantial quantities to have enough amount to improve its soil fertility. Mostly, farm residues are not in proper management since time and resouces are limited. As a result, soil fertility is decreasing and favour to use chemical inputs more and more. In contrast, green manures are more readily accessible and require less labor and other resources. It provides not only nutrients to the crops, sustaining high microbial biomass and high rate of enzyme activities in the soil (Sara 2006) [45].Sunn hemp, dhaincha, pulses, azolla and etc. are commonly used as green manure.Various kinds of green manure plants have different adoptability and nature and different contribution of biomass and nutrient contents. It is important to have wise management practices for different green manure plants for efficient contributions.

Green manuring involves incorporating undecomposed or fresh organic matter either locally or from a distance (Pieters 1927) [1]. Green manures stand as a biologically sustainable and ecologically friendly option, providing dual advantage of boosting crop yield and ensuring soil fertility within sustainable agricultural approaches (Singh et al., 1991) [2]. By combining chemical fertilizer N with green manures, a sustainable and environmentally responsible agricultural system can be fostered.

Global rice production is 525.5 million tonne in the year 2022-23 and predominantly produced from Asia (FAO 2024) [54]. In order to meet the demand of the current world population which will be 9.7 billion in 2050, sustainable production has to be continued. According to the literature review, it was found that green manuring effect significantly on increasing rice yields. Various rational combination of Nitrogen chemical fertilizers and green manure provide different impacts on rice yields. The paper aims to observe the common green manure plants and their potential contribution of nutrients various management practices and potential impacts on soil fertility and rice yields.

2. Nature and Adoptability of Potential Green Manure Plants

Green manuring is an ancient practice. China has a 3000 years history of using green manure for soil fertility improvement and crops yields. By the end of 1970, the green manure cultivating area was reached to 10 million ha, mostly, it was planted in the rice fields. Afterwards, cultivating area was decreasing due to the substitution of chemical fertilizers. Currently, only 2-3 million ha are planted with green manure (Cao et al.,2009) [46] (Yang et al.,2012) [30]. Development of green manure plants depends on suitable soil and climatic conditions of a particular area**.** There are two types of green manure such as in situ green manure which can be grown in the field and green leaf manure which are collected from shrub and trees (Singh et al 2013) [48]. The most commonly used green manure plants are focused in the paper as following.

2.1 Sunn hemp can be adopted to soil ranging from coarse to fine textured and on infertile as well as fertile soil. It grows best on well-drained soil with pH level from 5 to 7.5. Flowering will start at the days from 65 to 90 days. Its life span is 150 days (Rotar and Joy 1983) [3]. It is prominent fiber crop due to its use as green manure and fodder. It is very sensitive to wet soil conditions especially for 10 days after germination of seeds. After 60 days of planting, it will start to be woody and cutting into small pieces at the time of termination. It can be excellent for its rapid growth and relatively short growing season (NRCS 2011) [47]. It has root nodules and requirement of seed rate is 25 to 35 kg/ha.

2.2 Dhaincha is a quick growing succulent outstanding green manure crop. It can adopt well in waterlogged and alkaline soil. It prefers waterlogged condition. *Sesbania rostrata* has nodules on both stems and roots and it can adopt various conditions of soil and climate.It is widely recommended as green manure in many Asian countries because of its high biomass yields and flood tolerance. It is most suitable for pre-rice green manure in rainfed rice farming system (Garrity and Becker 1994) [4]. At 84 days after planting, dhaincha becomes woody and necessary to bury it about 30 to 60 days after planting for decomposition before planting rice (Singh and Kalamdhad 2014) [5]. Recommended seed rate of dhaincha is 20 to 25 kg/ha and it needs to be scarified with concentrated sulphuric acid for 15 mins and then washed with water and sown immediately(Singh 2013) [48].

2.3 Pules such as green gram, black gram, cow pea, pigeon pea is commonly grown as green manure. The leguminous crops have ability to fix nitrogen during growing and provide green matter nitrogen when incorporated into soil. Pulses contain much protein which is required for human, afterwards its residue can provide green manure. An assessment of dry matter and nitrogen yield of various kinds of pulses mentioned that cow pea produce the highest mean dry matter of 2367 kg/ha and 1.143% of N (Shah, Ahmad and Rahman 2011) [6]. They are known as fast growing plants and short duration, high tolerance to biotic & abiotic stress and high seed production (Meena et al.,2015) [49].

Even though, there are many kinds of green manure plants, above mentioned green manure plants are commonly applicable to the field. Those plants are adoptable to many soil types, however dhaincha prefer waterlog condition whereas sunn hemp does not. They can adopt wide range of soil pH but pules cannot adopt soil pH under 5. Days to harvest are more or less similar for both sunn hemp and dhaincha at 50 to 70 days whereas pulses has shorter days to harvest. Biomass contributions for both sunn hemp and dhaincha are similar to each other, however pulses provide less biomass. All of them can fix the atmospheric nitrogen. In fact, the amount of N fixation and biomass contribution depend on their specific age at the time of harvest. Different management on green manure plants and their biomass and nitrogen contributions are mentioned in the table 1.

Table 1. Harvesting days and potential biomass availability of different green manure plants

Sr.	Green Manure	Day to Harvest (days)	Fresh Biomass (ton/ha)	Dry Biomass (kg/ha)	N (kg/ha)	Reference
1.	Sunn hemp			5000-11500	100-200	(Ozores- Hampton 2012) [7]
	Sunn hemp	70	15 -20		75-80	(Singh et al.,2014) [5]
2.	Dhaincha (*Sesbania aculeata*	56-70	10-20		75-80	(Singh et al.,2014) [5]
	Sesbania rostrata	56-70	15-20		150-180	(Singh et al.,2014) [5]
	Sesbania rostrata	40-60			50-70	(Kolar et al,1993., Manguiat et al.,1992;

						Meelu et al.,1992) [8]
3.	Pulses (cow pea)	49		4400	95	(Singh 1984) [9]
	Pulses (cow pea)			2354	25.09	(Shah, Ahmad and Rahman 2011) [6]

Green manuring is used to be practiced in different forms such as incorporation into soil in situ before cultivating next crop, simultaneous cultivation with main crop and cut & carry from other annual or perennial leguminous trees. Regarding to crop establishment, fertilizer application is usually not practiced in green manure plantation. However, phosphorus application in sesbania (dhaincha) produce 4.2 ton/ha dry matter yields and 105 kg N/ha nitrogen content while 4 ton/ha of dry matter and 88 kg N/ha was obtained without Phosphorus application (Singh 1984) [9]. The effects of different green manure plants on rice yield and soil nitrogen balance are shown in the table 2.

Table. 2 Effect of different green manures on rice yield and soil nitrogen balance

Green manure crops	**Green matter (tonne/ha)**	**N added (kg/ha)**	**Rice grain yield (tonne/ha)**	**Increase percent over no green manure**	**Soil N percent with continuous with green manure**
Sunn hemp	27.8	134	3.47	198	0.109
Dhaincha	21.1	133	3.62	207	0.141
Cowpea	21.0	74	3.33	180	0.101

(Shah, Ahmad & Rahman 2011) [6]

3. Decomposition and Mineralization Process in Soil

Incorporation of legume green manure into soil undergoes decomposition and mineralization process (Meena et al., 2018) [10]. Decomposition is a biological breakdown and transformation of complex organic compounds into simpler organic and inorganic molecules (Fox et al. 1990) [11]. Mineralization is the process of conversion of organic carbon and nitrogen to plant available mineral forms. NH_4 -N and NO_3 N are released from mineralization process. Those processes are affected by the types of soil, crops, crop growth stage at which it is incorporated, and prevailing climatic conditions.Among these, the dominant factors are the quantity and quality of green manure crops (Meena et al., 2018) [10]. Decomposition rate depends on C/N ratio and lignin content of green manure. The lower C/N ratio and lignin content, the faster the decomposition rate Moreover, soil factors, which affected the decomposition and mineralization of green manure, are the soil texture, structure, soil reaction, microbial activity, and the status of soil nutrients (Dinnes et al., 2002) [12]. Verbene et al 1990 said decomposition rate of green manure was higher in sandy soil than fine texture soil. And then availability of N in soil influences on those process (Meena et al., 2018) [10]. According to the study of Brar and Sidhu (1995) [51], mineralization rate is decreasing with the time of incubation. Understanding mineralization process of Carbon and Nitrogen is important to optimize the management practices. In a study of cowpea decomposition in the soil, alternate wetting and drying the soil did not significantly reduce the carbon, however reduce the nitrogen from 46% to 29% comparing to continuously moist soil (Franzluebbers et al.,1994) [52] Ensuring synchronization between the decomposition and nitrogen release patterns of green manure and the demands of crops is crucial for nitrogen sustainability (Kaneko et al., 2023) [13].

4. Management of Green manures

The basic principle in green manure crops, should aim at maximum succulent green matter at burial. Due to many experiments, the plowing at the flowering stage provides the best result of green manure (Singh, Singh, Singh and Singh 2023) [14]. Regarding sunn hemp, the percentage of organic matter, nitrogen and other essential elements increased with the age of the plant and attained maximum at 60-75 days after sowing. Nitrogen content of the plant increases gradually up to 60 days of sowing and thereafter it declines. Thus, ploughing of the crop before or after 60 days would reduce the maximum manurial efficiency of the crop. Besides nitrogen, other inorganic constituents are also very important. In the dry mater the percentage of ash is gradually increased in the same directions as that of nitrogen. Thus, the maximum number of mineral elements is at two months stage (Srivastava and Pandit 1968) [15]. Other organic substances such as total carbohydrate and sucrose attain maximum at 60-75 days stage. If the primary objective of green manure is to maximize nutrients input without considering the characteristics of the materials, their decomposition rate, and their availability to subsequent crops, plowing may be conducted at 90 days after sowing. However, the quantity of fertilizer constituents alone does not determine the success of green manuring. Generally, it has been reported that green manuring at 60 days after sowing yielded the best results (Sarkar et al., 2007) [16]. A study conducted over two years revealed that significant disparities in the incorporation of green manure between 50 DAS (days after sowing) and 60 DAS for sunn hemp. Various parameters including total carbon, total nitrogen, C/N ratio, nitrate N (NO_3-N), acid detergent fiber, and neutral detergent fiber resulted considerable differences. In both 2019 and 2020, sunn hemp nitrogen and acid detergent fiber yields were considerably higher at 50 DAS compared to 60 DAS. These findings underscored the crucial role of seeding and harvest timing in estimating decomposition rates (Kaneko et al., 2023) [13]. According the review study, minimum variations were observed between sunn hemp cultivars, suggesting that cultivar selection might not significantly influence decomposition outcomes (Kaneko et al., 2023) [13].

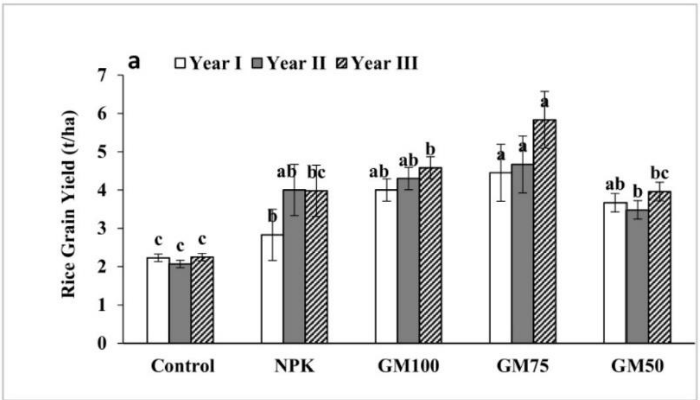
Once the decision on the appropriate age for harvesting is made, the duration required for incorporation into the soil before the main crop cultivation becomes a crucial consideration. An experiment demonstrated that burying sesbania (dhaincha) one day before transplanting rice resulted in significantly higher yields compared to burying it one to two weeks before rice transplantation (Beri and Meelu 1981) [17]. The other research mentioned that the waiting period between strawberry plantation and incorporation of sunn hemp was 8 days for the first time and 22 days for the second time. The research recommended that shortening the waiting period may synchronize N supply with crop uptake (Li et al/, 2020) [18].

5. Fertilizer compensation and impact on Rice yield

A field experiment in 2004-2005, rice crop reached 50% flowering stage earlier by 6-7 days due to green manure (sunn hemp) incorporation comparing to the without sunn hemp incorporation plots and only root application plots. Only roots application plot was 8.9 percent yield higher than control plots. The yield of only shoot application and whole plant application were 27.7 % and 28.75% higher than control treatment respectively (Neelima 2008) [19]. Then, the study recommended that with shoot or total incorporation and 60 kg N/ha chemical fertilizer was comparable to the rate of 180 kg N/ha (Neelima 2021) [19]. Further, incorporation of green manure 20 ton/ha (sunn hemp) without fertilizer N (inorganic Nitrogen) produce 91% greater grain yield than control (without nitrogen) on average across 3 years. Rice yield response to combination of green manure 20 ton/ha and Nitrogen fertilizer 60 ton/ha was greatest which yield 8-17% more than the combination of green manure 0 ton/ha and Nitrogen fertilizer 120 ton/ha treatment (Aulakh et al., 2000) [20]. Another study proved that rice grain yield with pretransplant incorporation of green manure 20 and 40 (sesbania) ton/ha was ranged from 5.18 to 5.81 ton/ha while the grain yield with fertilizer nitrogen 120 kg N/ha was 5.4 ton/ha (Aulakh et al., 2000). Then, the residual effect of green manure (sesbania) produces 25% higher yield of wheat crop under rice-wheat cropping system than chemical nitrogen fertilizer application which has no residue (Aulakh et al., 2000) [20].

A Research mentioned that the application of cowpea and dhaincha on a dry basis of 3.4 ton/ha and 7.2 ton/ha in dry basis respectively resulted in equal rice yield with the application of recommended dose of chemical fertilizer of N-P-K 80-25-35 kg/ha. Then, cowpea was recommended as better green manure crop than dhaincha mainly in the wet season (Bhuiyan and Zaman 1996 [43]; Selvi and Kalpana 2009 [44]; Meena 2018 [10]).

Soil organic matter and total Nitrogen in 0-15 cm layer are decreasing over the time when fertilizer N or legume green manure were added as sole and main sources in double rice cropping system. Excessive sole application of green manure exhibits a negative impact on rice yield (Dawe et al., 2003[20]; Thorup-Kristensen et al., 2012 [21]) and the optimum combination rates depends on crop species, soil type and soil fertility (Yadav et al., 2000) [22]. The combination of green manure 20 ton/ha and N 60 kg/ha has higher yield than green manure 40 ton/ha and N 60 kg/ha (Aulakh et al., 2000) [20]. Further, combined application of 20% from green manure & 80% from fertilizer nitrogen and 40% from green manure & 60% from fertilizer nitrogen were observed that increased the rice yields and soil fertility (Xie et al., 2016) [23]. Naz et al., (2023) [55] studied effect of green manure on rice yield for 3 consecutive years, the study resulted that rice grain yield was highly significant in the treatment of green manure with 75% recommended chemical fertilizer rate compare to the other treatments of sole application of 100 chemical fertilizer and combine application of green manure with 100% chemical fertilizer rate, combine application of green manure and 50% chemical fertilizer rate and control. The results are as shown in the figure. The study was concluded that application of green manure can reduce the fertilizer application 25-50% and save money for fertilizer.



(Naz et al., 2023)

Fig 1; Effect of green manure on rice yield, control (without chemical or green manure amendment, NPK (no green manure, 100 chemical fertilizer recommendation rate), GM 100 (Green manure and 100 chemical fertilizer recommendation rate), GM75 (Green manure and 75% chemical fertilizer recommendation rate), GM50 (Green manure and 50% chemical fertilizer recommendation rate)

6. Soil fertility Improvement

6.1 Nitrogen balance

Sunn hemp incorporation significantly increased soil Nitrate Nitrogen NO_3-N fluxes (by 66% to 185%) and also enhanced extractable soil NO_3-N concentration (by 20% to 94%) compared with the weedy fallow control during the first 3 weeks after incorporation (Li, Zhao, Maltais and Paudel et al., 2021) [24]. After 4 years of experiment, application of 120 kg N/ha in both crops (rice-wheat rotation) resulted in 35 kg of residual NO_3- N/ha in 150 cm soil profile whereas only 19 kg NO_3- N/ha remained with green manure 20 ton/ha and chemical fertilizer 60 kg N/ha in rice-wheat rotation system. It was shown that integrated application of green manure and chemical fertilizer decrease the potential nitrate contamination in ground water (Aulakh et al., 2000). Incorporation of green manure 20 ton/ha added 77 to 128 kg N/ha in the aboveground material (Aulakh et al., 2000) [20]. Soil organic matter was mostly accumulated in the soil treated with green manure and rice straw. A study concluded that applying high quantities of diverse organic amendment can increase soil organic carbon content and rice yield in red paddy soil. Soil organic fraction was increased 15-58%, 16-61%, 14-50% and 12-53% by combined treatments of green manure (Chinese milk vetch) and chemical fertilizers 100% treatment when compare to only chemical fertilizer 100%. The study concluded that green manure (Chinese milk vetch) has potential to reduce 20-40% of chemical fertilizer (Li et al., 2020)[18]. A field experiments conducted to compare the summer green manure crops such as green gram, cowpea and dhaincha revealed that dhaincha produced 38.56 ton/ha and in turn led to the recycle of 180.5, 22.6, 267 N-P-K kg/ha (Pooniya et al.,2012) [25].

6.2 Carbon balance

Soil organic matter content influences on soil physical and biological properties as well as improve soil capacity to regulate ecosystem services. Soil organic matter contain 58% of soil organic carbon. Green manure contribution to soil has positive impact on increasing soil organic matter/ soil organic carbon. Kamran et al., (2021) [26]; Zhang et al., (2023) [27] found that soil organic carbon sequestration was increased by the application of green manure which significantly increase soil macro aggregation. A long-term experiment from 2008 to 2020 in Southern China mentioned that Carbon sequestration was increased 3.95-4.17% by the application of green manure with chemical nitrogen fertilizer in paddy soil meanwhile yield was increasing compared with the application of chemical fertilizer alone (Gao et al.,2020) [28]. A meta-analysis documented that soil organic carbon in the 0-20 cm soil layer increased with the increase in rotation years at the rate of 0.0139 and 0.2211 g/kg annually in the fallow- rice and green manure- rice respectively (Gao, Guo-pend and Cao2023) [29]. Flooding and anaerobic paddy soil reduce the decomposition rate of green matter and increase the formation of water-stable aggregate fraction, and thus increase soil carbon sequestration (Yang, Zheng, Jun, Liao and Ji, 2012) [30]. A study mentioned that total carbon stock was increasing over 300 days in both of soil layer (0-5 cm) and (5-10 cm) from 5.81 to 8.84 ton/ha and 5.81 to 8.36 ton/ha respectively. The study was conducted to investigate the changes in stock of C and N in organic matter fraction in soil by the fertilization of sunn hemp and ammonium sulfate for coffee crop (Pereira 2018) [31].

6.3 Other Nutrients Availability

Phosphorus is one of the macro elements for crops. Researches concerned with green manure and Phosphorus availability was limited. One study mentioned that incorporation of green manure can enhance the availability of Phosphorus (Cavigelli and Thien 2003) [32]. In addition, a glasshouse study was done by using the ^{32}P – ^{33}P labeling technique to determine the relative contribution of green manure and P fertilizer to P uptake by Setaria grass (*Setaria sphacelata*). It was found that total P uptake of Setatia plant in the green manure treatment was three to four times greater than P fertilizers. It means green manure mobilize more soil P and both P with green manure and other decomposition products were involved in reduction of soil P retention capacity (Bah, Zaharah and Hussin2006) [33]. An experiment showed that the periodical changes in available Zn and Cu contents in soil recorded highest in the treatments 50% recommended N from chemical fertilizer and 50% N through dhaincha with the simultaneous highest uptake of Zn and Cu by rice grain and straw (Sarkar et al., 2015) [34]. Regular incorporation of dhaincha green manure before rice transplanting increases rice yield and correct Fe and Mn deficiencies (Nayyar and Chhibba, 2000) [35].

6.4 Improvement of soil physical properties

Soil physical properties are contributing as important characteristics for crop productions. Green manuring application not only provide nutrients to the soil but also improve soil physical and biological properties. Incorporation of sunn hemp as green manure into the soil will release the organic acid, amino acid, sugars, vitamins and mucilage during growing as well as after decomposition (Shukla et al., 2011) [38]. These substances are capable to bind soil particles together and form better soil aggregation which in turn increases water holding capacity (MacRae and Mehuys 1985) [39]. Water holding capacities of the green manuring (rape, Chinese milk vetch and ryegrass) has increased 4.7, 13.0 and 10.3% respectively in the field of 28 years continuous cultivation of rice- rice farming system. The rest of soil physical properties including soil organic carbon improvement are mentioned in the table 3 (Yang et al., 2012) [40]. Soil organic carbon content increases the soil aggregation which in turn increase the soil structure and reduce the soil erosion (Tisdall and Oades 1982) [41]. The other study proved that soil physical properties of porosity is improved with the application of chemical fertilizer and green manure incorporation and reduce bulk density, however, sole application of chemical fertilizer did not show the positive results of physical properties (Naz et al.,2023) [53].

As a result of improved physical properties, green manuring can increase the fertilizer used efficiency. It was proved that combined application of 10 ton/ha of Bokashi, 10 ton/ha of sunn hemp green manure and 50% recommended rate of chemical fertilizer provided non-significant yield of 100% recommended fertilizer rate on maize production (Yuliana, Sunarni and Islami 2015) [36]. A study mentioned that under the integration of green manure and with different rate of chemical fertilizer, soil organic matter was significantly and positively correlated with soil total nitrogen, N uptake and P uptake of wheat (Muhammad et al., 2022) [37].

Table 3. Different soil physical properties with different green manure treatments

Treatments	Soil Organic Carbon (g/kg)	Bulk density g/cm^3	Total Porosities (Capillary and non-capillary)
R-R-WF (rice-rice-fallow)	15.71	1.32	30.21
R-R-RP (rice-rice-rape)	16.97	1.27	38.06
R-R-MV (rice-rice-Chinese milk vetch)	16.46	1.28	38.87
R-R-RG (rice-rice-ryegrass)	16.77	1.25	40.29

(Yang et al.,2012) [40]

7. Discussion

Various types of green manure plants offered dual advantages by both fixing nitrogen and providing green matter. They have different adoptability to climate, soil type and soil properties. Biomass and nutrient contribution depend on age of harvest and favorable weather. In addition, decomposition and mineralization processes are influenced by soil water, temperature, soil texture, soil reaction and soil microbial reaction. In order to optimize the carbon and nitrogen contribution to the soil, proper management practices are important.

Researches indicated that the use of green manure has enhanced rice yields compared to cultivation without green manure. In addition, combining green manure with chemical fertilizer yields superior results compared to sole application of green manure. The application of chemical fertilizer of 60 kg N/ha with sunn hemp incorporation provide the comparable yield of rice to the double rate of 120 kg N/ha. Likewise, large amount of dhaincha application 40 ton/ha produced 5.81 ton/ha of rice meanwhile, fertilizer nitrogen

120 kg N/ha did 5.4 ton/ha. Combination of dhaincha 20 ton/ha and chemical fertilizer 60 kg N/ha provide the yield of 6% higher than the dose of 120 kg N/ha (Aulakh et al.,2000) [20]. It means half amount of chemical fertilizer can be reduced with the substitution of green manure 20 ton/ha. The combined application of chemical fertilizer and green manure enhances soil organic matter content rather than green manure amendment only.

Some papers mentioned that the exceed amount of green manure provide negative impact on rice yield (Dawe et al., 2016 [21], Thorup, Dresboll and Kristensen 2012 [42]). It was proved according to the results of combined application of 20% green manure & 80% fertilizer nitrogen exceed the rice yield than 40% of green manure & 60% fertilizer nitrogen (Xie et al., 2016). Further, the combination of green manure 20 ton/ha & N 60 kg/ha has higher yield than green manure 40 ton/ha & N 60 kg/ha (Aulakh et al., 2000) [20].

Alongside its chemical benefits, the use of green manure improves soil physical properties and stimulates biological activities. Green manure provides soil carbon; its content at 0-20 cm soil layer increased at the rate of 0.0139 and 0.2211 g/kg/yr. Especially in the paddy soil, anaerobic soil reduces the decomposition rate and increase the carbon sequestration (Yang et al., 2012) [30].

In order to have optimal biomass it is needed to consider their adaptability, access to water, sufficient growth period, and biomass production capacities and nutrient contents. Although cow pea produces relatively low amount of biomass than sunn hemp and dhaincha, it resulted in equal yields of rice and it was recommended as better green manure (Bhuiyan and Zaman 1996 [43]; Selvi and Kalpana 2009 [44]; Meena, 2018 [10]). It means carbon and nitrogen ratios are important factors as well as to biomass gained.

Key factors for optimizing nutrient supply and synchronization are number of days to harvest and incorporation days before main crop plantation. While green manuring is considered sustainable, it poses challenges in terms of time, labor, and land management, particularly in regions with three harvests per year. Seed scarcity, particularly for crops like sunn hemp, presents a significant obstacle. Despite being drought-resistant, optimal crop establishment requires sufficient moisture. Additionally, the cost of cultivating green manure can sometimes exceed that of applying chemical fertilizers. Furthermore, obtaining the required amount of green manure may prove challenging under certain conditions. Limited farmer knowledge about the diverse uses of green manure, including fodder, energy, weed and pest control, and soil conservation are still remaining as challenges. Mainly, short window period between two cash crops and water requirements in certain conditions are constraint to farmers. Researches concerned with establishment of each green manure plant in relation to specific climate and management practices for each plant ensuring synchronization are still limited.

8. Conclusion

Green manures are socially, economically and environmentally sustainable source of nutrient application for improving and maintaining soil fertility and crop productivity. Encouraging the synchrony of crop demand and N supply increases the fertilizer efficiency.At the same time it can decrease the damage to the environment. Integrated application of green manure and chemical fertilizer keep the crop yields which can be gained with the 100% application of chemical fertilizers. Then, it can improve the soil physical properties of carbon sequestration which in turn increase the nitrogen fertilizer use efficiency and decrease the soil bulk density. It can be concluded that green manuring improves the soil health and have potential for long term sustainability.

Promoting successful green manuring requires farmers to have adequate knowledge of the optimal conditions for different green manures. In addition, other potential usages of green manure such as production of organic fertilizer by using green manure plants, seed production technologies and so on which can generate the second income for farmers should be disseminated to farmers. It is essential to introduce regionally suitable green manure varieties and promote their widespread adoption. Additionally, it is important to provide facilities for producing sufficient green manure biomass and available enough green manure seeds to overcome the challenges associated with cultivating green manure.

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9. References

1.Pieters, A. J. (1927). Green manuring: principles and practice. J. Wiley & sons, Incorporated.
2. Singh, Y., Khind, C. S, and Singh, B. (1991). Efficient management of leguminous green manures in wetland rice. Advances in Agronomy, 45, 135-189. Rotar, P.P. and Joy, R.J. (1983) “Tropic Sun” Sunn Hemp; *Crotalaria juncea* L.
3. Rotar, P. P, and Joy, R. J. (1983). 'Tropic Sun' Sunn Hemp; *Crotalaria juncea* L.
4. Garrity, D. P, and Becker, M. (1994). Where do green manures fit in Asian rice farming systems. In Green manure production systems for Asian rice lands: selected papers from the international rice research conference. IRRI, Manila (pp. 1-10).
5. Singh, W. R, and Kalamdhad, A. S. (2014). Potential for composting of green phumdi biomass of Loktak lake. Ecological engineering, 67, 119-126.
6. Shah, Z., Ahmad, S. R, and Rahman, H. U. (2011). Sustaining rice-wheat system through management of legumes I: effect of green manure legumes on rice yield and soil quality. Pak. J. Bot, 43(3), 1569-1574.
7. Ozores-Hampton, M. (2012). Developing a vegetable fertility program using organic amendments and inorganic fertilizers. HortTechnology, 22(6), 743-750.
8. Meelu, O. P., R. A. Morris, R. E. Furoc, and M. A. Dizon. "Grain yield response in rice to eight tropical green manures." (1992): 133-136.
9. Singh, N. T. (1984). Green manures as sources of nutrients in rice production. Organic matter and rice, 217-228.
10. Meena, B. L., Fagodiya, R. K., Prajapat, K., Dotaniya, M. L., Kaledhonkar, M. J., Sharma, P. C, and Kumar, S. (2018). Legume green manuring: an option for soil sustainability. Legumes for soil health and sustainable management, 387-408.
11. Fox, R. H., Myers, R. J. K, and Vallis, I. (1990). The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and nitrogen contents. Plant and soil, 129, 251-259.
12. Dinnes, D. L., Karlen, D. L., Jaynes, D. B., Kaspar, T. C., Hatfield, J. L., Colvin, T. S., Cambardella, C. A. (2002). Nitrogen management strategies to reduce nitrate leaching in tile-drained Midwestern soils. Agronomy journal, 94(1), 153-171.
13. Kaneko, M., Kato, N., Hattori, I., Matsuoka, M, and Vendramini, J. M. (2023). Seeding and Harvesting Times and Climate Conditions Are Important for Improving Nitrogen and Fiber Contents of Green Manure Sunn Hemp. Sustainability, 15(9), 7103.

14. Singh, P., Singh, A., Singh, V. K, and Singh, O. (2023). Green Manuring for Sustainable Agriculture. In Encyclopedia of Green Materials (pp. 1-6). Singapore: Springer Nature Singapore.
15. Srivastava, S. C, and Pandit, S. N. (1968). Relative role of sunnhemp tops and roots in contributing to green manuring benefits to sugarcane. Indian Journal of Agricultural Sciences, 38(2), 338-+.
16. Sarkar, S. K, and Ghoroi, A. K. (2007). Sunnhemp as green manure. International Journal of Agricultural Sciences, 3(1), 244-248.
17. Beri, V, and Meelu, O. P. (1981). Substitution of nitrogen through green manure in rice.
18. Li, Z., Zhang, X., Xu, J., Cao, K., Wang, J., Xu, C, and Cao, W. (2020). Green manure incorporation with reductions in chemical fertilizer inputs improves rice yield and soil organic matter accumulation. Journal of Soils and Sediments, 20, 2784-2793.
19. Neelima, T.L, and Murthy, V.B. (2008). Growth and yield attributes of rice as influenced by N fertilizer and differential incorporation of sunn hemp green manure, Journal of Rice Research, 2(1),45-50
20. Aulakh, M.S., Khera, T.S, and Doran, and J. W. (2000). Yields and dynamics in a rice-wheat System using green manure and inorganic fertilizer, Soil Science Society of America Journal, 64(5), 1867-1976
21. Dawe, D., Dobermann, A., Ladha, J. K., Yadav, R. L., Bao, L., Gupta, R. K., ...and Zhen, Q. X. (2003). Do organic amendments improve yield trends and profitability in intensive rice systems? Field Crops Research, 83(2), 191-213.
22. Yadav, R. L., Dwivedi, B. S., Prasad, K., Tomar, O. K., Shurpali, N. J, and Pandey, P. S. (2000). Yield trends, and changes in soil organic-C and available NPK in a long-term rice–wheat system under integrated use of manures and fertilisers. Field Crops Research, 68(3), 219-246.
23. Xie, Z., Tu, S., Shah, F., Xu, C., Chen, J., Han, D, … and Cao, W. (2016). Substitution of fertilizer-N by green manure improves the sustainability of yield in double-rice cropping system in south China. Field Crops Research, 188, 142-149.
24. Li, J., Zhao, X., Maltais-Landry, G, and Paudel, B. R. (2021). Dynamics of soil nitrogen availability following sunn hemp residue incorporation in organic strawberry production systems. HortScience, 56(2), 138-146.
25. Pooniya, V., Shivay, Y. S., Rana, A., Nain, L, and Prasanna, R. (2012). Enhancing soil nutrient dynamics and productivity of Basmati rice through residue incorporation and zinc fertilization. European Journal of Agronomy, 41, 28-37.
26. Kamran, M., Huang, L., Nie, J., Geng, M., Lu, Y., Liao, Y, and Xu, Y. (2021). Effect of reduced mineral fertilization (NPK) combined with green manure on aggregate stability and soil organic carbon fractions in a fluvo-aquic paddy soil. Soil and Tillage Research, 211, 105005.
27. Zhang, Z. H., Jun, N. I. E., Liang, H., Wei, C. L., Yun, W. A. N. G., Liao, Y. L, ... and Cao, W. D. (2023). The effects of co-utilizing green manure and rice straw on soil aggregates and soil carbon stability in a paddy soil in southern China. Journal of Integrative Agriculture, 22(5), 1529-1545.
28. Gao, S. J., Guo-peng, Z, and Cao, W. D. (2020). Effects of milk vetch (*Astragalus sinicus*) as winter green manure on rice yield and rate of fertilizer application in rice paddies in south China. Journal of Plant Nutrition and Fertilizers, 26(12), 2115-2126.
29. Gao, S. J., Shun, L. I., Zhou, G. P, and Cao, W. D. (2023). The potential of green manure to increase soil carbon sequestration and reduce the yield-scaled carbon footprint of rice production in southern China. Journal of Integrative Agriculture, 22(7), 2233-2247.
30. Yang, Z. P., Zheng, S. X., Jun, N. I. E., Liao, Y. L, and Jian, X. I. E. (2012). Effects of long-term winter planted green manure on distribution and storage of organic carbon and nitrogen in water-stable aggregates of reddish paddy soil under a double-rice cropping system. Journal of Integrative Agriculture, 13(8), 1772-1781.
31. Pereira, W. D., Martins, F. L., Santos, R. H. S., de Oliveira, T. S, and Caballero, S. S. U. (2018). Changes in the stocks of C and N in organic matter fractions in soil cropped with coffee and fertilized with sunn hemp and ammonium sulfate. Semina: Ciências Agrárias, 39(3), 999-1014.

32. Cavigelli, M. A, and Thien, and S. J. (2003). Phosphorus bioavailability following incorporation of green manure crops. Soil Science Society of America Journal, 67(4), 1186-1194.
33. Bah, A. R., Zaharah, A. R, and Hussin, A. (2006). Phosphorus Uptake from Green Manures and Phosphate Fertilizers Applied in an Acid Tropical Soil. Communications in Soil Science and Plant Analysis, 37(13–14), 2077–2093. https://doi.org/10.1080/00103620600770433
34. Sarkar, S., Santra, G. H, and Mandal, M. (2015). Effect of Green Manure and Bio-fertilizers on the Availability of Zinc and Copper and their Uptake by Rice (*Oryza sativa* L.). International Journal of Bio-resource and Stress Management, 6(4), 523-527.
35. Nayyar, V. K, and Chhibba, I. M. (2000). Effect of green manuring on micronutrient availability in rice–wheat cropping system of northwest India. Long-term Soil Fertility Experiments in Rice-Wheat Cropping Systems. Rice-Wheat Consortium Paper Series, 6, 68-72.
36. Yuliana, A. I., Sumarni, T, and Islami, T. (2015). Application of bokashi and sunn hemp (*Crotalaria juncea* L.) to improve inorganic fertilizer efficiency on maize (*Zea mays* L.). Journal of Degraded and Mining Lands Management, 3(1), 433.
37. Muhammad, G., Khan, S., Khan, M. A., Anjum, J., Alizai, N. A., Anjum, K, and Ziad, T. (2022). Green manuring for increasing nitrogen use efficiency and growth performance of wheat. Journal of Applied Research in Plant Sciences, 3(01), 177-186.
38. Shukla, K. P., Sharma, S., Singh, N. K., Singh, V., Tiwari, K, and Singh, S. (2011). Nature and role of root exudates: efficacy in bioremediation. African Journal of Biotechnology, 10(48), 9717-9724.
39. MacRae, R. J, and Mehuys, G. R. (1985). The effect of green manuring on the physical properties of temperate-area soils. In Advances in Soil Science, (3), 71-94.
40. Yang, Z. P., Xu, M. G., Zheng, S. X., Jun, N. I. E., Gao, J. S., Liao, Y. L, and Jian, X. I. E. (2012). Effects of long-term winter planted green manure on physical properties of reddish paddy soil under a double-rice cropping system. Journal of Integrative Agriculture, 11(4), 655-664.
41. Tisdall, J. M, and OADES, J. M. (1982). Organic matter and water-stable aggregates in soils. Journal of soil science, 33(2), 141-163.
42. Thorup-Kristensen, K., Dresbøll, D. B, and Kristensen, H. L. (2012). Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. European Journal of Agronomy, 37(1), 66-82.
43. Bhuiyan, N. I, and Zaman, S. K. (1996). Use of green manuring crops in rice fields for sustainable production in Bangladesh agriculture. In Biological Nitrogen Fixation Associated with Rice Production: Based on selected papers presented in the International Symposium on Biological Nitrogen Fixation Associated with Rice, Dhaka, Bangladesh, 28 November–2 December, 1994 (pp. 51-64). Dordrecht: Springer Netherlands.
44. Selvi, R. V, and Kalpana, R. (2009). Potentials of green manure in integrated nutrient management for rice–a review. Agricultural Reviews, 30(1), 40-47.
45. Sara,E, Birgitta,B and Anna M. (2006). Influence of various forms of green manure amendment on soil microbial community composition, enzyme activities and nutrient levels in leek. Applied Soil Ecology 37(1), 70-82
46. Cao W D, Haung H X. 2009. Ideas on restoration and development of green manures in China. Soil and Fertilizer Sciences in China 4, 1-3
47. Natural Resources Conservation Service. (2011). 'Tropic Sun' sunn hemp for cover crop use during the sugarcane fallow period. Plant material technical notes no.20
48. Singh, S., Singh, R. J., Kumar, K., Singh, B., & Shukla, L. (2013). Biofertilizers and green manuring for sustainable agriculture. Modern technologies for sustainable agriculture, 129-150.
49. Meena, R. S., Yadav, R. S., Meena, H., Kumar, S., Meena, Y. K., & Singh, A. (2015). Towards the current need to enhance legume productivity and soil sustainability worldwide: a book review.
50. Verberne, E. L. J., Hassink, J., De Willigen, P., Groot, J. J. R., & Van Veen, J. A. (1990). Modelling organic matter dynamics in different soils. Netherlands journal of agricultural science, 38(3A), 221-238.

51. Brar, D. S., & Sidhu, A. S. (1995). Effect of soil water on pattern of nitrogen release during decomposition of added greenmanure residue. *Journal of the Indian Society of Soil Science*, *43*(1), 14-17.
52. Franzluebbers, K., Weaver, R. W., Juo, A. S. R., & Franzluebbers, A. J. (1994). Carbon and nitrogen mineralization from cowpea plants part decomposing in moist and in repeatedly dried and wetted soil. *Soil Biology and Biochemistry*, *26*(10), 1379-1387.
53. Naz, A., Rebi, A., Naz, R., Akbar, M. U., Aslam, A., Kalsom, A., ... & Zhou, J. (2023). Impact of green manuring on health of low fertility calcareous soils. *Land*, *12*(3), 546.
54. FAO Cereal Supply and Demand Brief | Food and Agriculture Organization of the United Nations
55. Naz, A., Rebi, A., Naz, R., Akbar, M. U., Aslam, A., Kalsom, A., ... & Zhou, J. (2023). Impact of green manuring on health of low fertility calcareous soils. *Land*, *12*(3), 546.