

Review

Green Manure Cropping Systems and Their Ecological Functions: Current Knowledge, Mechanisms, and Future Perspectives

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Abstract

Green manure can improve soil fertility by influencing the structure of the soil microbial community and enzyme activity, which in turn affects the main cropping system, and can reduce the use of chemical fertilizers and pesticides, thus reducing environmental pollution. In this study, we reviewed the literature on different green manure cropping patterns, focusing on the effects of different green manure cropping patterns on soil microbial communities, soil enzyme activities, soil physicochemical properties, and the main crop diseases, pests, weeds, and agronomic traits, etc. The positive effects produced by green manure are mainly reflected in the following aspects: (1) improving soil physicochemical properties and soil enzyme activities; (2) influencing soil microbial diversity; (3) improving the overall health of the main crop; (4) increasing the yield of the main crop. This study systematically summarizes the green manure planting patterns and their effects on the main crops, and provides a theoretical basis for green manure planting to solve crop succession barriers and enhance soil fertility; in addition, green manure has a positive effect on the conservation of soil microbial diversity, improves soil quality, and enhances agricultural production, which contributes to the sustainable development of agriculture. Accordingly, this review systematically summarizes green manure cultivation patterns and synthesizes available literature concerning the ecological functions of green manures, including their modulating impacts on soil physicochemical characteristics, microbial assemblages, pests, pathogens, weeds, and crop productivity. Moreover, it identifies key research challenges in this field and proposes outlooks for the sustainable utilization and prospective development of green manures within agroecosystems.

Keywords: green manure; soil physicochemical properties; soil microbes; diseases; pests and weeds; agronomic traits

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1. Introduction

Green manure is defined as all or part of the living organisms produced by green plants during the growth process, which can be directly or indirectly tilled into the soil to be used as a soil fertilizer, or through different cropping patterns with the main crop for the purpose of soil enrichment and promoting the growth and development of the main

crop [1–3]. Cover crops are plants grown primarily between or alongside cash crops to protect and improve the soil rather than for harvest. They provide a wide range of ecosystem services, including reducing soil erosion and nutrient losses, improving nutrient use efficiency, fixing atmospheric nitrogen through symbiosis with legumes, enhancing soil quality, increasing soil organic matter, improving soil structure, suppressing weeds, and promoting soil biodiversity. Cover crops are mainly used to protect the soil surface and provide ecosystem services during fallow periods [4–6]. Green manure is not only a crop but also a high-quality source of biofertilizer, providing significant benefits in increasing crop nutrient supply and improving farmland ecology [7]. In the past 60 years, from the mid-to late 1950s to the present, it has been proven that green manure is an important material basis for crop production and an effective technical support for green agriculture [8]. By 2022, the area of green manure in China had reached 4.12 million hectares [9]. For traditional agriculture, green manure can maintain soil health, stifle soil degradation, inhibit weeds, and enhance microbial diversity, which in turn promotes the supply of nutrients to the main crop, improves the growing environment, and finally promotes high yield and quality of stable yield of the subsequent crop. For ecological agriculture, green manure can be used as a clean alternative to chemical fertilizer, and it also plays an important role in enhancing soil water storage capacity, improving ground cover, reducing the ineffective loss of nutrients, enhancing the function of gas regulation, improving the biological prevention and control of pests, diseases and grasses, and reducing the ecological benefits of erosion caused by wind, rain, and sand [10–13].

This review was retrieved from the Web of Science Core Collection, China National Knowledge Infrastructure (CNKI), and other mainstream Chinese and English databases. Keyword searches were performed using terms including green manure, soil physicochemical properties, and soil microbes. More than 100 peer-reviewed journal articles published between 1995 and 2026 were screened and sorted to synthesize current research on the ecological functions of green manures and to summarize their regulatory effects on soil physicochemical characteristics, microbial communities, insect pests, pathogens, weeds, and crop productivity. Meanwhile, this paper identifies prominent research challenges in this field and proposes research prospects for the sustainable utilization and long-term development of green manures within agroecosystems. This review also identifies key research gaps: inadequate understanding of the long-term ecological impacts of green manures, a scarcity of regionally adapted supporting management practices, and ambiguous intrinsic mechanisms underlying the interactions among green manures, soil microorganisms, and crop productivity [14,15].

2. Green Manure Planting Mode

Green manure planting mode is diverse, mainly crop rotation green manure, intercropping green manure, mixed green manure, and replanting green manure.

Crop rotation green manure refers to the same plot, green manure and the main crop in the season or the order of annual rotation planting. In rotational green manure, it improves soil physicochemical properties (fertility and aggregate structure), increases soil microbial diversity, and reduces soil-borne diseases [16].

Intercropping green manure is mainly aimed at the climatic characteristics of two seasons' deficiency and one season's surplus, planting green manure with main crops in the same plot and the same season. Reasonable intercropping of green manure can alleviate the contradiction between green manure and main crops competing for nutrients, make full use of the land, improve soil fertility, increase the yield and quality of the main crop, improve the ecological environment, and reduce the use of chemical fertilizer [17]. For example, intercropping maize (*Zea mays*) and leguminous green manure can improve soil nutrients, optimize the distribution of maize roots to improve root nutrient uptake

efficiency, improve the photosynthetic production capacity of maize to increase maize yields, and optimize the proportion of plant nutrient partitioning to increase the utilization rate of soil nutrients [18].

Mixed cropping of green manures refers to the mixing of two or more green manures at the same time and on the same plot, usually utilizing leguminous green manures with non-leguminous green manures, sprawling green manures with upright green manures, or green manures mixed with the main crop. The treatment of mixed sowing of Chinese milk vetch (*Astragalus sinicus*) and oilseed rape (*Brassica napus*) with a 20% N reduction enhanced rice (*Oryza sativa*) yield and soil inorganic N content, and increased the abundance of the dominant bacterial community [19]. In addition, mixed sowing of hairy vetch (*Vicia villosa*) with oats (*Avena sativa*) improved soil fertility, increased microbial carbon and nitrogen content and diversity, and increased the number of grains of hairy vetch and oats [20].

Replanting of green manures refers to the planting of short-growing, fast-growing green manures during the seasonal slack period after the previous crop has been harvested. Replanting of leguminous green manures, such as cowpea (*Vigna unguiculata*), mung bean (*Vigna radiata*), and Sesbania pea (*Sesbania cannabina*) during the summer slack period not only improves soil fertility and increases maize yields of the main crop, but also harvests additional forage [21]. The replanting of hairy vetch with moderate nitrogen reduction after wheat increased the grain yield of the main crop wheat (*Triticum aestivum*), and significantly improved the grain quality [22]. The replanting of common vetch (*Vicia sativa*) after wheat increased the grain yield and economic efficiency of the main crop, and the productivity of irrigation water and light energy utilization was also increased [23]. Taken together, these studies indicate that replanting legume green manure after wheat harvest can increase the yield and quality of the main crop, wheat, reduce the use of nitrogen fertilizer, potentially improve the economic efficiency and resource utilization, and is a sustainable planting model in dry areas.

3. Types of Green Manure

Green manure can be divided into 10 families, 42 genera, and more than 60 species according to the biological taxonomy, and there are 4 families, 20 genera, and 26 species with more applications in China [1]. Green manure is divided into two categories of leguminous and non-leguminous green manure according to the standard of botanical classification. Leguminous green manure has the function of nitrogen fixation and is the main type of green manure, and the common leguminous green manures are: Sesbania pea, arrow end common vetch, mung bean, erect milkvetch (*Astragalus laxmannii*), Chinese milk vetch, white clover (*Trifolium repens*), hairy vetch, etc. Non-leguminous green manure is now more common in cruciferous and gramineae crops, and common gramineae green manures include oats and perennial ryegrass (*Lolium perenne*), orchardgrass (*Dactylis glomerata*), etc. Cruciferous green manure has feitian radish (*Raphanus sativus*), February orchid (*Orychophragmus violaceus*), oilseed rape, etc. In addition, there are also some potassium-rich species from the Asteraceae family, the Amaranthaceae family, as well as some aquatic plants that can be used as green manure [8,11,24,25]. According to the literature statistics, common green manure species in North China, Northeast China, West China, South China, and Southwest China are shown in Table 1.

Table 1. Common green manure types in different regions of China.

District	Common Green Manure Varieties	Studies
North China (Tianjin, Shandong, Hebei, etc.)	February orchid (<i>O. violaceus</i>), Hairy vetch (<i>V. villosa</i>), Ryegrass (<i>Lolium perenne</i>), Soybean (<i>Glycine max</i>), Rye (<i>Secale cereale</i>)	The varieties listed are based on previous studies [26–30].
Northeast China (Heilongjiang, Liaoning, etc.)	Stylosanthes (<i>Stylosanthes guianensis</i>), Alfalfa (<i>Medicago sativa</i>), Common vetch (<i>V. sativa</i>), Lactuca indica (<i>Ixeris polycephala</i>), Red amaranth (<i>Amaranthus cruentus</i>), Grain Amaranth (<i>Amaranthus hypochondriacus</i>), Pacesetter (<i>Sorghum bicolor sudanense</i>), Sudangrass (<i>Sorghum sudanense</i>), Oilseed rape (<i>B. napus</i>), Rye (<i>S. cereale</i>), Oats (<i>Avena sativa</i>)	The varieties listed are based on previous studies [31–33].
West China (Gansu, Shaanxi, Shanxi, Xinjiang, Inner Mongolia, etc.)	Peanut (<i>Arachis hypogaea</i>), Oilseed rape (<i>B. napus</i>), Chinese milk vetch (<i>A. laxmannii</i>), Chickpeas (<i>Cicer arietinum</i>), Common vetch (<i>V. sativa</i>), Sweet clover (<i>Melilotus officinalis</i>), Pea (<i>Pisum sativum</i>), Grass pea (<i>Lathyrus sativus</i>), February orchid (<i>O. violaceus</i>), Sweet pea (<i>Lathyrus odoratus</i>), Hairy vetch (<i>V. villosa</i>), Alfalfa (<i>M. sativa</i>), Oats (<i>A. sativa</i>), Oil sunflower (<i>Helianthus annuus</i>), sunn hemp (<i>Crotalaria juncea</i>), Black soybean (<i>G. max</i>), Black cowpea (<i>Vigna cylindrica</i>), Mung bean (<i>V. radiata</i>), Soybean (<i>G. max</i>)	The varieties listed are based on previous studies [3,34–39].
South China (Anhui, Shanghai, Hubei, Hunan, Guangdong, Hainan, Jiangxi, Henan, etc.)	Okra (<i>Abelmoschus esculentus</i>), sunn hemp (<i>C. juncea</i>), Cassia tora (<i>Senna tora</i>), Lathyrus sativus (<i>Vicia villosa</i>), Red clover (<i>Trifolium pratense</i>), Common vetch (<i>V. sativa</i>), Alyce clover (<i>Alysicarpus vaginalis</i>), Wedelia chinensis (<i>Sphagnetocola calendulacea</i>), Crotalaria mucronata (<i>Crotalaria pallida</i>), Rye (<i>S. cereale</i>), Barley (<i>Hordeum vulgare</i>), Oilseed rape (<i>B. napus</i>), Chinese milk vetch (<i>A. laxmannii</i>), Alfalfa (<i>M. sativa</i>)	The varieties listed are based on previous studies [40–49].
Southwest China (Chongqing, Sichuan, Guizhou, Yunnan)	Chinese milk vetch (<i>A. laxmannii</i>), Coneflower (<i>Rudbeckia laciniata</i>), February orchid (<i>O. violaceus</i>), ryegrass (<i>L. perenne</i>), Oilseed rape (<i>B. napus</i>), Mung bean (<i>V. radiata</i>), Oats (<i>A. sativa</i>), Radish (<i>R. sativus</i>), Cow vetch (<i>Vicia cracca</i>), Hairy vetch (<i>V. villosa</i>), Common vetch (<i>V. sativa</i>)	The varieties listed are based on previous studies [50–55].

4. Impact of Different Green Manure-Crop Patterns on Soils

4.1. Effects of Different Green Manure-Crop Patterns on Soil Enzymes and Physicochemical Properties

Soil is fundamental for the growth and development of green manure and main crops, and the effect of green manure on crop growth and nutrient utilization is closely related to improvements in soil physicochemical properties. In the short term, green manure application can rapidly improve soil fertility, although the extent of improvement varies among green manure species [56]. Green manure increases soil organic matter [57], organic carbon [58], soil nitrogen [59,60], soil potassium [21], soil phosphorus [61,62], and soil zinc [63].

Soil pH is an important indicator of soil fertility and strongly influences plant growth and fertilizer utilization. Different green manure species exhibit contrasting effects on soil pH. Gramineae green manure can increase soil pH [51], whereas leguminous green manure may decrease soil pH through the secretion of organic acids following incorporation [64,65]. However, some studies have reported no significant effect of leguminous green manure on soil pH [66]. In addition, intercropping perennial lupine (*Lupinus perennis*) with oilseed rape increased soil pH while reducing Cd and Hg concentrations in tea plantation soils [67].

Green manure also rapidly improves soil physical properties. Both leguminous and non-leguminous green manures enhance soil aggregate stability and water infiltration [58]. Planting green manure in a corn–soybean rotation significantly affects saturated hydraulic conductivity, with the improvement becoming more pronounced over time [68].

Green manure also delays runoff initiation, reduces runoff and sediment loss, and decreases nutrient leaching, thereby mitigating agricultural nonpoint source pollution. In particular, nitrate leaching can be reduced by up to 95% [69].

With continuous cultivation, the beneficial effects of green manure become more pronounced through the gradual enhancement of soil fertility, biological activity, and carbon sequestration. Compared with continuous watermelon (*Citrullus lanatus*) cropping, crop rotations involving soybean, melon, chili (*Capsicum annuum*), and oil sunflower (*Helianthus annuus*) significantly increased soil organic matter, total nitrogen, alkali-hydrolyzed nitrogen, total phosphorus, and available phosphorus while reducing soil pH. These rotations also enhanced soil enzyme activities, increased rhizosphere microbial biomass carbon and nitrogen, microbial entropy, and basal respiration, and altered microbial carbon utilization patterns [70]. Likewise, replacing continuously cultivated watermelon with oil sunflower, chili, or pea after five years significantly increased catalase activity, thereby enhancing soil detoxification capacity. Oil sunflower increased urease activity, whereas pea enhanced sucrase activity [71].

Long-term studies and meta-analyses further indicate that continuous green manure application reduces soil bulk density and influences soil water content, although the magnitude of these effects varies with soil depth [57]. Continuous cultivation of common vetch, hairy vetch, smooth vetch, cow vetch, and radish promoted the accumulation of total soil organic carbon, particularly within large soil aggregates, while the extent of carbon sequestration differed among green manure species [53]. Similarly, soils planted with green manure barley (*Hordeum vulgare*) exhibited lower electrical conductivity and bulk density, together with higher porosity and soil organic matter than soils without green manure [72].

Overall, the effects of green manure on soil properties are highly context-dependent rather than universal. Variations in climate, soil texture, green manure species composition, and the physicochemical characteristics of plant residues can substantially influence the magnitude and persistence of changes in soil fertility, physicochemical properties, and biological activity. Therefore, these factors should be carefully considered when evaluating the ecological functions and agronomic benefits of green manure under different production systems.

4.2. Effects of Different Green Manure-Crop Patterns on Soil Microbes

Soil nutrient supply to plants is closely related to the abundance and community structure of rhizosphere microorganisms [73,74]. Changes in soil microbial community composition are significantly associated with soil chemical properties [75], and soil microorganisms play indispensable roles in regulating nitrogen cycling, including nitrification and denitrification, thereby contributing to sustainable ecosystem functioning [76].

Overall, green manure improves soil microbial communities by enhancing bacterial and fungal diversity, stimulating beneficial functional microorganisms, and promoting microbial-mediated nutrient cycling, although the magnitude of these effects varies with green manure species and soil conditions. Green manure generally promotes bacterial diversity and enriches beneficial bacterial communities, thereby improving nutrient transformation and soil ecological stability. For example, the intercropping of perennial lupine and oilseed rape altered the soil bacterial community structure and increased the relative abundance of beneficial microorganisms [67]. Similarly, planting yellow lupin (*Lupinus luteus*) and pea before sowing spring wheat enhanced soil microbial populations, microbial diversity, and biochemical activities [77]. In addition, incorporation of wheat and leaf mustard (*Brassica juncea*) residues altered the composition of cucumber rhizosphere microbial communities, indicating that different green manure species exert distinct effects on microbial community structure [78].

Green manure also enhances fungal diversity and activity, particularly by stimulating beneficial fungi involved in organic matter decomposition and nutrient transformation. Compared with chemical fertilizers or no green manure, hairy vetch increased fungal biomass and diversity, increased the relative abundance of *Cladosporium* species, and enhanced soil phosphatase activity [79]. Planting alfalfa also significantly increased soil active phosphorus fractions, phosphorus uptake, and enzyme activities [62]. Beyond changes in microbial diversity, green manure promotes functional microbial groups involved in nutrient cycling. Growing buckwheat (*Fagopyrum esculentum*), millet (*Echinochloa crus-galli*), leaf mustard (*Brassica hirta*), and oilseed rape significantly increased soil microbial respiration, which was positively associated with the high carbon content of incorporated organic residues [80]. Likewise, leguminous green manures, including Chinese milk vetch and soybean, promoted soil organic carbon sequestration by increasing microbial residues [81]. A meta-analysis further demonstrated that green manure increased microbial biomass carbon and soil enzyme activities in northern China [56], confirming its positive role in microbial-mediated nutrient cycling. Recent evidence also demonstrates that beneficial plant-associated microorganisms contribute to plant performance through genotype-dependent interactions that promote plant growth and stress adaptation. These findings reinforce the importance of microbial functional diversity as a key component of sustainable cropping systems and complement the ecological benefits attributed to green manure-mediated modifications of soil microbial communities [82].

Crop rotation of watermelon with pinto bean (*Phaseolus vulgaris*), chili pepper, and pumpkin (*Cucurbita moschata*) further demonstrated that green manure-based cropping systems can improve soil microbial community composition. Compared with continuous cropping, these rotation systems increased soil microbial diversity, bacterial and actinomycete populations, and the bacterial-to-fungal ratio (B/F), while reducing fungal abundance [83].

5. Impact of Green Manure on Main Crops

5.1. Effect of Green Manure on Main Crop Diseases

The suppressive effects of green manure on soil-borne diseases involve multiple complementary mechanisms, including allelopathy and biofumigation, microbial antagonism, induced systemic resistance, and the development of disease-suppressive soils. During growth and decomposition, green manure improves nutrient availability and soil physicochemical properties while releasing bioactive compounds that directly inhibit pathogens, nematodes, and weeds [24,84–86]. However, the effectiveness of biofumigation depends on green manure species, biomass incorporation rate, and pathogen pressure, and repeated applications are often required to achieve stable disease suppression [87–89].

Green manure also reshapes the rhizosphere microbiome by increasing microbial activity, diversity and the abundance of beneficial microorganisms, thereby enhancing microbial competition and antagonism against pathogens [85]. For example, mung bean green manure significantly reduced *Ralstonia solanacearum* populations in tobacco soil [50], while buckwheat and hairy vetch promoted beneficial microorganisms such as *Streptomyces*, *Pseudomonas* and *Chryseobacterium*, resulting in reduced disease severity and improved crop performance [90,91]. Similar responses have been reported in wheat, potato, banana and watermelon intercropping systems, where green manure reduced the incidence of several soil-borne diseases by modifying soil microbial communities and suppressing pathogen proliferation [92–95].

In addition to direct pathogen suppression, green manure can induce systemic resistance by stimulating defense-related signaling pathways and enriching beneficial rhizobacteria. Brassica green manures activated salicylic acid- and ethylene-mediated defense responses and promoted the accumulation of antimicrobial metabolites [96],

whereas beneficial microorganisms enriched by green manure induced the expression of defense-related genes and enhanced host resistance [97,98]. Collectively, these mechanisms contribute to the establishment of disease-suppressive soils, indicating that the disease control capacity of green manure results from the synergistic interaction of direct pathogen inhibition, microbial antagonism, enhanced host immunity, and long-term improvements in soil health, rather than from a single mechanism.

5.2. Effect of Green Manure on Insect Pests of the Main Crop

Green manure affects pests through four main mechanisms. First, it improves soil health, including soil structure, nutrient availability, and microbial activity, which promotes the growth and vigor of the main crop, thereby enhancing its natural resistance and tolerance to pest attack [99]. Second, green manure suppresses plant-parasitic nematodes through allelopathic effects and crop diversification practices such as rotation and intercropping, which interrupt nematode life cycles and reduce their population density [100]. Third, green manure increases the abundance and diversity of natural enemies of pests, such as predators and parasitoids, by providing habitat, shelter, and food resources, thereby strengthening biological pest control and reducing pest populations [101,102]. Fourth, certain green manure species act as biofumigants, releasing biologically active volatile compounds during decomposition that suppress soil-borne pests and other harmful organisms, providing an environmentally friendly alternative to chemical pesticides [86]. These mechanisms contribute to sustainable pest management by reducing pest pressure while improving agroecosystem health.

Intercropping maize with green manure can reduce the incidence and severity of pests and diseases and thus increase yield. Green manure-treated maize did not show significant symptoms of African stem borer (*Busseola fusca*), leaf blight (*Alternaria tenuis*), or maize stripe virus. The type and amount of green manure influenced disease incidence and severity, as well as growth and yield parameters. Similarly, green manure type and amount affected pest and disease incidence and severity, as well as growth and yield, but the degree of effect varied among different green manures [103]. Intercropping white clover and cowpea in tea plantations affected the community of the tea pest false-eyed green leaf bee and its natural enemies, parasitic wasps and spiders, and the number of individual natural enemy insects; the diversity index of parasitic wasps was significantly higher under intercropped green manure treatments than in the control tea plantations [102]. In orchards intercropped with annual green manure oats, oilseed rape and perennial green manure alfalfa in Aral City, Xinjiang, natural enemy richness and ecotope width increased in orchards intercropped with green manure in comparison with clean tillage, pest richness decreased, ecotope overlap indices of natural enemies to pests increased, and the ecotope overlap indices of the golden striped moth (*Lithocolletis ringoniella*), codling moth (*Cydia pomonella*), and the euzophera pyriella Yang (*Euzophera pyriella*) occurred in lower numbers and at lower levels of damage than in clean tillage orchards [101]. Intercropping cowpea with pumpkin (*Cucurbita moschata*) showed that the cowpea treatment had a higher abundance and diversity of pollinators than the no-cowpea control, and that the cowpea intercropping treatment had more beneficial insects than the pest brown marmorated stink bug (*Halyomorpha halys*) [104].

In addition to insects, green manure also reduces the population size, density, and incidence of parasitic nematodes [99,100,105,106]. Three brassica green manures: turnip, mustard (*Brassica juncea*), and oilseed rape were planted in land that had been planted with roasted tobacco during the autumn idle period. The three green manures significantly reduced the incidence of tobacco root-knot nematode and black shin disease, and the yield and quality of roasted tobacco were improved compared with bare land [99].

Autumn rotation of sudangrass inhibited root-knot nematode infestation, thereby protecting susceptible succeeding crops of lettuce (*Lactuca sativa*), chard (*Beta vulgaris*), and melon (*Cucumis melo*), which exhibited lower average gall index compared to no sudangrass. Sudangrass was associated with the low-resistance lycopersicum crop tomato (*Solanum lycopersicum*) and chili in rotation showed sustainable control of root-knot nematode populations, which helped to conserve the low-resistant crops [106]. Mono-cropping of showy rattlebox (*Crotalaria spectabilis*) or pearl millet (*Pennisetum glaucum*), as well as intercropping of both green manures, were effective in controlling root-knot nematode and improving yields of okra (*Abelmoschus esculentus*) [100]. Green manure mustard, feitian radish, and arugula (*Eruca sativa*) were returned to the field and planted with post-crop susceptible potatoes; the feitian radish treatment consistently reduced potato cyst nematode egg viability, both in the summer leisure period and winter leisure period. The planting of mustard and arugula in the summer leisure period also led to a significant reduction in potato cyst nematode egg-laying vigor, and green manure has biofumigant capacity against potato cyst nematode [105].

5.3. Effect of Green Manure on Weeds

Weeds can compete with the main crop for light, water, and nutrients, increasing the incidence of pests and diseases in the main crop, leading to growth restriction and yield reduction. Green manures achieve weed-suppression in two main ways: directly competing with weeds for resources during growth, forming a physical barrier to achieve suppression [58,107], and generating allelopathy and thus suppressing weeds [108,109]. Green manure species, mulching time, and planting years can all affect the suppression effect: different weeds respond differently to green manure; gramineae green manure has the strongest weed-suppression effect, and weed biomass and density are significantly lower than the rest of the species. Mixing of multiple green manures does not improve the weed-suppression effect. The suppression effect of green manure planting time more than 60 days improved significantly, and the suppression effect increased with the increase in planting years [110]. Planting clover (*Trifolium*) in semi-arid areas of China can reduce weed density and biomass, significantly reduce soil water storage, and increase the number of predatory arthropods in the field [111]. Shinyleaf purple flower vetch (*Vicia villosa*) and common vetch can cover the ground quickly in the early stage to inhibit weed growth. Rat grass (*Vulpia myuros*) suppresses weeds by forming a lodged cover layer, improves soil organic matter and available potassium, enhances phosphatase activity and microbial diversity, and its fibrous root system, together with the surface mulch, aids in soil retention and moisture conservation [112]. Single sowing of perennial ryegrass and hairy vetch as well as mixed sowing of the two in winter significantly reduced weed damage and soil weed seed bank, with differences in weed suppression effects among different green manures; summer planting of crotalaria mucronata (*Crotalaria spectabilis*), mung bean, Indian cowpea (*Vigna unguiculata*), Dolichos lablab, and soybean in summer showed better weed suppression than natural grasses and winter green manure residue mulch [110].

5.4. Effect of Green Manure on Agronomic Traits of Main Crops

Green manure can affect the agronomic traits of the main crop by influencing nutrient cycling, soil fertility, and plant physiological metabolism [25,113,114]. Numerous studies have shown that green manure improves crop growth and yield by increasing nutrient availability and enhancing soil quality. Compared with oats grown alone, intercropping oats with red clover (*Trifolium pratense*) or alfalfa significantly increased maize grain yield [115]. Similarly, soybean grown as a summer green manure increased soil N and Zn availability and improved subsequent wheat yield [63]. Green manure also enhanced sugarcane growth [116], maize productivity [103], watermelon yield and fruit quality

[72,104,117]. These benefits are mainly attributed to improved nutrient cycling, higher soil organic matter and more efficient land use [118].

However, yield responses to green manure are not always positive and vary considerably with green manure species, crop type, management practices and environmental conditions. Previous studies reported that maize yield decreased by 8% following non-leguminous green manure but increased by 7% following leguminous green manure, whereas soybean yield showed little response to preceding green manure crops [58]. A recent global meta-analysis further demonstrated that green manure increased subsequent crop yield by an average of 12%, although the response differed among crops, with significant increases in maize and wheat but little effect on tobacco [119].

Water availability is another important factor determining yield responses to green manure. Although green manure generally improves soil fertility, it may also compete with the subsequent crop for soil moisture, particularly in rainfed and semi-arid regions. Yield benefits were evident under irrigated conditions but disappeared when annual precipitation was below 800 mm because green manure reduced soil water storage [119]. Similarly, silage maize yield decreased following green manure incorporation during an extremely dry year, whereas positive effects were observed under normal rainfall, highlighting the importance of rainfall distribution and irrigation management [120]. Therefore, the agronomic benefits of green manure depend not only on improved nutrient supply but also on balancing nutrient inputs with soil water availability.

Integrated management approaches combining water, nutrient, and soil conservation practices have further demonstrated that optimizing multiple agronomic components simultaneously can improve crop productivity while increasing resource-use efficiency, reinforcing the importance of integrated soil management strategies within sustainable production systems [121].

6. Effects of Green Manure on Greenhouse Gas Emissions

Green manure contributes to climate-smart agriculture by enhancing soil carbon sequestration while influencing greenhouse gas emissions. Long-term incorporation of green manure generally increases soil organic carbon through additional organic matter inputs, improved aggregate stability, and enhanced microbial carbon turnover, thereby strengthening the soil carbon sink [119,122]. Global meta-analyses further showed that green manure increased soil carbon sequestration by approximately 64%, although the magnitude depended on management practices, soil properties, and the duration of application [119]. The effects of green manure on greenhouse gas emissions are more variable than its effects on carbon sequestration. Applying green manure as an additional nitrogen source may increase CO₂ and N₂O emissions because of accelerated decomposition and nitrogen mineralization, whereas partially replacing mineral N fertilizer with green manure generally maintains crop productivity while reducing N₂O emissions and overall global warming potential [119,123]. In paddy systems, green manure may temporarily stimulate CH₄ emissions by supplying labile carbon substrates during decomposition, although appropriate water management and partial fertilizer substitution can effectively mitigate this effect [124,125]. In contrast, several studies in upland systems reported lower N₂O emissions, improved net ecosystem carbon balance and enhanced soil carbon storage following long-term green manure incorporation [126–128]. In summary, the climate benefits of green manure depend on species selection, C:N ratio, fertilizer substitution rate, water management and long-term application, highlighting the importance of optimizing management practices to achieve carbon sequestration while minimizing greenhouse gas emissions.

7. Economic Feasibility of Green Manure

The economic feasibility of green manure is a key factor influencing its adoption in sustainable agriculture. Although green manure application may increase short-term production costs due to additional biomass and labor inputs, these costs are often compensated by reduced fertilizer requirements, improved crop productivity, and enhanced resource-use efficiency [129–131]. Previous studies have shown that integrating green manure with optimized fertilizer management or diversified cropping systems can increase net income, benefit–cost ratio, and overall profitability [131,132]. Similarly, leguminous green manure can partially replace mineral nitrogen fertilizers in cereal production, while appropriate application rates maximize economic returns by balancing input costs and yield gains [133,134]. In general, the economic benefits of green manure depend on cropping systems, management practices, and local resource availability, but current evidence indicates that it is a cost-effective strategy for improving both farm profitability and the long-term sustainability of agricultural production.

8. Conclusions

In summary, the selection of suitable green manure for a reasonable planting management mode has a positive impact on soil health, main crop yield increase, quality optimization, and suppression of weeds and diseases. In addition, part of the crops used as green manure can not only achieve land nourishment, but also provide a source of forage, which is an effective measure for the sustainable development of the animal husbandry industry.

From the 1950s to the present, green manure technology development and research have been carried out for nearly 70 years, but from technological breakthroughs to industrial proliferation, there is still a certain time process. The effect on soil, main crops and diseases varies greatly depending on the type and variety of green manure, as well as the environment and soil conditions, so it is one of the difficulties in actual production to conduct seed introduction tests to select the most effective green manure in order to build green manure planting and management modes adapted to different regions, and the optimization of germplasm resources and innovation is also a technological breakthrough that needs to be sustained.

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