Utilisation of green manures as organic substrates in soilless culture : A review

ABSTRACT

Green manuring with inclusion of legumes is the most feasible option to fix atmospheric nitrogen up to 80-100 kg of nitrogen in 45-60 days. They are easily decomposable improving soil organic carbon, nutrient availability, physicochemical and biological properties of soil, and crop productivity and hence can be used as a substrate in the form of dry powder in soilless culture. The scope of utilizing organic materials for crop production remains viable in recent years particularly in containerized crop production. Soilless culture as a crop production system could solve global issues such as the shortage of water, environmental pollution and instability of ecological system in various ways providing optimum environmental medium for crop growth in order to gain maximum yield and high quality products. Henceforth, less land area is required for agriculture production system resulting in increased land productivity. With this background, this review projects to maximize the utilization of the properties of green manures as an alternative grow-media substrate in the emerging soilless cultivation system.

Keywords: Daincha, grow-media, legumes, sustainability

1. INTRODUCTION

“The world population is growing, and it is anticipated to reach 9.7 billion by 2050”[1, 2]. Meeting demand will require a 50% increase in food supply by 2030 and a 70% increase in the next 40 years [3]. However, population expansion, industry, and urbanisation are encroaching on arable land for food production, and it is expected to shrink by one-third of its current availability (Fig. 1) [4,5]. New food production technology is being developed to support agriculture's transition in response to population expansion and resource demands [6,7]. “Soilless culture is an emerging and promising technique for overcoming current agricultural threats. It is the most sustainable and environmentally acceptable alternative to traditional soil-based intensive agriculture, is now regarded as a convenient approach for conserving energy, fertilizers, and water. The biggest tasks handled in closed soilless systems are salinity of circulating solution, non-uniform nutrient supply, root pathogen control, removal of undesired taste and ill-health related compounds in the product, and so forth”[8].

“Green manuring has become a very important agricultural practice since last three decades, and green manuring practices are promising tools for the better sustainability of agriculture in the longer run and with almost no hazards to the environment”[9]. “Green manures (GM) rich in N and P readily decompose, hence can also be used as a substrate in the form of dry powder for grow-media culture”[10]. Hence, this review gives knowledge regarding the composition, rates and placement of GM crops, in future, to propose holistic system and precise agricultural practices to deal with constrain during adaptation of GM-based cropping system and utilisation of green manure dry powders as one of the choice as alternative substrate for soilless cultures.

2. UTILIZATION OF ORGANIC SUBSTRATES FOR SOILLESS CULTURE

Soilless culture systems are currently taking up new dimensions in the modern greenhouse industry due to their several advantages. Use of recyclable organic resources as soilless media is gaining importance worldwide during last fifty years [11] for intensive plant production due to environmentally friendly disposition [12] of resources. “The term ‘soilless culture’ generally refers to any method of growing plants without the use of soil as a rooting medium”[13]. “Soilless culture is a distinct technology used to produce agricultural and horticultural crops”[14]. It entails growing crops in an absence of soil in a closed environment, protected cultivation, and vertical farming. The most accurate control over the supply of water, nutrients, pH, temperature, etc. are the major advantages of soilless culture which apparently increase the crop productivity by reduction of labour and making more crops per year. The common soilless culture only takes eight to ten weeks for crop harvesting.

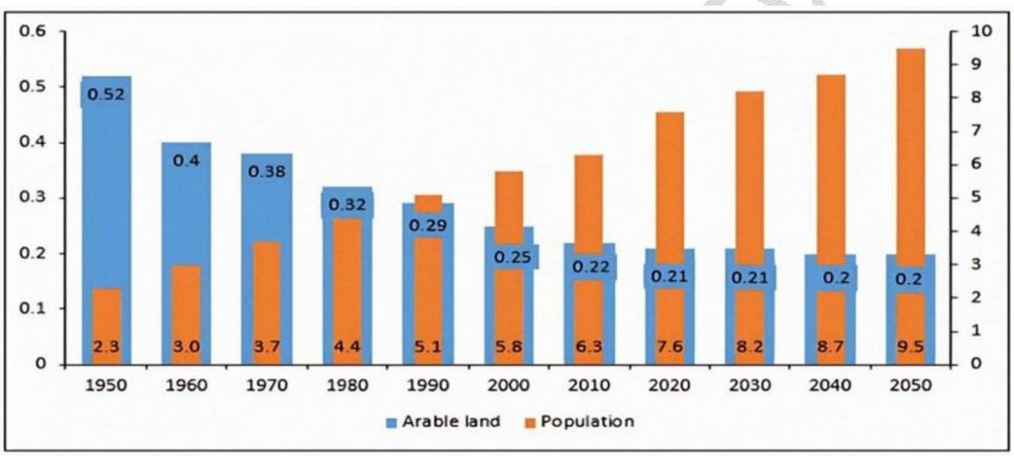


Fig.1. World population (billions) versus arable land (ha per person) 1950-2050 [15]

The soilless crop production system is divided into two categories: (i) water-based culture, such as deep water culture (DWC by Gericke 1929), float hydroponics (developed by University of Arizona, 1860), nutrient film technique (NFT, Allen Copper, 1965), and aeroponics (suggested by Richard Stoner, 1983) [16] and (ii) substrate-based culture, or substrate culture using nutrient/substrate growing media. Soilless systems enable optimization of both physical and chemical characteristics in the root environment and a more efficient control of pathogens. As a result, higher yields at a reasonable produc-tion cost can be attained [17].

“Growing media have been used for both the production of high-value vegetables and ornamental plants, as well as for plant propagation. Growing media or substrates are defined as all solid materials, other than soil, which either alone or in mixtures can guarantee better plant growth conditions than agricultural soil in one or many aspects”[18]. “Organic constituents are majorly used in soilless media composition. Need based utilization of different inorganic substrates is made in growing media which include rockwool, perlite, pumice, zeolite, tuff, volcanic porous rock, expanded clay granules, and vermiculite”[13].

Organic substrates can be synthetic or can consist of a natural organic matter. Substrate culture uses natural organic nutrient substrates such as peat, coir, plant waste, sawdust, bark, rice hulls, rice husk, rice straw, compost, vermicompost, meal, cake, farm yard manure (FYM), coco peat, brick shards, bio control agents, bio fertilizers, paper waste, wood sawdust, peat moss, sphagnum moss, bagasse or natural substrates such as sand, gravel, tuff, pumice, perlite, rock wool, vermiculite, montmorillonite, etc. as the growing medium.

"The most available and applicable organic materials are peat, composts, bark and wood residues. The swamp rose mallow grown in containers with vermicompost showed improved plant dry weight"[19]. "Vermicompost mixed with coir in 2:1 ratio as container substrate increased plant height and fresh weight in *Beta vulgaris* L". [20]. Bhat et al. [21] revealed that "substrates containing vermicompost, coco-peat, perlite and sphagnum peat moss (2:1:1:1 or 1:1:1:1 v/v) produced significantly better growth, yield and quality in tomato, cucumber and capsicum than other substrate combinations". Kameswari et al. [22] obtained "highest values of plant height, plant spread, number of branches per plant, duration of flowering, flower weight, spray length and number of flowers per plant were in the potting media containing cocopeat + sand + FYM+ vermicompost".

"Different substrates were compared for soilless culture in watermelon and the plant growth, yield, fruit quality and plant nutrient uptake were highest with vegetative growth in basaltic mix, sand, peat and greenhouse soil respectively and highest yield was in perlite" [23]. Majdi et al. [24] recorded "peat + perlite had most effect on growing traits and yield of green pepper". Huang et al. [25] studied "the combined effect of biochar and vermicompost amendments on the plant growth of basil and tomato. The results showed that plants in Biochar: Vermicompost: Peat based substrate exhibited similar growth indexes and total dry weight as in 100 % Peat based substrate".

2.1 Scope of utilizing organic substrates in soilless crop production

The stability of soil organic matter depends on the sustained addition organic materials in soils by way of incorporation of crop residues and organic manures and on the rightly driven biological activity. Formation of particulate organic matter in accountable proportion imparts major roles in continuous cropping systems where integrated nutrient management practices are judiciously undertaken. Prevailing conducive agro-climatic conditions also favour more accumulation of particulate organic matter. Recycling of organic matter in soils is a long-term process.

The scope of utilizing organic materials for crop production remains viable in recent years particularly in containerized crop production. Finding proper combination of organic materials to compose effective growing media for anchoring root and supporting plants adequately with water and nutrients is the need of the hour.

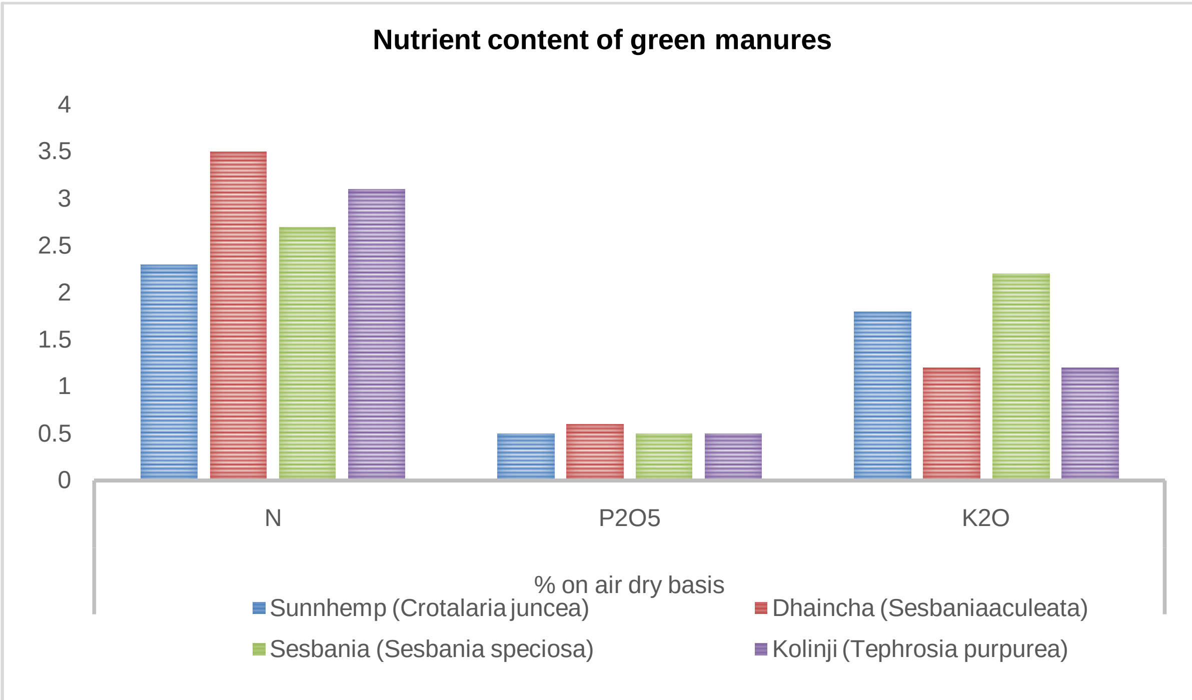
3. GREEN MANURING CROPS

Green manuring is the action of agronomic practices and assimilation of legume and non-legume green plants into the soil either by adopting in-situ or the plants developed abroad and congenital into the soil for abundance improvement. Green manures are made by incorporating green plant materials (either freshly cut weeds or rotation crop debris) into soils. Green admixture crops may include legume crops; non-grain, aroma, and beat legumes; abiding coarse multifunctional shrubs; and crops suitable for green leaf manuring (Table 1). "Upon decay, green manures enrich the soil with organic matter and to a lesser extent with nutrients such as nitrogen and phosphorus. Ample time for the green manure to decompose is allowed between the incorporation of weed/crop debris in the soil and the planting of the new crop" [26].

Legume crops and tree species suitable for green manuring in different agro-climatic zones are mentioned in Table 2 and nutrient composition of some of the green manures and green leaf manures are given in Fig. 2. and some of common green manures and green leaf manures of tropical region are depicted in Fig. 3. And Fig. 4.

Table 1. Categories of green admixture crops [27]

Legume crops	**Non-grain, aroma and beat legumes**	
Pigeon pea (*Cajanuscajan)*	Sunn hemp (*Crotalaria juncea*)	Subclover (*Trifoliumsubterraneum*)
Green gram (*Vignaradiata*)	Dhaincha (*Sesbania species, S. Aculeata*)	Strawberry clover (*T. Fragiferum*)
Cowpea (*Vignaunguiculata*)	Wild indigo (*Tephrosiapurpurea*)	Persian clover (*Trifoliumresupinatum*)
Soybean (*Glysine max*)	Black henna (*Indigoferatinctoria*)	Red clover (*Trifoliumpratense*)
Groundnut (*Arachis hypogea*)	Barseem (*Trifoliumalexandrinum*)	White clover (*Trifoliumrepens)*
Cluster bean (*Cyamopsistetragonoloba)*	Broadbean (*Viciafaba*)	*Desmodium*
Sub-tropical grasses and weeds	White lupin (*Lupinusalbus*)	*Centosemia*
Panicum maximum	Blue lupin (*Lupinusangustifoilus*)	*Stylosanthes*
Pennisetum purpureum	Yellow lupin (*Lupinusluteus)*	
Tripsacumlaxum	Common vetch (*Vicia sativa*)	
Aduthodavesica	Fenugreek (*Trigonellafoenumgraecum*)	
Eicchorniacrassipes	Candied clover (*Melilotus spp*.)	
Trianthemaportulacastrum	Trefoil (*Lotus spp.)*	
Ipomoea carnea	Black medic (*Medicagolupulina*)	
Calotropisgigantea	Lucerne or alfalfa (*Medicagosatvia*)	
Green Leaf manures		
Leucaenaleucocephala(Subabul)	*Azadirachtaindica (*neem)	*Tephorsia candida*
Gliricidia spp.	*Derris indica*	*Dodoneaviscosa*
Cassia siamea(Kassod tree)	*Cassia tora*	*Hibiscus viscosa*
Cassia auriculata	*Cassia accidentalis*	*Delonixelata*
Delonixregia	*Peltophorumferrugenum*	*Cassia nigricans*



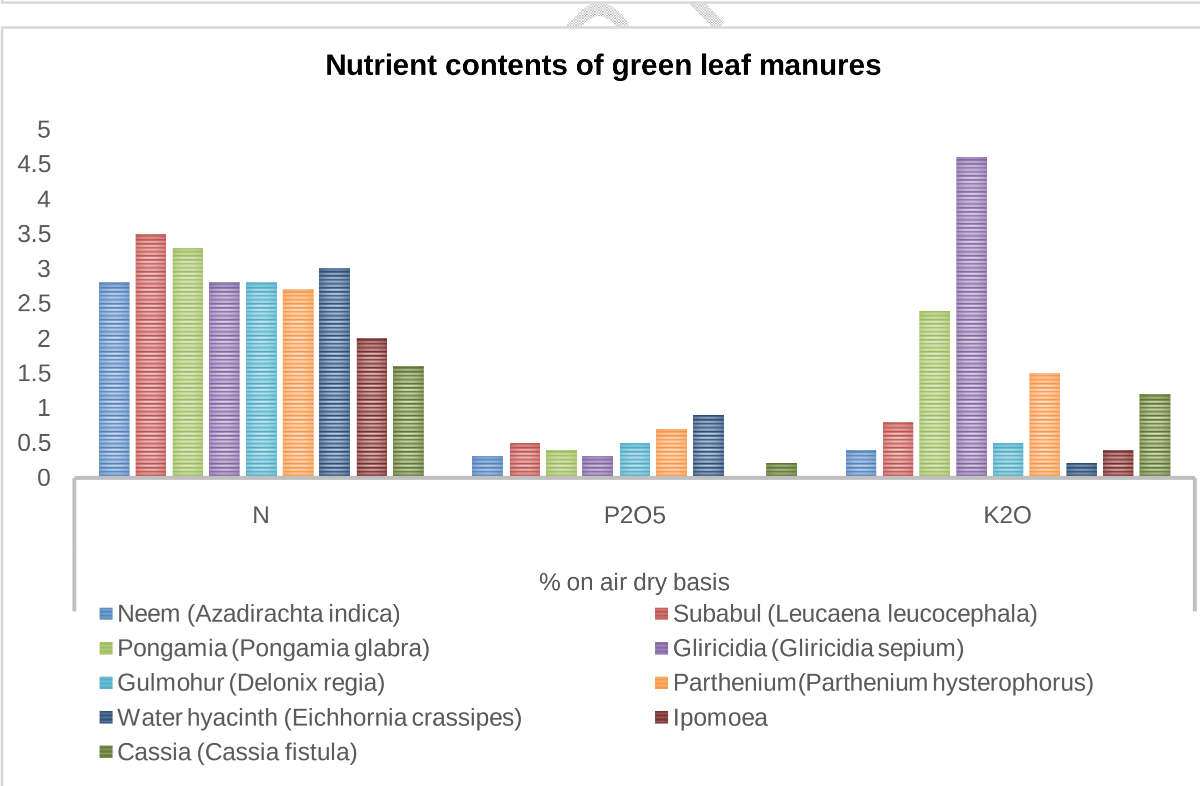


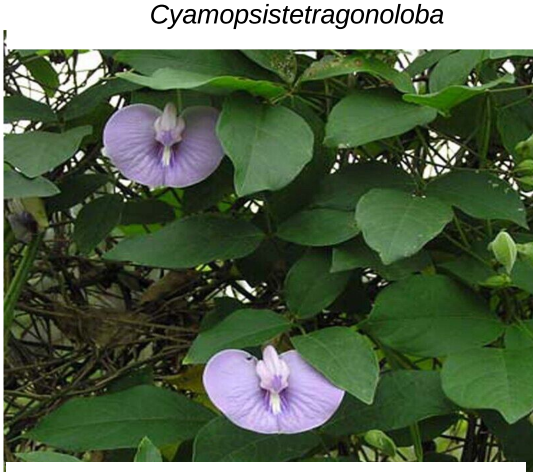
Fig. 2. Nutrient content of Green manures

Table 2. Leguminous green manure crops for different regions [28,29,30]

(A) **In situ green manure crops**			
(a) **Tropical region**		(b) **Temperate region**	
Common name	**Scientific name**	**Common name**	**Scientific name**
Cluster bean	*Cyamopsistetragonoloba*	Subterranean clover	*Trifoliumsubterraneum*
Cowpea	*Vignaunguiculata*	Ladino clover	*Trifoliumrepens*
Pueraria	*Puerariaphaseoloides*	Crimson clover	*Trifoliumincarnatum*
Green gram	*Vignaradiata*	Faba bean	*Viciafaba*
Lablab	*Lablab purpureus*	Soybean	*Glycine max*
Dhaincha	*Sesbania aculeate*, *S. rostrata*	Red clover	*Trifoliumpratense*
White lupin	*Lupinusalbus*	Black lentil	*Lens culinaris*
Gray bean	*Mucunacinerecum*	Alfalfa	*Medicago sativa*
Pigeon pea	*Cajanuscajan*	Barrel medic	*Medicagotruncatula*
Sunn hemp	*Crotalaria breviflora,* *C. juncea*, *C. striata*	Hairy vetch	*Viciavillosa*
Buffalo bean	*Mucunaaterrima*	Milk vetch	*Astragalussinicus*
Jack bean	*Canavaliaensiformis*	Winter pea	*Pisumsativum*
Velvet bean	*Mucunadeeringiana*	Sweet clover	*Melilotusofficinalis*
Stylo	*Stylosanthesguianensis*	Cura clover	*Trifoliumambiguum*
Desmodium	*Desmodiumovalifolium*	Purple vetch	*Viciabenghalensis*
Milk vetch	*Astragalussinicus*	Common vetch	*Vicia sativa*
Zornia	*Zornialatifolia*	**(B) Ex situ green leaf manuring shrubs and trees**	
Jumby bean	*Leucaenaleucocephala*	**Common name**	**Scientific name**
Kudzu	*Puerariaphaseoloides*	Subabul	*Leucaenaleucocephala*
Adzuki bean	*Vignaangularis*	Gliricidia	*Gliricidiasepium*
Black gram	*Phaseolus mungo*, *P. trilobus*	Karanj	*Pongamiaglabra*
Soybean	*Glycine max*	Milkweed	*Calotropisgigantea*
Alfalfa	*Medicago sativa*	Tephrosia	*Tephrosiapurpurea*
Wild indigo	*Indigoferatinctoria*	Wild indigo	*Indigoferateysmannii*
Berseem	*Trifoliumalexandrinum*	Sesbania	*Sesbaniaspeciosa, S. rostrata*
		Kassod	*Cassia tora*

Cluster beans
Cyamopsistetragonoloba

Cowpea
Vignaunguiculata



Pueraria
Puerariaphaseoloides

Green gram
Puerariaphaseoloides

Lablab
Lablab purpureus

Dhaincha
Sesbania aculeate, S. rostrata

Fig. 3. Green manures

White lupin
Lupinusalbus

Trifoliumalexandrinum

Cajanuscajan

Crotalaria breviflora,, C. juncea, C. striata

Mucunaaterrima

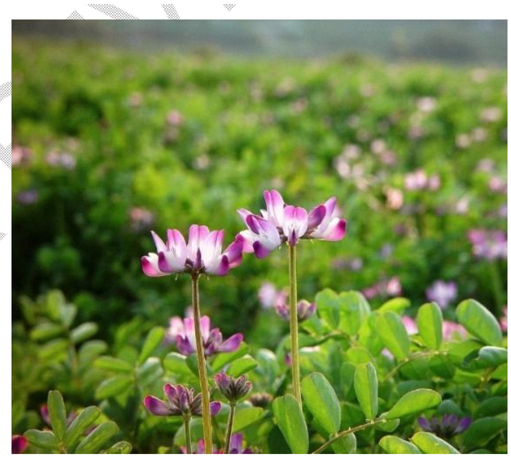
Canavaliaensiformis

Fig. 3. Green manures of tropical region (contd.)

Mucunadeeringiana

Stylosanthesguianensis

Desmodiumovalifolium



Astragalussinicus

Zornialatifolia

Leucaenaleucocephala

Fig. 3. Green manures of tropical region (contd.)

Puerariaphaseoloides

Vignaangularis

Glycine max

Indigoferatinctoria

Fig. 3. Green manures of tropical region (contd.)

Gliricidia
Gliricidia sepium

Karanj
Pongamia glabra

Milkweed
Calotropis gigantea

Tephrosia
Tephrosia purpurea

Wild indigo
Indigofera teysmannii

Kassod
Cassia tora

Fig. 4. Green leaf manures of tropical region

3.1 Nitrogen contribution by Green manuring

"Nitrogen is the primary macronutrient responsible for plant vegetative development. Plants contain 1-6% nitrogen by weight, which is necessary for a number of plant metabolic processes. Plants consume it in the forms of NO_3^- (nitrate) and NH_4^+ (ammonium), as well as amide. It is a component of many metabolically active chemicals, including amino acids, protein, nucleic acids, purines, compounds, co-catalysts, and alkaloids. Nitrogen in plants undergoes a few compound-catalyzed processes, resulting in NH_3, which is absorbed into amino acids and subsequently consolidated into proteins and nucleic acids. It is an essential component of the porphyrin ring in chlorophyll, which turns light energy into chemical energy during photosynthesis. The rate of nitrogen uptake by plants at different developmental stages has a significant impact on yield and yield-attributing characteristics" [31].

"Green manures, particularly legumes, contribute a higher amount of nitrogen. They fix atmospheric di-nitrogen by symbiosis with rhizobia *(Rhizobium, Bradyrhizobium, Sinorhizobium, and Mesorhizobium*). The legume rhizobium symbiosis compensates for 40% of global fixed nitrogen" [32]. Fig. 5. depicts soil enrichment with nitrogen by fixation and mineralization. "Nitrogen supply in green manures varies depending on the species and total biomass generated"[33]. "Leguminous green manures have been reported to fix up to 80-100 kg of nitrogen in 45-60 days"[34]. "The Azolla-Anabaena symbiosis may fix 2-4 kg N/ha per day"[35]. "Green manure nitrogen is superior to urea nitrogen in terms of plant growth and development, as well as crop grain output" [36].

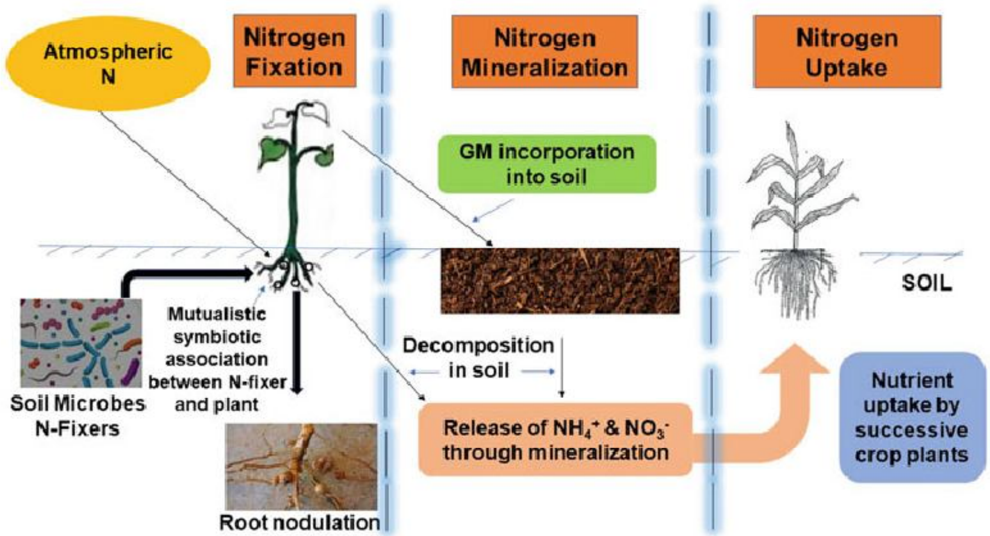


Fig. 5. Soil enrichment with N by fixation and mineralization [37]

Nitrogen supply by green manures is not exigent in nature, it's a gradual and slow process. Green manuring crops not only fix atmosphere di-nitrogen, but they also help to conserve nitrogen in the soil. By green manuring, the decomposing plant provides necessary nutrients for crop growth, reducing the need for chemical fertiliser throughout the juvenile period. Green manures improve soil qualitative characteristics with comparable efficiency to mineral fertilisers, but mineral fertilisers deteriorate soil conditions [38]. However, concrete information on rate of decomposition and quantity of available of nutrients released is scanty with daincha incorporation [39].

A slower rate of nitrogen release by green manures reduces nitrogen losses by leaching, denitrification, and NH_3 volatilization. Soil supplemented with green manure showed no NH_3 volatilization losses. The portion of green-manure nitrogen available for a subsequent harvest is typically between 40% and 60% of the total amount contained in green manuring crops. Green manure nitrogen is divided into two parts: 'fast N' and 'slow N'. Fast N degrades quickly and is readily available to plants, whereas Slow N degrades slowly and is available to plants for an extended period of time [40]. Some green manuring crops along with their nitrogen contribution is presented in (Table 3).

Table 3. N accumulation in major leguminous green manure crops

Crop species	Growth duration (days)	N accumulation (kg ha^{-1})	Reference
Glycine max	45	115	[41]
Crotalaria juncea	45	169	
Cajanuscajan	45	33	
Sesbaniaaculeata	45	225	
Vignaradiata	45	75	
Dolichos lablab	45	63	
Indigoferatinctoria	45	45	
Sesbaniarostrata	56	176	[42]
Sesbaniaaculeata	56	144	
Vignaunguiculata	45	75	
Vignaradiata	45	75	[43]
Sesbaniarostrata	60	219	[44]
Sesbaniacannabina	60	171	
Sesbaniaaegyptiaca	57	39	[45]
Sesbania grandiflora	57	24	
Cluster bean	49	91	[36]
Common vetch	Flowering	105–210	
Sweet clover	Flowering	150–300	
Milk vetch	Flowering	65–131	[46]

Green manure crops can provide the rice crop with 50–80 kg N/ha [47]. According to Mann et al. [48], after three years of continuous green manuring, soil organic matter, N, and P grew to 1.09%, 0.37%, and 10.2 ppm respectively. Saravana and Perumal[49] concluded that the addition of green manure (*S. aculeata*) and fertiliser N together enhanced the status of accessible N. *S. rostrata* had the highest total soil nitrogen levels, followed by *S. aculeata*, and green gram incorporation had the lowest levels [50].

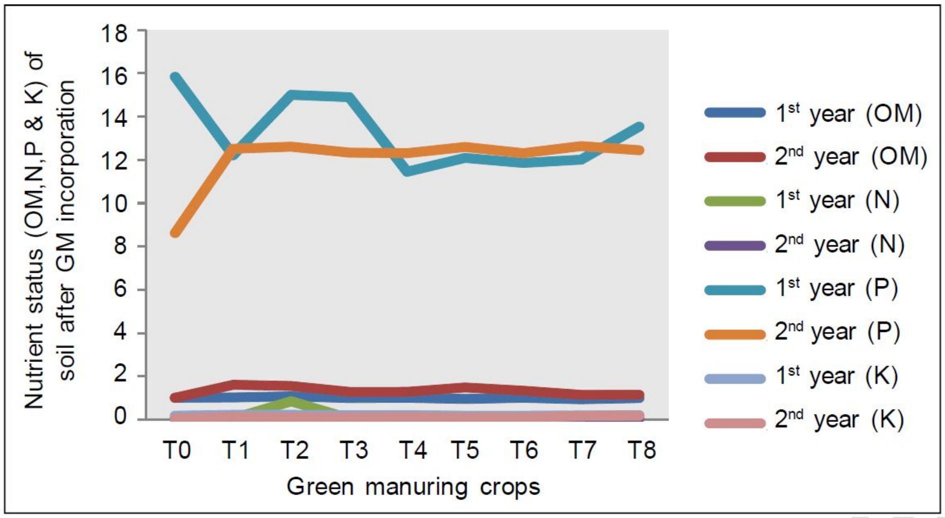


Fig.6. Effect of in situ green manure incorporation on soil properties at two consecutive years (T0= Control, T1= *S. aculeata*, T2= S*. rostrata*, T3= *C. juncea,* T4= *V. radiata*, T5= *V. mungo*, T6= *V. unguiculata*, T7= *L. leucocephala*, T8= *M. pudica*) [51]

The soil nutrient balance after incorporation of different green manures specially *S. rostrata*, *S. aculeata* and *C. juncea* exhibited positive balance of nutrients than other green manures [52]. While evaluating the effect of different in-situ green manuring on soil organic matter (%), N (%), P (ppm) and K (meq/100 gm) contribution on pre-sown rice soil in 2015 and 2016, Irin and Biswas [51] concluded that after two consecutive year, Green Manure-Transplant Aman-Mustard Cropping Pattern increased soil organic matter, nitrogen, phosphorus and potassium compared to initial soil by which N fertilizer rates could be reduced after the incorporation of green manures in the succeeding and following crops (Fig.6).

3.2 Contribution of other nutrients by green manuring

Green manures, especially those with deep roots, collect nutrients from deeper regions and make them available after decomposition. Green manuring crops release and recycle nutrients (nitrogen, phosphorus, and potassium) during decomposition, which aids in integrated plant nutrient management [53,54,55,56,57,58,59]

"Phosphorus availability is frequently reduced in calcareous and acidic soils due to interaction with calcium carbonate and iron oxide"[60]. "Phosphorus release following decomposition is typically associated with phosphorus levels in green manure. About 40 to 60 percent of phosphorus is immediately released during the degradation of plant biomass. In organically managed system, mineralization of available organic phosphorus in soil is the primary source of phosphorus. The phosphorus in the soil has to be made available to the plants"[61]. "Green manure absorption into soil improves the phosphorus cycle and increases the availability of sparingly soluble phosphorus"[62,63]. "Green manure crops collect a considerable amount of P, which decomposes into bicarbonates (H_2CO_3). This bicarbonate can solubilize soil mineral P, ensuring sufficient phosphorus for subsequent crops"[64,65]

"Addition of green manures increase the soil organic carbon subsequently leading forward to reduction on soil pH. This decrease in soil pH reduces the phosphate fixation in soil with iron and aluminium"[66]. "Ultimately availability of phosphous increases. Lupins grown in phosphorus deficient soil were found to extrude protons and different organic acids"[67,68]. "Green manuring uplifts the P uptake of succeeding crops by converting the fixed phosphorus into readily available forms"[62]. "P deficiency stimulates the formation of cluster roots in green manuring crops which are more active in P mobility and uptake"[68]. "In waterlogged conditions, green manures increased the availability of P through the mechanism of reduction, chelation and favourable alteration in soil pH. Higher availability of phosphorus from rock phosphate was reported due to green manuring in the rice fields" [62].

Table 4. Effect of green manuring crops and nitrogen levels on physical and chemical properties of postharvest rice soil [69]

Treatment	Bulk density (g/cc)	pH	OC (%)	Total N (%)	Available P (mg/kg)	Exchangeable K (meq/100 g soil)	Available S (mg/kg)
Initial value	1.35	5.76	0.81	0.064	4.86	0.138	21.21
Control	1.32	5.73	0.83	0.055	4.69	0.129	20.57
S. aculeata + N0	1.19	5.60	0.90	0.073	5.75	0.205	22.38
S. aculeata + N15	1.17	5.60	0.92	0.081	6.11	0.219	22.61
S. aculeata + N30	1.15	5.60	0.93	0.093	6.23	0.223	22.83
S. aculeata + N45	1.13	5.61	0.93	0.098	6.43	0.248	23.01
S. aculeata + N60	1.11	5.62	0.97	0.106	6.71	0.269	23.19
C. juncea + N0	1.19	5.61	0.89	0.069	5.86	0.194	22.53
C. juncea + N15	1.19	5.61	0.89	0.075	6.16	0.216	22.76
C. juncea + N30	1.17	5.62	0.90	0.088	6.38	0.219	22.91
C. juncea + N45	1.15	5.63	0.91	0.095	6.55	0.242	23.13
C. juncea + N60	1.12	5.62	0.94	0.103	6.83	0.261	23.36
N60	1.22	5.67	0.84	0.083	5.58	0.248	22.15
CV (%)	2.25	2.01	2.55	2.05	4.95	3.060	2.23
LSD (0.05)	0.04	0.19	0.039	0.003	0.51	0.011	0.28

"On decomposition, organic P in green manure biomass could provide a relatively labile form of P to succeeding crops, thereby create a larger pool of mineralizable soil organic P to supplement soluble inorganic P pools. The extensive root system of green manure crops improved the physical condition of the soil and liberated CO_2 and organic acids, which help in dissolving native potassium in soil and thereby increases the availability of potassium and per cent increase noticed was 2.1 to 4.9 %"[70]. Incorporation of *Sesbaniaaculeata* and *Crotalaria juncea* with N significantly increased soil organic carbon, N, P, K, Ca, and S [69] (Table 4).

"Green manure crops can fix up to 153 kg K/ha and up to 20 kg P/ha"[71]. "Dhaincha and green gram increased the soil available potassium by 3.7 and 2.4 per cent respectively. P and K utilization to an extent of 10 to 12 per cent was observed in field conditions due to green manure incorporation. GM crops contain appreciable amounts of NPK including other trace elements also"[72]. "They also mobilize S, P, Si, Zn, Cu, Mn and other nutrient element as a result of increased microbial activity (CO_2 formation) and decreased redox potential"[73]. "Green manuring with *Sesbaniarostrata* increased both availability in soil and accumulation in plant of Fe, Mn and Cu due to the development of intense reducing condition, complex formation and greater nutrient holding capacity"[74]. Eriksen and Thorup-Kristensen[75] found that cruciferous crops such as winter rape or fodder radish were particularly effective at preventing sulphur leaching into lower soil profiles. Green manures such as forage chicory accumulate large amounts of micronutrients including sulphur, boron, manganese, molybdenum, and zinc [76]. Green manuring crops promote mycorrhizal growth on the roots of succeeding crops, increasing soil phosphorus (P) and micronutrient availability [77]. Soil P and K contents were highest in plot with Crotalaria, while soil Ca content was highest in plot with *Mucuna*[78].

Decomposition of daincha biomass increases humus, available nitrogen and lower down the C:N ratio of soil. Nutrient content of 60 days old dhaincha plants had 3 per cent N in addition to K, Ca, Mg, P, S and micronutrients. Addition of dhaincha biomass to soil at 1.0 t ha^{-1} added about 33 kg N, 1 kg P, 14 kg K, 14 kg Ca, 16 kg Mg and 2 kg S [79]. Across maize developmental stages, the green manuring treatment increased dry matter accumulation and N uptake by 28-114% and 83% to 146%, respectively. Green manure treatment significantly increased soil organic carbon by 3.90–12.23% over all N application rates, and total nitrogen and available nitrogen were significantly increased by 3.79–15.76% and 4.87–17.29%, with total phosphorus and available phosphorus by 6.1–13.6% and 9.6–5.3% respectively during maize developmental stages in the North China Plain [80].

In green manuring plot, the number of filled grain/panicle and highest grain yield (4t/ha) was obtained due to expected slow released nitrogen available throughout the growth period of rice [81]. After three years of continuous green manuring, the soil organic matter and N increased up to 1.09% and 0.37%, respectively [82]. Accountable increase in soil organic matter depended on the biomass producing ability of different dhaincha accessions [83]. Root, leaf and stubbles of dhaincha after decomposition improved the organic matter status of soil on green manuring due to that organic matter and total N status of soil ranged from 1.42 to 1.58% from initial level 1.51%and from 0.075 to 0.098% from initial level 0.078 per cent respectively after three years of continuous incorporation [84].

When comparing the different natural farming practices on yield of black gram, combination of Beejamrutha, Jeevamrutha, mulching and green manure treatment significantly recorded higher growth and yield attributes along with yield (1.062 t/ha) [85] which may be attributable to higher nutrient availability throughout crop growth, which was further ensured by improved microbial activity in the soil [86,87,88]. In rice-based cropping system, the rice grain yield increased 32 to 77 per cent over control due to incorporation of daincha as green manure along with different doses of NPK fertilizers, which can be attributed to the efficient and adequate nutrients supply from daincha biomass decomposition and release nutrients for utility of the crop [89,90].

Among the organic manures, *Sesbaniaaculeata* played a vital role in improving the uptake of NPK due to quick release of N from the added green manure with increased availability of P through the mechanism of reduction and chelation at favourably changed soil pH, release of K through the priming effect and direct contribution of K by green manure [91]. Effect of incorporation of dhaincha biomass in soil was noticed in increased organic matter content and total nitrogen. The amount of organic matter content varied from 1.582 to 2.133 per cent before incorporation and 1.995 to 2.271 per cent after incorporation of dhaincha biomass in soil. Likewise, the total N in soil varied from 0.088 to 0.118 per cent before incorporation and 0.106 to 0.126 after incorporation [92].

Application of 100 percent NPK through inorganic fertilizers along with 6.25 t ha^{-1}dhaincha found out from resulted in higher nutrient uptake in crop, greater soil available nitrogen, phosphorus, potassium and organic carbon in soil. This effect was followed in application of 100% N through dhaincha + balance P and K through inorganic fertilizers [93]. Green manuring enhanced boron and iron content of soil. Further, decomposed materials of S*esbania* also serve as chelating compounds and help in increasing the availability of metallic micronutrients like Zn, Cu, Mn in succeeding crop [37]. Incorporation of dhaincha remarkably increased soil pH, organic carbon, N, P, K and S compared to initial soil nutrients status at the peak period of 50 days after incorporation and declined thereafter except in soil pH, K and S [94].

3.3 Improvement in soil conditions on green manuring

Daincha incorporation as green manure improved the soil physical environment, made the soil softer indicated by reduced bulk density, increased porosity of soil, increased the availability of major nutrients and ultimately favoured in increased yield of rice [95]. Further, green manuring with daincha crop improves soil structure, aeration, permeability and also protect leaching of nutrients from the soil.Green manuring effects on crop growth and nutrient utilization are associated with an improvement in soil physiochemical properties, such as bulk density, water conductivity, and carbon and N levels [96,97].

Soil water stored in 2-year *Sesbania* improved fallows was greater than in continuously cropped fertilized or unfertilized maize in eastern Zambia [98]. Incorporation of green manures reduced soil bulk density compared with the control and NPK fertilizer in consecutive years (Fig.7). However, there were no significant differences in bulk density between Moringa, Pawpaw, Mesquite and Neem leaves used as green manure [99]. Water-stable aggregate ratio (%) and carbon percent of soil macro-aggregates (>250 μm) and micro-aggregates (53 - 250 μm) in green manure treated plot were significantly higher than in NPK (Fig. 8). Thus, green manure promoted soil aggregation and stabilized carbon in soil aggregates confirming green manure supplies nutrient, improves soil carbon storage and soil physical stability [100].

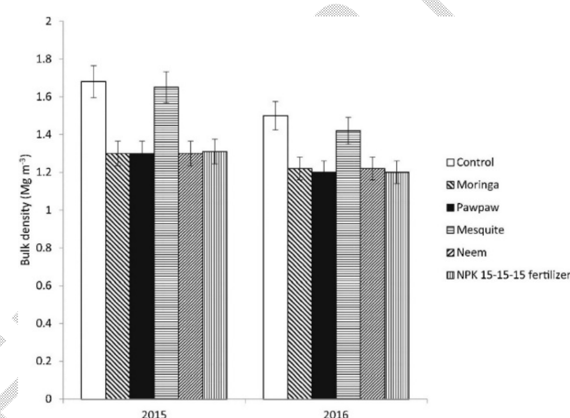


Fig. 7. Effect of various green manures and NPK fertilizer on soil bulk density [99]

Incorporation of green manures had slightly lowered soil pH compared with control and this decrease in soil pH may be due to production of CO_2 and organic acids during decomposition of incorporated green manures [69] (Table 4). Reduction from initial soil pH (7.64 to 7.96) was observed after green manuring resulting to lower pH (7.47 to 7.88). The reduction in pH might be due to incorporated *Sesbania* leaves whose sap has a pH of 4.0 and strongly acidic in nature. After decomposition, a marked influence in neutralizing the high pH of soil occurred due to production of organic acids [70,99]. Some other authors also reported that application of different types of green manures also decreased soil pH [101,102].

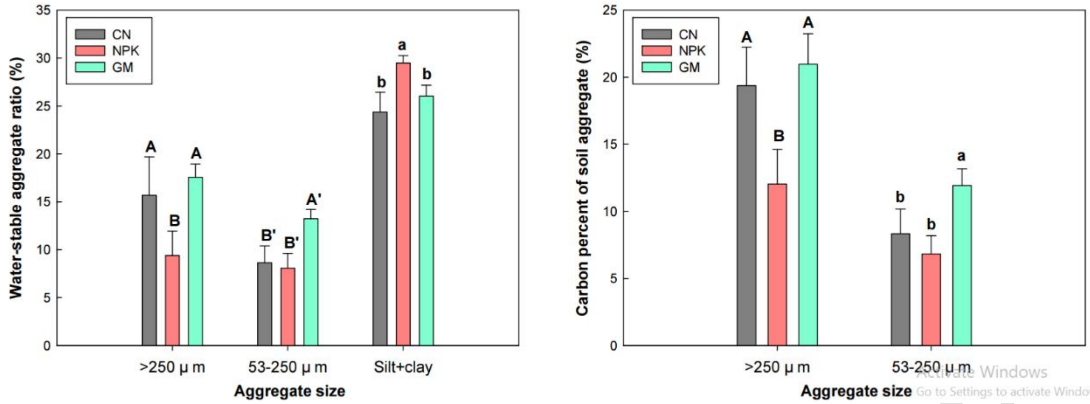


Fig. 8. Distribution of water-stable aggregate and carbon of each fraction in treatments: CN, control; NPK, chemical fertilizer treatment; GM, green manure treatment [100]

Salinity of the soil increases after adding green manure due to increase in cations and anions or increasing in release of salts and nutrients from decomposing biomass. Organic carbon content significantly improved by incorporation of *Sesbania* green manure upto 6.7 to11.8 per cent over check. The status of available N was improved when *Sesbania* was incorporation at 45 days of growth from 2.7 per cent in check plots to 4.8 percent in daincha incorporated plots [70].

Soil available P extracted was highest in green manured fields which may be due to the improved physical condition of the soil, by providing aeration and enhancing the microbial activity and mineralization of P from green manure biomass as well as chelation of calcium in alkaline soil and aluminium in acid soils [103]. Incorporation of daincha at 45 days of growth resulted in slight increase in available phosphorous from 21.2 to 22.3 kgha^{-1}[70].

3.4 Effect of green manuring on biological activity

The decomposition of green manures serves major functions for microflora providing both C and energy for growth and formation of new cell material, which further multiplies its colony saprophytically on the decomposing OM [104]. A large number of soil microorganisms exist in the soil as long as there is a C source for energy [9]. Green manures promote soil microbial growth and activity, mineralization [105,106], and improve soil fertility and quality [107]. Soil microbes decompose organic matter by producing numerous enzymes, which increases soil enzymatic activity [53,108]. Green manure provides nutrients rich in organic carbon to the microbial biomass and increases the biodiversity of soil microorganisms, resulting in disease suppression, and improved soil structure, soil properties, and crop health [9,109,110].

"GM has two main positive points from the microbiological point of view:(a) primarily it provides nutrient-rich OM for the microbial community which easily converts organically bound nutrients in plant residues to easily available nutrient form to the crops; (b) secondly it enhances the biodiversity of soil microorganisms. This microbial diversity can be increased by incorporating different legume green manure in crop rotation and cropping system programs"[105,110].

Green manure treatments can significantly increase the number of soil fungus, bacteria, and actinomycetes[111]. "Green manure treatment increased soil microbial biomass carbon and nitrogen by 1.94%-93.07% and 2.30%-145.07%, respectively"[104]. "Soil microbial biomass carbon and nitrogen is an important index for assessing rhizosphere effect"[112]. Green manures can supply nutrients for the reproduction of soil microbes, increasing diversity and making the environment suitable for new microorganisms to develop in that site. Green manure applications not only enhanced the amount of soil microorganisms, but also boosted soil enzymatic activities due to root exudations and the efficiency of soil nutrient transformation, which is all advantageous.

Due to soft and succulent nature, dhaincha plants decompose readily in soil within 60 days. The rate of decomposition is very rapid within one to two weeks after incorporation and then decline gradually [113]. Daincha fixes atmospheric nitrogen through legume-Rhizobium symbiosis and hence its accumulated nitrogen in above ground matter has the potentiality to enhance growth and yield of subsequent crops when incorporated and decomposed [114,115]. The increase in total N content of soil due to incorporation of daincha may be attributed to the mineralization of N green manure biomass due to greater multiplication of soil microbes, which could have converted organically bound N to inorganic form [8] in rice-based cropping system [89].

"Mineralization of nutrients from decomposing green manure was initially very low later increased at a faster rate up to 5-7 weeks and thereafter declined with time"[84]. "Green manure decay rates would increase when N contents were increased or would decrease if the N content declined"[116]. "In wetland rice fields, 40 per cent of carbon and 80 per cent nitrogen of Sesbania mineralized in initial 10 days of incorporation while release of N was highest in the fifth week after incorporation"[117]. In another study, the peak N release occurred after 5-8 weeks of decomposition of green manure and declined thereafter. Decomposition rate becoming slow or declining after a certain period might be due to declined microbial activity controlled by soil temperature, oxygen, substrate availability and microorganism activity as well C:N ratio [118].

Green manure application, particularly when combined with organic fertilisers, increased alpha diversity in the soil bacterial community, whereas the fungus community showed the opposite tendency. It also changed the soil microbial populations during both the growth and incorporation phases, particularly the taxa involved in the carbon, nitrogen, and sulphur cycles. Compared to fallow treatments, green manure application significantly raised microbial biomass carbon by 29.8%-72.9%, regardless of the kind of combination fertiliser used. Green manure increased urease activity by 35.6%-142.6% and β-glucosidase activity by 65.9%-172.9% compared to fallow treatments. However, it decreased catalase activity by 22.5%-55.6% [119] (Fig. 9).

"The mineralization rate of incorporated green manure was higher during the first week of its incorporation and extended till 20 days, then the process slowed down"[120]. "In the initial process of decomposition of Sesbania plant, the rate of decomposition is high and decomposable substances are released rapidly"[39]. Firstly, celluloses are decomposed and used by microorganisms, more recalcitrant such as lignin and tannin are decomposed consequently decomposition rates decreased [121].

"In the initial stages of incorporation of daincha, leaf, bark and other soft parts break down and these parts contain small soluble carbon molecules like starches and amino acids which are easy to break down. However, more recalcitrant molecules like lignin consist of complex molecules; consequently, it takes a longer time of decomposition and thus nutrients reserve in soil and release latter"[122]. At 50 days after incorporation, the available nutrients were gradually declined possibly due to leaching of nutrients or fixation in soil.Sesbania as a legume provides high quality residues with lower C/N, lignin, and polyphenol contents [123].

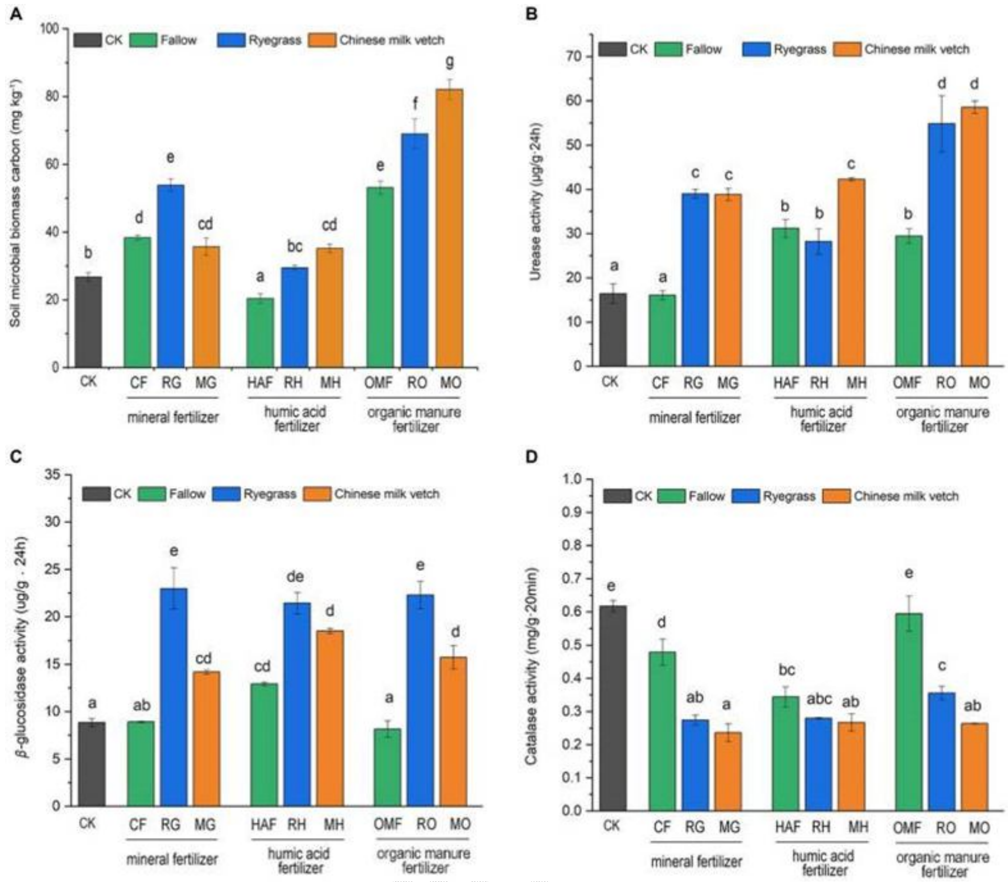


Fig. 9. Effects of application of green manure combined with different fertilizers on (A) the soil microbial carbon, (B) urease activity, (C) β-glucosidase activity and (D) catalase activity during the green manure incorporation period. Control (CK) - gray bar, fallow treatments - green, ryegrass incorporation treatments - blue and Chinese milk vetch incorporation treatments - orange bars [119]

Ash, crude protein and crude fibre content in dhaincha contribute to increase the soil nutrients status [94,124]. "Histidine, arginine and aspartate are the most abundant amino acids produced in seed exudates of Sesbania. A number of bacteria can use amino acids such as arginine, histidine, glutamate, glutamine, alanine and alanine and other amino acids as a sole nitrogen source in the presence of a suitable carbon source"[125]. Chanda et al., [126] reported "biochemical properties of Sesbania species indicating substantial content of ash (9.03 %), crude fibre (25.57 %), crude protein (18.22 %), lignin (21.97 %), holo-cellulose (70.28 %) and alpha-cellulose (41.22 %)". "During four years of continuous experiment with ryegrass (*Loliummultiflorum* L.) application to soil, soil microbial biomass carbon and nitrogen, soil respiration, soil enzymatic activities such as urease, invertase, and catalase were improved when compared to the control"[104].

3.5 Potentials of green manure as a substrate and amendment

Green manures are also grown for animal fodder [127], ground cover, firewood and other uses in traditional agro-forestry systems. To minimise chemical inputs in agriculture, green manure has been adopted preference over inorganic fertiliser[96,128]. Daincha is a popular and ideal green manure because of quick growing nature and its green matter is succulent and easily decomposable at low moisture content. On addition to soil, daincha can add significant amount of organic matter and nitrogen [129].

Advantageously many green manure crops grow well even in marginal lands with little or no input. Daincha can exhibit luxuriant growth in soil with a high salinity up to electrical conductivity of 10 dS m^{-1}. Due to this stability daincha and other few Sesbania spp. have been recommended for reclamation of saline and sodic soils [130]. Long duration cultivation of dhaincha for about 10-12 year would eliminate desertification of marginal lands and hence its cultivation is recommended to rehabilitate degraded lands into productive crop lands [131]. Daincha crop has an annual yield potential of upto 20 tonnes of drymatter per hectare under appropriate production strategy [132]. At an dry matter production rate of 5.2 t ha^{-1} of Sesbania nitrogen equivalent to 135 kg ha^{-1} is produced [89].

Fig. 10. Effect of salinity and composition of growing media on growth and yield of ribbed gourd in soilless culture under matric suction irrigation. (A) Matric suction assembly (B) Fruiting in growing media CP+VC+GM (1:1:1) [10]

Green manures which are rich in nitrogen and phosphorus readily decompose, hence were used as a substrate in the form of dry powder. However, individually no single substrate qualifies to be fit for use as soilless media and notably in each there may be limitations. Hence a combination of coirpith (CP), vermicompost (VC), green manure (Daincha) (GM) and sand (S) were used as substrates on the evaluation of growth and yield of ribbed gourd in soilless culture under matric suction irrigation in which crops were raised in growing media in containers that were interconnected by tubs and tubes to maintain moisture always by matric suction (Fig. 10). “Growing media having CP: VC: GM: S with salinity of 0.5–1.0 dS m^{-1} recorded the highest fruit yield (8.884 kg pot^{-1}) and water use efficiency (312.1 kg fresh fruit mm^{-1})” [10].

4. CONCLUSION

Legumes including *Sesbaniaaculeata, Sesbanarostrata, Vignaradiata and Vigna mungo* are the potential green manure crops for their capability of nodule formation and nitrogen fixation. Incorporation of green manures in field remarkably increased soil organic matter, N, P, K and S compared to initial soil status and attained a peak level at 50 days after incorporation. Hence, inclusion of green manures as dry powder in addition to other grow media substrates will be an alternative choice to obtain significant increase in growth and yield parameters of crops in soilless culture. As soilless culture expands research, education, and agricultural opportunities, there are great capabilities to confront these challenges of the green revolution and promote for a soilless one.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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