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ANALYSIS OF THE BENEFITS OF GREEN MANURE RETURNING AND ITS APPLICATION IN ECOLOGICAL FARMS

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Green manure, a traditional practice of incorporating plant materials into soil, enhances soil fertility and structure. After a decline post-1990s, its use in China has rebounded due to green agriculture policies, reaching 3.71 million hectares by 2022. However, adoption on ecological farms remains limited (42.9%), often hampered by single-species use and suboptimal management.
This study conducted a meta-analysis of 15 articles (183 effect sizes) to evaluate green manure's ecological benefits. Results show it generally increases subsequent crop yields (78.7% of data showed positive effects), with a mean increase of 13.8%. Benefits depend on species, crop type, and climate; legume green manures, for example, increased wheat yield by 5.1%, while non-legumes decreased it. Green manure consistently improved soil microorganisms (100% positive effects) and nutrient cycling (82.9% positive), boosting available nitrogen, phosphorus, and potassium. It also enhanced soil organic carbon (87.5% positive), sequestering carbon with a mean increase of 17.3%.
Trade-offs exist: green manure can reduce soil moisture and increase greenhouse gas emissions by an average of 40.7%. In China, primary models include intercropping (e.g., in maize fields, tea plantations, orchards) and rotation (e.g., in rice-wheat systems).
For ecological farms, which require multi-functional technologies, green manure supports soil health and nutrient management. Successful application requires selecting species suited to local conditions and integrating it with practices like fertilizer reduction.
Challenges to wider adoption include insufficient evidence of direct economic benefits for farmers and a lack of strong policy support. Overcoming these requires better policy incentives, improved ecological compensation, and synergistic application with other sustainable practices to realize green manure's full potential in agriculture's green transformation.

Key words: *Green Manure, Ecological Farm, Meta-analysis, Soil Health, Sustainable Agriculture.*

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АНАЛІЗ ПЕРЕВАГ ПОВЕРНЕННЯ ЗЕЛЕНОГО ДОБРИВА ТА ЙОГО ЗАСТОСУВАННЯ В ЕКОЛОГІЧНИХ ФЕРМАХ

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Зелене добриво, традиційна практика закопування рослинних матеріалів у ґрунт, покращує родючість і структуру ґрунту. Після спаду в його використанні після 1990-х років у Китаї воно відновилося завдяки політиці зеленого сільського господарства, до 2022 року площа його посівів досягла 3,71 мільйона гектарів. Однак його застосування на екологічних фермах залишається обмеженим (42,9%) часто через використання одного виду й неоптимальне управління. Дослідження провело метааналіз 15 статей (183 розміри ефекту) для оцінки екологічних переваг зеленого добрива. Результати показують, що воно загалом підвищує врожайність культур (78,7% даних показали позитивний ефект) із середнім збільшенням на 13,8%. Переваги залежать від виду, типу культури та клімату; наприклад, бобові зелені добрива підвищили врожайність пшениці на 5,1%, тоді як небобові – знизили.

Зелене добриво стабільно покращувало стан ґрунтових мікроорганізмів (100% позитивних ефектів) і кругообіг поживних речовин (82,9% позитивних), підвищуючи вміст доступного азоту, фосфору та калію. Воно також підвищувало органічний вуглець у ґрунті (87,5% позитивних), секвеструючи вуглець із середнім збільшенням на 17,3%.

Існують компроміси: зелене добриво може знижувати вологість ґрунту й підвищувати викиди парникових газів у середньому на 40,7%. У Китаї основні моделі включають сумісні посіви (наприклад, на полях кукурудзи, чайних плантаціях, фруктових садах) і сівозміни (наприклад, у системах рис-пшениця).

Для екологічних ферм, які потребують багатофункціональних технологій, зелене добриво підтримує здоров'я ґрунту й управління поживними речовинами. Успішне застосування вимагає підбору видів, пристосованих до місцевих умов, та інтеграції з практиками, як-от зменшення використання добрив.

Проблемами для ширшого впровадження є недостатність доказів прямого економічного ефекту для фермерів і брак сильної політичної підтримки. Для подолання цих проблем потрібні кращі політичні стимули, покращена екологічна компенсація та синергетичне застосування з іншими сталими практиками для реалізації повного потенціалу зеленого добрива в зеленій трансформації сільського господарства.

Ключові слова: *зелене добриво, екологічна ферма, метааналіз, здоров'я ґрунтів, стале сільське господарство.*

Introduction

Green manure refers to plant materials that are directly plowed under or applied to farmland after composting. It was once an important source of organic matter in farmland. Green manure is a quintessential part of traditional Chinese agriculture, capable of enhancing soil fertility, improving soil structure, and promoting increased crop yields (Cao Weidong et al., 2017; Cao Weidong et al., 2024). China has a long history of green manure cultivation, with the planting area reaching 13 million hectares in the 1970s, before declining after the 1990s due to rural reforms and the widespread use of chemical fertilizers. With the rise of green agriculture concepts, the national Soil Organic Matter Enhancement Subsidy Project was launched in 2006, and the Green Manure Industry Technology System was established in 2017, driving the national green manure planting area to recover to 3.71 million hectares by 2022, covering 4.12 million hectares of farmland (Cao Weidong et al., 2017; Cao Weidong & Gao Songjuan, 2023). In 2017, the Ministry of Agriculture included green manure in the modern agricultural system, making it a key technology for national farmland ecological construction. Currently, numerous green manure varieties with good ecological adaptability have emerged across China, and planting models are continuously being innovated (Wang Qiangsheng et al., 2021; Huang Weihong et al., 2024). However, a survey by Hu Xiaofang et al. (Hu Xifang et al., 2024) based on 431 national-level ecological farms found that only 42.9% of farms adopted green manure planting, and existing models generally suffer from issues such as single species selection, unreasonable spatiotemporal configuration, and poor functional synergy, leading to the ecological value of green manure not being fully realized.

The construction of ecological farms is an important vehicle for promoting the green transformation of agriculture (Xu Xiangbo et al., 2024). As of 2023, 776 ecological farms in China have been awarded the title of National-level Ecological Farm (Xu Xiangbo et al., 2024). As composite systems practicing agricultural ecology principles, the construction of ecological farms needs to follow the principles of "holism, coordination, recycling, regeneration, and diversity". According to the "Technical Specification for Ecological Farm Evaluation" by the Ministry of Agriculture and Rural Affairs (Ministry of Agriculture and Rural Affairs of the People's Republic of China, 2018), ecological farms scientifically manage the agricultural bio-environmental system to achieve efficient resource recycling while ensuring the quality and safety of agricultural products. This multi-objective synergistic system characteristic places higher demands on green manure technology: it must not only undertake the traditional function of nutrient supply but also play a comprehensive role in aspects such as crop-livestock integration [e.g., the forage-fertilizer coupling of legume (Fabaceae) green manure and farming systems], landscape ecology (spatiotemporal optimization of perennial green manure and crop rotation), and biodiversity maintenance (configuration of nectar plants and natural enemy conservation green manure). However, existing research mostly focuses on the evaluation of single functional benefits of green manure, lacking a comprehensive and systematic assessment of its overall benefits.

In summary, comprehensively reviewing green manure planting and utilization models and systematically evaluating the benefits of green manure are of crucial significance for promoting green manure in ecological farms and enhancing their production efficiency. Based on relevant domestic and international research results, this paper uses the literature review method to outline green manure planting and utilization models and their ecological benefits, and proposes strategies for the application of green manure in ecological farms. Simultaneously, this paper analyzes specific cases of national-level ecological farms, aiming to explore practical and referential green manure utilization models for ecological farms and provide guidance for the rational application of green manure in ecological farms.

Material and Methods

Literature Review. Green manure returning, as an eco-friendly agricultural measure, has garnered widespread attention from scholars domestically and internationally. This study employed meta-analysis to summarize research on green manure planting and utilization models and the effects of green manure returning on improving soil fertility and crop yield, among other aspects. Meta-analysis, based on original observational data from a large number of research articles, can reveal underlying overall trends and serve as an important indicator for measuring the overall understanding of a particular topic (Gurevitch J et al., 2018). Therefore, the literature review section of this paper systematically summarizes green manure planting and utilization models and focuses on published meta-analysis articles to quantitatively analyze the ecological benefits of green manure. This study searched for journal articles published before October 1, 2025, using the keywords "green manure" and "meta-analysis" in "Web of Science" and "CNKI". Among these, 15 meta-analysis articles on green manure research were retrieved (Ding et al., 2018; Muhammad et al., 2020; Ma et al., 2021; Zhang et al., 2021; Kichamu-Wachira et al., 2021; Liang et al., 2022; Garba et al., 2022; Yue et al., 2022; Hu et al., 2023; Jia et al., 2024; Xu et al., 2024; Li et al., 2024; Khan et al., 2025; Huang et al., 2025; Xu et al., 2025), extracting information such as green manure species, soil properties, yield, and their corresponding effect sizes, totaling 183 data points. Green manure returning has multiple functions; this paper categorized the extracted indicators related to the effects of green manure into six categories: crop yield, soil physicochemical properties, nutrient cycling, carbon sequestration, soil microorganisms, and greenhouse gas emissions. The different categories and their specific indicators are shown in Table 1.

This paper first classified the effect of green manure on each specific indicator as a positive impact, negative impact, or no impact based on whether the effect size was significant and the nature of the indicator. For example, if green manure returning significantly increased crop yield, it was considered a positive impact; if it significantly increased greenhouse gas emissions, it was considered a negative impact. Then, according to the classification in Table 1, the number of effect sizes showing positive, negative, and no impact for specific indicators within the six ecological benefit categories was counted to reflect the role of green manure returning. Additionally, this paper extracted the specific numerical values of each indicator's effect size to reflect the magnitude of the effect of green manure returning in the six aspects: crop yield, soil physicochemical properties, etc.

Table 1

Categories of ecological benefits of green manure involved in this study and their specific indicators

Category of ecological benefit	Specific indicator
Crop yield (10, 61)	Crop yield (rice, maize, wheat, potato, etc.)
Soil physicochemical property (7, 40)	Soil bulk density, pH, moisture content, salt content, and activities of soil invertase / urease / phosphatase / catalase / xylosidase
Nutrient cycling (10, 41)	Total nitrogen, total phosphorus, available nitrogen / phosphorus / potassium, ammonium nitrogen, nitrate nitrogen, hydrolyzable nitrogen, ammonia volatilization, and nitrogen use efficiency
Carbon sequestration (5, 16)	Soil organic carbon
Soil microorganism (4, 15)	Microbial biomass carbon, microbial biomass nitrogen, total soil phospholipid fatty acids, total soil bacteria, total soil fungi, soil actinomycetes, and arbuscular mycorrhizal fungi (AMF) spore density
GHGs emissions (3, 10)	Methane emission, and nitrous oxide emission
The first and second numbers in parentheses represent the count of meta-analysis articles and effect sizes, respectively.	

Green manure returning has various ecological functions such as improving soil properties and increasing yield, but trade-offs may exist between different effects. To assess the trade-offs between different functions of green manure, this paper assigned values to the indicators of each ecological benefit category in each meta-analysis article: positive effect assigned +1, negative effect assigned -1, no effect assigned 0 (Yousefi et al., 2024). In this way, the specific performances in each ecological benefit category were converted into a unified numerical standard. Subsequently, this paper summed the numbers for the indicators of each ecological benefit category and divided by the number of records for that category's indicators, then ranked the performance of green manure based on this. This ranking method allows for the comparison of different ecological benefits of green manure and the analysis of their trade-off relationships.

Results

Green Manure Planting and Utilization Models. Currently, the main green manure planting and utilization models in China include intercropping/relay cropping and rotation with main crops (Table 2). Intercropping/relay cropping models are widely used. For grain crops, corn (Zea mays) is often intercropped with green manures such as alfalfa (Medicago sativa), soybean (Glycine max), konjac (Amorphophallus konjac), common vetch (Vicia sativa), rapeseed (Brassica napus), and yellow sweetclover (Melilotus officinalis), while wheat (Triticum aestivum) is intercropped with yellow sweetclover (Tian Fei et al., 2008; Xu Wenguo et al., 2009; Liu Zhongkuan et al., 2009; Wang Ting et al., 2010; Kong Deping et al., 2010; Meng Fengxuan et al., 2010; Li Wenting et al., 2021). In tea plantations and orchards, green manures like common vetch, hairy vetch (Vicia villosa), rat-tail fescue (Vulpia myuros), perennial ryegrass (Lolium perenne), white clover (Trifolium repens), alfalfa, roundleaf cassia (Chamaecrista rotundifolia), and Crotalaria micans are often interplanted (Wang Jianhong et al., 2009; Dong Hao et al., 2020; Gong Xue et al., 2023). Furthermore, orchards often intercorp multiple green manures; for example, apple (Malus pumila) orchards and grape (Vitis vinifera) vineyards often intercorp green manures like white clover, perennial ryegrass, alfalfa, and tall fescue (Festuca elata) (Hui Zhumei et al., 2004; Yue Taixin et al., 2009; Wang Yingjun et al., 2013; Qin Jingyi et al., 2016; Li Yuanxue et al., 2019; Cheng Bin et al., 2021; Cheng Bin et al., 2021). In rotation models, rice (Oryza sativa) fields often utilize the winter fallow period to plant green manure, which is later plowed under before planting rice (Yang Binjuan & Huang, 2016; Yang et al., 2017). In dryland wheat planting areas, the summer fallow period is typically used for rotation by planting green manures such as soybean, mung bean (Vigna radiata), Vigna cylindrica, sunn hemp (Crotalaria juncea), yellow sweetclover, common vetch, and rapeseed (Li et al., 2019; Lu Zhuocheng et al., 2021; Lu Yitong et al., 2021).

Table 2

Main cultivation and utilization patterns of green manure in China

Utilization pattern	Crop type	Green manure type	Reference
Intercropping	Maize	Alfalfa, soybean, konjac, common vetch, rapeseed, sweet clover, etc.	(Tian F et al., 2008; Xu W G et al., 2009; Liu Z K et al., 2009; Wang T et al., 2010; Kong D P et al., 2010; Li H T et al., 2021)
	Wheat	Sweet clover	(Meng F X et al., 2010)
	Tea garden	Common vetch, hairy vetch, rattail fescue, ryegrass, white clover, alfalfa, round leafed cassia, smooth crotalaria, etc.	(Gong X et al., 2023; Wang J H et al., 2009)
	Apple orchard	White clover, ryegrass, alfalfa, tall fescue, clover, bluegrass, rattail fescue, weeping lovegrass, wild oat, etc.	(Dong H et al., 2020; Cheng B et al., 2021; Qin J Y et al., 2016; Wang Y J et al., 2013; Li Y X et al., 2019)
	Grape vineyard	Alfalfa, white clover, tall fescue, etc.	(Xi Z M et al., 2004; Yue T X et al., 2009)
	Pear orchard	Ryegrass, sweet clover, white clover, etc.	(Liu C et al., 2014; Sun J P et al., 2016; Wu Y S et al., 2013)
	Peach orchard	Chicory, alfalfa, white clover, ryegrass, clover, hairy vetch, etc.	(Weng B Q et al., 2013; Zhang X X et al., 2011)
	Citrus, tangerine, and pomelo orchard	Rice bean, cowpea, soybean, mung bean, ryegrass, white clover, etc.	(Li F L et al., 2013; Fu X Q et al., 2015; Wen M X et al., 2011)
	Kiwifruit orchard	Ryegrass, white clover, grass vetch, hairy vetch, common vetch, little bluestem, etc.	(Wu X H et al., 2019; Qin Q et al., 2020)
	Walnut orchard	White clover	(Qian J F et al., 2019)
	Mulberry garden	Hairy vetch	(Pang J G et al., 2017)
Rotation	Rice	Chinese milk vetch, ryegrass, rapeseed, broad bean, hairy vetch, common vetch, etc.	(Yang W Y et al., 2017; Yang B J & Huang G Q, 2016)
	Wheat	Soybean, black bean, mung bean, cylindrical cowpea, sunhemp, sweet clover, common vetch, rapeseed, etc.	(Li W G et al., 2019; Lü Z C et al., 2021; Lyu Y T et al., 2021)

Analysis of Green Manure Benefits. This study systematically collated 15 meta-analysis articles related to green manure, extracting 183 effect size data points, revealing the effects of green manure on key indicators such as crop yield, carbon sequestration, and greenhouse gas emissions, providing a theoretical basis for subsequent strategy development and practice of green manure in ecological farms.

Impact of Green Manure on Crop Yield. There were 61 effect sizes for subsequent crop yield. Among these, 7 indicated that green manure had a negative impact on crop yield, 6 showed no impact, and 48 confirmed a positive impact, accounting for 11.5%, 9.8%, and 78.7% respectively. This fully indicates that in most cases, green manure promotes increased crop yield. The effect of green manure on increasing subsequent crop yield is relatively stable, with most study effect sizes concentrated between 5.0% and 20.0%, and a mean effect size of 13.8%. The impact of green manure on subsequent crop yield is related to the green manure species and the type of subsequent crop. Meta-analysis research shows that compared to fallow control, legume green manure increased wheat yield by 5.1%, while non-legume green manure decreased wheat yield by 7.2%; both legume and non-legume green manure increased corn yield, with increases of 12.0% and 9.4% respectively; in potato (Solanum tuberosum) cultivation, legume green manure had no significant effect on yield, while non-legume green manure increased potato yield by 5.9% (Kichamu-Wachira et al., 2021). The impact of green manure on subsequent crop yield is also influenced by local climatic conditions. A meta-analysis study focusing on Africa showed that in humid regions, green manure returning increased crop yield by 98.9%, while in semi-arid regions, crop yield increased by 34.0% (Liang et al., 2022). A green manure meta-analysis study in China reached similar conclusions, indicating that green manure had a stronger yield-enhancing effect on subsequent crops in humid regions compared to arid regions (Zhang Shaohong et al., 2021). Furthermore, soil fertility and nitrogen application levels also influence the effect of green manure. Under low nitrogen levels [1-99 $kg(N)\cdot hm^{-2}$], green manure returning increased crop yield by 66.3%, while under high nitrogen levels [>100 $kg(N)\cdot hm^{-2}$], green manure returning had no significant effect on crop yield (Liang et al., 2022). When soil organic matter content was 0-10 $g\cdot kg^{-1}$, grain crop yield increased by 32.6%; when soil organic matter content was 10-20 $g\cdot kg^{-1}$, grain crop yield increased by 10.2%; however, when soil organic matter content was >30 $g\cdot kg^{-1}$, green manure returning had no significant effect on crop yield (Zhang Shaohong et al., 2021).

Impact of Green Manure on Soil Physicochemical Properties, Microorganisms, and Nutrient Cycling. Green manure returning can improve soil properties and is of great significance for the sustainable development of soil fertility. Plowing under green manure can increase soil organic matter and available nutrient content, making it an important measure for soil fertilization. Regarding soil physicochemical properties, 17 effect sizes showed a negative impact from green manure, 3 showed no impact, and 20 effect sizes indicated a positive impact, accounting for 42.5%, 7.5%, and 50.0% respectively. The indicators showing negative impacts were all related to soil water content; green manure planting consumes soil moisture, thereby reducing soil water content and leading to water resource competition for subsequent crops. A meta-analysis by Zhang Shaohong et al. (Jia et al., 2024) based on data from 46 green manure-related literature sources on the Loess Plateau showed that although planting green manure reduced soil moisture in the Loess Plateau region, it significantly promoted the yield of subsequent grain crops. Plowing under green manure about 13 days earlier and controlling legume green manure biomass between 2200-3100 $kg\cdot hm^{-2}$ could effectively mitigate the negative impact of green planting on soil moisture. Compared to conventional tillage without green manure, green manure returning can increase the content of large aggregates in the 0-30 cm soil layer, enhance soil aggregate stability, and reduce soil bulk density (Li Yuanxue et al., 2019). There are many indicators for soil physicochemical properties, and the impact of green manure on them is complex, showing significant variation across different studies, with its effects influenced by multiple factors such as soil type, green manure species, and planting management practices.

Regarding soil microorganisms, all 15 effect sizes indicated a positive impact from green manure, accounting for 100%, with effect sizes ranging from 11.0% to 51.0% and a mean of 26.0%. This clearly shows that green manure promotes the growth and activity of soil microorganisms, helps maintain the biodiversity and functional stability of the soil ecosystem, plays a core role in soil ecological processes, and the promoting effect is quite significant. For example, reasonably intercropping forage rapeseed and returning it to the field can increase soil nutrient content and enzyme activity in subsequent wheat fields, effectively enhance bacterial community diversity, and promote the growth of beneficial soil microbial communities (Qin Jingyi et al., 2016). In nutrient cycling studies, 2 effect sizes showed a negative impact, 5 showed no impact, and 34 showed that green manure had a positive impact on nutrient cycling, accounting for 4.9%, 12.2%, and 82.9% respectively. Green manure returning can significantly increase soil nitrate nitrogen, available phosphorus, and available potassium content, with increases ranging from 6.2% to 60.0%. Additionally, green manure returning can reduce ammonia volatilization and soil nitrogen leaching (Ding et al., 2018; Kichamu-Wachira et al., 2021; Liang et al., 2022; Xu et al., 2024).

Impact of Green Manure on Carbon Sequestration and Greenhouse Gas Emissions. There were 16 effect sizes for carbon sequestration, of which 2 showed no impact and 14 indicated a positive impact, accounting for 12.5% and 87.5% respectively. The effect sizes ranged from -7.8% to 66.1%, with a mean of 17.3%. This indicates that, compared to the no-green-manure control, green manure returning increased soil organic carbon content by 17.3%. This shows that green manure plays an important role in carbon sequestration, making key contributions to increasing soil carbon storage. Changes in soil organic carbon are affected by factors such as mean annual temperature, green manure species and planting duration, initial soil organic carbon content, microbial community status, green manure biomass and its incorporation amount, and soil texture (Tian Fei et al., 2008). Compared to the control, soil organic carbon content significantly increased by 30% after legume green manure returning and by 47% after non-legume green manure returning (Ding et al., 2018). A meta-analysis by Kichamu-Wachira et al. (Liang et al., 2022) focusing on Africa showed that the effect of green manure returning on soil organic carbon is influenced by time; in short-term (<3 years) experiments, soil organic carbon content increased by 12.6%, while in long-term (>20 years) experiments, green manure returning had no significant effect on soil organic carbon content.

Green manure returning can increase soil organic matter input, benefiting the accumulation of soil organic matter, but it also affects farmland greenhouse gas emissions. This study found that regarding greenhouse gas emissions, 6 data points found a negative impact, 2 showed no impact, and only 2 studies indicated a positive impact, accounting for 60.0%, 20.0%, and 20.0% respectively. The effect sizes ranged from -5.1% to 132.0%, with a mean of 40.7%. This indicates that, compared to the no-green-manure control, green manure returning increased farmland greenhouse gas emissions by an average of 40.7%.

Trade-offs Between Different Ecological Benefits. Planting green manure has multiple ecological benefits, but trade-off relationships exist between different benefits. Green manure returning has a positive impact on soil microorganisms, with a comprehensive value of 1.00, indicating that its promoting effect on soil microorganisms is extremely significant. The comprehensive value for carbon sequestration is 0.88, showing that green manure has a strong positive significance in carbon sequestration, playing an important role in increasing soil organic carbon content and soil carbon sink capacity, as well as mitigating climate change. The comprehensive value for crop yield is 0.67, fully illustrating that green manure plays a relatively obvious role in promoting crop yield in most cases, holding important application value in agricultural production. The comprehensive value for nutrient cycling is 0.78, meaning that green manure shows a positive role in promoting soil nutrient transformation, release, and recycling, helping to maintain the balance and sustainable supply of soil nutrients, meet plant growth nutrient demands, and enhance nutrient use efficiency in ecosystems. The comprehensive value for soil physicochemical properties is 0.08, mainly because green manure planting reduces soil moisture, but has positive effects on other physicochemical properties (such as soil bulk density, enzyme activity, etc.) (Kichamu-Wachira et al., 2021; Hu, 2023). Regarding greenhouse gas emissions, the comprehensive value is -0.40, indicating that green manure returning leads to an increase in greenhouse gas emissions. This is related to various factors such as the green manure decomposition process, soil microbial metabolic activity, and environmental conditions, requiring further in-depth research on its internal mechanisms to explore effective control measures (Xu et al., 2024; Li, 2024).

Application Strategies for Green Manure in Ecological Farms. Ecological farms are committed to achieving harmony and unity between agricultural production and ecological environmental protection, and their technical demands are diverse and comprehensive. From the perspective of soil quality improvement, ecological farms need technologies that can increase soil organic matter content, improve soil structure, and enhance soil water and fertilizer retention capacity to ensure long-term productivity of arable land. In nutrient management, there is a need to reduce dependence on external chemical fertilizers, establish sustainable nutrient cycling systems, and avoid soil degradation and environmental pollution caused by excessive fertilizer application. Simultaneously, ecological farms also focus on maintaining biodiversity, requiring technical means to create environments suitable for the survival of various organisms and promote ecosystem stability and balance. Green manure can largely meet these technical needs. Green manure has positive effects on soil microorganisms, carbon sequestration, crop yield, and nutrient cycling, but shows negative and relatively neutral impacts on greenhouse gas emissions and soil physicochemical properties, respectively. In agricultural ecosystem management, these differences should be fully considered, green manure should be applied rationally according to local conditions to maximize the utilization of its ecological functions, and targeted measures should be taken to address potential negative impacts, promoting the sustainable development of agricultural ecosystems.

The realization of green manure's ecological functions is influenced by various factors, such as farmland fertilization levels, green manure biomass and incorporation amount, green manure species, and main crop species. Climate zone and soil characteristics are fundamental factors determining the benefits of green manure (Cao Weidong et al., 2017). Conditions like temperature, precipitation, and sunlight in different climate zones, as well as soil texture, fertility, and pH, affect the growth, development, biomass accumulation, and ecological functions of green manure. Under suitable climatic and soil conditions, green manure can better exert its ecological service functions and improve the sustainability of crop production systems. Deeply understanding the impact of these factors on the ecological benefits of green manure helps farmers scientifically and rationally select and manage green manure based on local actual conditions, achieving efficient and sustainable development of crop production systems.

Discussion

Although the ecological benefits of green manure are clear, its promotion and application in ecological farms still face many challenges. The current adoption rate of green manure in ecological farms still has significant room for improvement (Cao Weidong et al., 2017). How to more effectively promote the adoption of green manure in ecological farms, thereby achieving multiple goals such as reducing fertilizer and pesticide use and protecting biodiversity in ecological agriculture, still has many problems that need further resolution. A key bottleneck lies in the quantification and recognition of economic benefits. Numerous field experiments show that green manure, especially legume green manure, can not only improve soil fertility but even increase crop yields, thus the promotion of green manure has received widespread attention (Kichamu-Wachira, 2021; Hu Xifang et al., 2024; Xu, 2024). However, the effective promotion of green manure relies on farmers' recognition and active participation. Although relevant case studies exist (Qin Jingyi et al., 2017), current research on economic benefit indicators of concern to farmers is still insufficient. If a direct link between green manure planting and farmers' income increase cannot be clearly established, its promotion will always face the “last mile” obstacle. Besides, the integration and innovation of technical models are also core challenges for promotion and application. Currently, ecological farms have a high application rate of policy-driven single technical measures (such as soil testing and formulated fertilization, and straw returning); while the application rate of other, albeit more complex, technical measures that can achieve higher comprehensive benefits is relatively low (Cao Weidong et al., 2017). Based on this, policy guidance can be used to incentivize qualified ecological farms to actively explore and apply more comprehensive and effective ecological agricultural technical measures according to local conditions. Furthermore, synergistic implementation with other ecological measures should be explored, such as chemical fertilizer reduction, organic fertilizer application, and reduced tillage/no-tillage.

These practical challenges ultimately point to the necessity of systematic policy support. Promoting the use of green manure in ecological farms requires policy support and innovation. In the context of agricultural green transformation, policies have played a crucial role in promoting the development of ecological farms and the application of green manure within them. Currently, support policies oriented towards green ecological agriculture are still insufficient, subsidies for ecological technical measures need to be strengthened, and the mechanism for premium prices for high-quality products in the market is difficult to effectively achieve, causing difficulties in the construction of ecological farms (Hu Xifang et al., 2024). Green manure has a unique and irreplaceable role in China's major agricultural strategic tasks (such as farmland ecological improvement, integrated cultivation and maintenance of arable land, etc.) (Cao Weidong et al., 2017). Therefore, it is particularly important to introduce a series of policies to assist the development of ecological farms and improve ecological compensation mechanisms (Gao Shangbin et al., 2019). Simultaneously, relevant supporting policies should be established and improved, closely linking green manure promotion with supportive policies for ecological farm construction. Through synergistic policy efforts, the green transformation of agriculture can be comprehensively promoted, fully leveraging the advantages of green manure in ecological farms and facilitating the green transformation of agriculture.

Conclusions

Green manure provides effective technical support for the green and sustainable development of agriculture. It has unique and effective roles in reducing agricultural non-point source pollution, improving the farmland ecological environment, and integrating cultivation and maintenance of arable land. The construction of ecological farms is of great significance for the development of ecological agriculture. Integrating green manure into ecological farm construction has important practical significance for the sustainable development of Chinese agriculture. This study found that green manure returning can effectively improve soil properties and enhance soil fertility; however, this process consumes soil moisture. Although the effect size of green manure planting on subsequent crop yield fluctuates considerably, the overall trend is towards yield increase. Green manure returning is beneficial for promoting soil organic matter accumulation and has a positive effect on carbon sequestration, but it also leads to increased greenhouse gas emissions. Overall, planting green manure has multiple benefits, but trade-offs exist between its different effects. Therefore, this study extracted the core application strategy for green manure: it is essential to select varieties according to local conditions, rationally plan planting patterns, and coordinate with other ecological measures such as chemical fertilizer reduction and reduced tillage/no-tillage to maximize its benefits. Currently, the adoption rate of green manure in ecological farms still needs significant improvement, and many problems urgently need resolution. For example, current research on economic benefit indicators of concern to farmers is insufficient, and a direct link between green manure planting and farmers' income needs to be established. The integration of green manure planting and utilization models with ecological farm planting models requires innovation and optimization. Promoting the application of green manure also requires policy support and innovation, expanding comprehensive ecological agricultural technologies according to local conditions, improving the policy system, and assisting the green transformation of agriculture.

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