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Long-Term Effects of Rice Cultivation on Soil Organic Nitrogen Dynamics

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Abstract This study aims to investigate the long-term effects of rice cultivation on soil organic nitrogen dynamics. Rice is an important food crop worldwide. Its cultivation has a significant impact on soil ecosystems, especially on the dynamic changes of soil organic nitrogen. By reviewing existing literature, the changes in soil organic nitrogen content under different planting years and management measures were analyzed to reveal the effects of rice cultivation on soil health. This study found that long-term rice cultivation may lead to fluctuations in soil organic nitrogen content and affect the physical and chemical properties of the soil. Seasonal and interannual changes, agricultural management practices (such as fertilization and crop rotation) and other factors play an important role in the dynamic changes of organic nitrogen. This study provides new insights into the understanding of the soil nitrogen cycle mechanism and proposes a scientific basis for sustainable agricultural management. Through reasonable agricultural management measures, such as the use of organic fertilizers and green manures and the optimization of flooding management in rice fields, soil health can be improved, the stability and availability of soil organic nitrogen can be enhanced, and rice yield and ecological environment protection can be promoted.
Keywords Soil organic nitrogen; Nitrogen dynamics; Nutrient management; Biochar; Microbial biomass

1 Introduction

Rice cultivation plays a significant role in global food security, particularly in regions such as southern China and the Indo-Gangetic Plains of India. However, the long-term effects of rice cultivation on soil health, specifically soil organic nitrogen (SON) dynamics, remain underexplored. This systematic review aims to elucidate the impacts of prolonged rice cultivation on soil organic nitrogen composition, mineralization, and overall soil fertility. Understanding these effects is crucial for developing sustainable agricultural practices that maintain soil health and productivity. The accumulation and dynamics of soil organic carbon (SOC) and total nitrogen (TN) are critical for soil fertility and crop productivity. Studies have shown that changes in cropping systems, such as the transition from rice-garlic to rice-fava, can significantly influence SOC and TN stocks, thereby affecting soil microbial biomass and nitrogen use efficiency (Zhang et al., 2017). Long-term rice cultivation has been observed to enhance soil nitrogen accumulation and availability, stabilizing within a century of continuous cultivation (Wang et al., 2017). However, the interaction between irrigation regimes, soil texture, and nitrogen management also plays a crucial role in determining nitrogen uptake and use efficiency in rice crops (Hamoud et al., 2019).

Continuous rice cultivation can lead to significant changes in soil chemical properties, microbial biomass, and carbon metabolism rates. For instance, long-term rice monoculture has been shown to alter soil microbial communities and reduce microbial biomass, despite increases in soil organic matter and total nitrogen (Wei et al., 2022). The application of nitrogen-enriched biochar has been found to improve rice yields and soil carbon storage while moderating greenhouse gas emissions (Yin et al., 2021). Additionally, integrated nutrient management practices, combining organic and inorganic fertilizers, have been demonstrated to sustain high rice yields and improve soil chemical and bacterial properties (Chen et al., 2017).

Soil organic nitrogen is a vital component of soil fertility, influencing nutrient availability and soil microbial activity. Long-term studies have highlighted the importance of maintaining soil organic nitrogen through the application of organic manures and crop residues. For example, the use of farmyard manure and green manure in combination with inorganic fertilizers has been shown to significantly increase soil nitrogen fractions and improve nitrogen utilization efficiency. Moreover, the inclusion of legumes in crop rotations can enhance soil nitrogen retention and reduce nitrogen leaching (Singh et al., 2018).

2 Study Area and Methods

2.1 Overview of study site

The study site for examining the long-term effects of rice cultivation on soil organic nitrogen (SON) dynamics is located in Cixi, Zhejiang Province, China. This region is characterized by uniform marine deposits, providing a consistent landscape and climate for the study (Wang et al., 2017). Additionally, another significant study was conducted at the Central Farm of Odisha University of Agriculture and Technology (OUAT) in Bhubaneswar, India, under the aegis of ICAR, New Delhi (Mukhi et al., 2022). This site is situated in a subtropical climatic region, which is crucial for understanding the broader implications of rice cultivation on soil properties.

The climatic conditions in Cixi, Zhejiang Province, are typical of a subtropical monsoon climate, which includes hot, humid summers and mild, dry winters. This climate is conducive to rice cultivation, which requires substantial water availability during the growing season (Wang et al., 2017). Similarly, the Bhubaneswar site experiences a subtropical climate with distinct wet and dry seasons, which is ideal for studying the effects of continuous rice-rice cropping systems on soil properties (Mukhi et al., 2022).

The soil in Cixi, Zhejiang Province, is primarily composed of paddy soils derived from marine deposits. These soils are characterized by their high clay content and poor drainage, which are typical of paddy fields (Wang et al., 2017). The soil pH in this region has been observed to decrease from 8.5 to 6.8 with prolonged rice cultivation, indicating significant changes in soil chemistry over time (Wang et al., 2017).

In Bhubaneswar, the soil type is classified as acidic Inceptisol, which is known for its low soil organic carbon (SOC) and cation exchange capacity (CEC). The initial soil pH was recorded at 5.8, with low SOC content (4.3 g/kg) and CEC of 3.75 cmol (p+)/kg (Mukhi et al., 2022). These soil characteristics are essential for understanding the nutrient dynamics and the impact of long-term rice cultivation on soil fertility.

The study sites in Cixi, Zhejiang Province, China, and Bhubaneswar, India, provide a comprehensive understanding of the long-term effects of rice cultivation on soil organic nitrogen dynamics. The uniform marine deposits and subtropical monsoon climate in Cixi, along with the acidic Inceptisol and subtropical climate in Bhubaneswar, offer valuable insights into the changes in soil properties and nutrient dynamics under prolonged rice cultivation (Wang et al., 2017; Mukhi et al., 2022).

2.2 Research methods

The soil samples for this study were collected from various rice paddy fields with different cultivation histories. Specifically, a chronosequence of rice paddy soils (50, 100, 300, and 700 years) was selected from uniform marine deposits in Cixi, Zhejiang Province, China (Wang et al., 2017). Additionally, samples were taken from a long-term experiment site in the coastal areas of Southeast China, where organic materials such as green manure, pig manure, and rice straw had been applied continuously for 10 years (Yu et al., 2020a). Another set of samples was collected from a 32-year field experiment in Nanchang, Jiangxi Province, China, which involved the application of both inorganic and organic fertilizers (Chen et al., 2017).

The experimental design involved comparing soil samples from different cultivation periods and treatments to assess the long-term effects of rice cultivation on soil organic nitrogen (SON) dynamics. The study included control samples from salt marsh soils and tidal flat soils to provide a baseline for comparison (Wang et al., 2017). The effects of various organic materials (milk vetch, rice straw, poultry manure) on soil aggregate and density-based fractions were also evaluated (Yu et al., 2020b). Additionally, the impact of different fertilization treatments (chemical fertilizers, organic manures, and their combinations) on soil properties and microbial communities was examined (Chen et al., 2017; Wang et al., 2021).

Soil organic nitrogen was fractionated using the modified Bremner method, which separates SON into different fractions such as amino acid N, ammonium N, amino sugar N, and hydrolyzable unknown (Wang et al., 2017). The soil aggregate was classified using the wet-sieving method, and light fraction (LF) and heavy fraction (HF) were classified according to density fractionation (Mukhi et al., 2022).

This study used the flooded culture method to determine nitrogen mineralization, which helps to understand the availability of nitrogen for plant uptake over time (Wang et al., 2017) and measured soil total nitrogen (TN), organic carbon (C), and other chemical properties using standard laboratory techniques. For instance, the Elementar Vario ISOTOPE elemental analyzer was used to measure aggregate organic C (AC) and total N (AN) concentrations (Mukhi et al., 2022). Soil pH, organic matter, and alkali-hydrolyzed nitrogen concentrations were also determined (Wei et al., 2022).

Microbial biomass C (MBC) and N (MBN) were measured to assess the microbial activity in the soil. Phospholipid fatty acids (PLFAs) were analyzed to determine the microbial community structure, focusing on fungi and bacteria (Schmidt-Rohr et al., 2004). Advanced solid-state NMR spectroscopy was used to detect nitrogen-bonded aromatics in soil organic matter (Wang et al., 2018).

Non-parametric methods and principal component analysis (PCA) were used to compare carbon metabolism characteristics and distinguish soil chemical properties among different soil samples across seasons (Wei et al., 2022). Correlation analysis was performed to understand the relationships between organic C content and total N content in soil profiles. By employing these comprehensive methods, the study aimed to elucidate the long-term effects of rice cultivation on soil organic nitrogen dynamics, providing valuable insights into soil fertility and sustainable agricultural practices.

3 Effects of Long-term Rice Cultivation on Soil

3.1 Effects of rice cultivation on soil organic nitrogen content

Long-term rice cultivation has been shown to significantly influence soil organic nitrogen (SON) content. Studies indicate that soil total nitrogen (TN) increases with the duration of rice cultivation, stabilizing after approximately 100 years (Wang et al., 2017). This increase in TN is attributed to the accumulation of various nitrogen fractions, including amino acid N, ammonium N, amino sugar N, and hydrolyzable unknown N, which exhibit exponential growth over time. Continuous rice-wheat cultivation without fertilization, however, results in a decrease in total soil nitrogen and its fractions, highlighting the importance of nutrient management practices (Kaur and Jp, 2018).

The dynamic changes in organic nitrogen in paddy soils are influenced by both biotic and abiotic factors. Long-term application of organic manures combined with inorganic fertilizers has been shown to sustain high rice yields and improve soil chemical properties, including organic nitrogen content (Chen et al., 2017). The integration of organic and inorganic fertilizers enhances soil properties such as bulk density, soil porosity, soil organic carbon, and total nitrogen, which in turn improve nitrogen use efficiency and grain yield (Iqbal et al., 2019).

3.2 Effects of seasonal changes on soil organic nitrogen

Seasonal variations also play a crucial role in the dynamics of soil organic nitrogen. During the rice growth stages, the response of nitrogen runoff loss and nitrogen variation in standing water is significantly influenced by soil properties and bacterial communities (Zhang et al., 2021). The tillering stage, in particular, shows notable differences in nitrogen loss due to variations in soil organic carbon, pH, and bacterial composition (Zhang et al., 2021).

Interannual changes in soil organic nitrogen are evident in long-term studies. For instance, a 27-year field experiment demonstrated that partial replacement of mineral fertilizers with in situ crop residues maintained soil fertility and rice yields comparable to those achieved with full mineral fertilization (Chen et al., 2021). This approach not only sustained soil organic carbon and total nitrogen levels but also improved nutrient use efficiency and yield stability over the years (Chen et al., 2021).

3.3 Changes in soil physical and chemical properties

Rice cultivation has a significant impact on soil pH. Long-term rice cultivation tends to lower soil pH, as observed in a chronosequence study where soil pH dropped from 8.5 to 6.8 over 700 years of cultivation (Wang et al., 2017). The application of organic manures in combination with chemical fertilizers can alleviate soil acidification, thereby maintaining a more balanced pH level (Chen et al., 2017).

The content of soil organic matter (OM) is crucial for maintaining soil health and fertility. Long-term application of manures along with chemical fertilizers has been shown to increase soil OM, which in turn supports higher rice yields and improved soil properties (Chen et al., 2017). The integration of organic and inorganic fertilizers enhances soil organic carbon, contributing to better soil structure and nutrient availability (Iqbal et al., 2019).

The nitrogen mineralization rate is a key factor in the availability of nitrogen for plant uptake. Long-term rice cultivation improves soil nitrogen mineralization rates, as demonstrated by higher net mineralization rates in paddy soils compared to non-cultivated soils (Wang et al., 2017). The use of organic manures and crop residues further enhances nitrogen mineralization, supporting sustainable rice production (Kaur and Jp, 2018).

The long-term effects of rice cultivation on soil organic nitrogen dynamics are multifaceted, involving changes in nitrogen content, soil physical and chemical properties, and nitrogen mineralization rates. The integration of organic and inorganic fertilizers, along with proper nutrient management practices, is essential for sustaining soil fertility and achieving high rice yields over extended periods.

4 Effects of Rice Planting on Soil Organic Nitrogen

4.1 Positive and negative effects of rice cultivation on soil organic nitrogen

Long-term rice cultivation has been shown to significantly impact soil organic nitrogen (SON) dynamics. On the positive side, rice cultivation can enhance soil nitrogen (N) accumulation and availability, which is crucial for maintaining soil fertility and supporting sustainable agricultural practices. For instance, a study on paddy soils in China demonstrated that soil total nitrogen (TN) increased significantly with cultivation time, indicating improved soil N fertility (Wang et al., 2017). Additionally, the application of organic fertilizers in rice fields has been found to increase soil urease and catalase activities, which are beneficial for soil health and crop yield (Liu et al., 2021).

However, there are also negative effects associated with long-term rice cultivation. Intensive rice cropping can lead to a decline in grain yield due to decreased availability of soil nitrogen, particularly when nitrogen is bonded to aromatic compounds in soil organic matter, making it less available to plants (Schmidt-Rohr et al., 2004). Furthermore, continuous rice cultivation without proper management can result in soil acidification and nutrient imbalances, which can negatively affect soil health and crop productivity (Figure 1) (Liu et al., 2021).

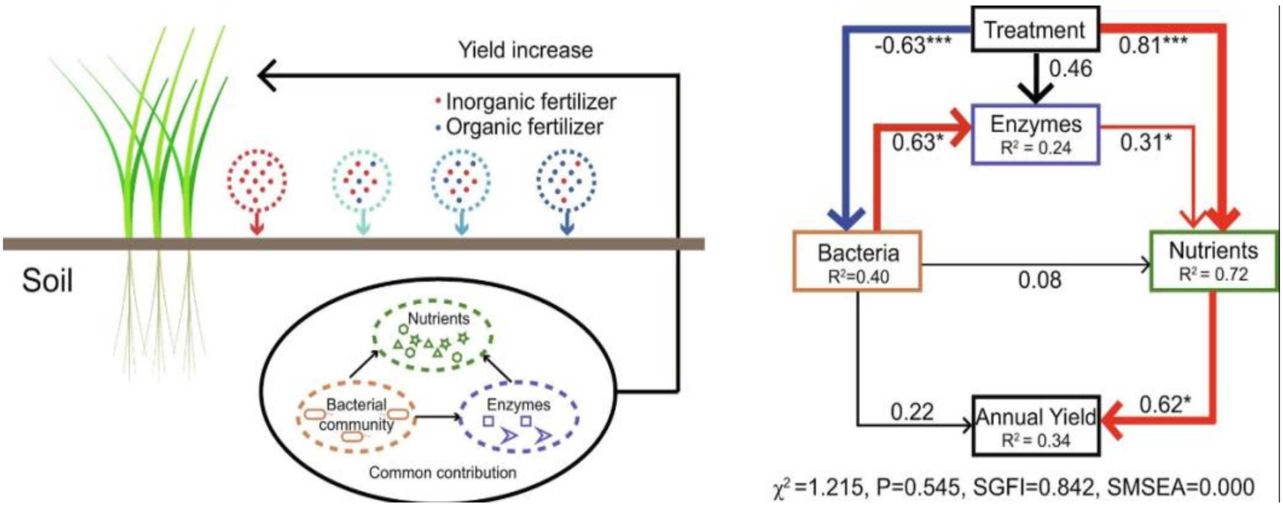

Figure 1 Effects of fertilizers on crop yields (Adopted from Liu et al., 2021)

4.2 Comprehensive effects of long-term cultivation on soil health

Long-term rice cultivation has comprehensive effects on soil health, influencing various soil properties and processes. The incorporation of organic materials, such as rice straw and manure, has been shown to improve soil structure, increase soil organic carbon (SOC) content, and enhance soil microbial activity (Ku et al., 2019; Yu et al., 2020a). These changes contribute to better soil fertility and higher crop yields. For example, long-term organic material applications in paddy fields significantly increased SOC, microbial biomass carbon (MBC), and active organic carbon (AOC), which are essential for maintaining soil structure and fertility (Yu et al., 2020a)

PLS-SEM analysis showed that soil microbial biomass carbon (MBC) had a significant effect on the physical components of organic carbon, but had no significant effect on the chemical structure of carbon in microaggregates and macroaggregates. These results indicate that soil microorganisms are the driving force for the accumulation of physical components of organic carbon (POC and MOC). By continuously adding exogenous organic matter (OM treatment), microorganisms were stimulated, accelerating the decomposition and renewal of organic matter. Soil organic fragments digested by microorganisms were captured by soil clay minerals or aggregates, gradually forming MOC or POC and becoming primary soil particle units (possibly microaggregates). These primary soil particle units continue to aggregate to form larger aggregates (Figure 2) (Zhao et al., 2023).

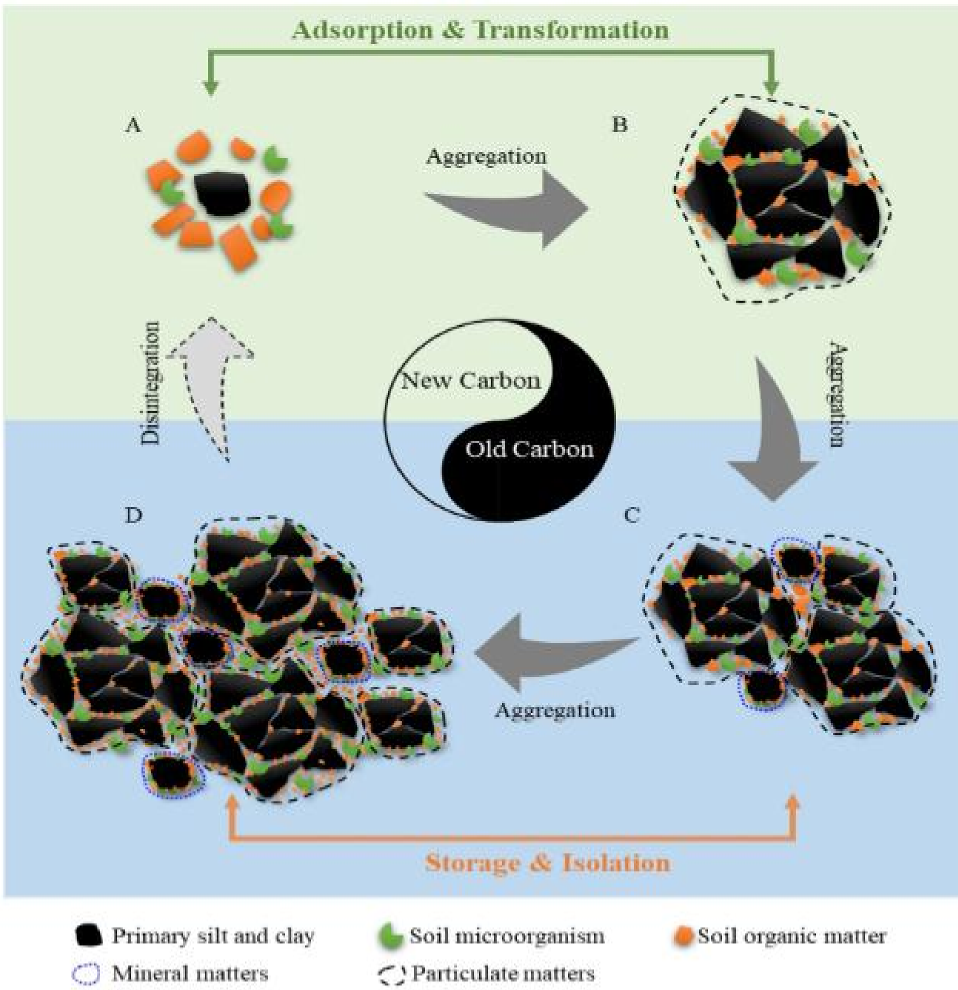

Figure 2 Schematic overview of soil aggregation process and organic C accumulation mechanisms in aggregates (Adopted from Zhao et al., 2023)

This aggregate formation mechanism is consistent with the aggregate hierarchy theory. According to the characteristics of electron microscope images, the silt+clay components and microaggregates are independent monomers, but small and large macroaggregates are soil complexes composed of multiple soil particle units

(Figure 3). Considering that the contents of MOC and POC in large-sized aggregates are much higher than those in small-sized aggregates, it can be speculated that the complex structure of macroaggregates may be a hotbed for the accumulation of physical components of organic carbon. However, the relationship between aggregate structural characteristics and the accumulation of organic carbon components needs to be further clarified in future studies (Zhao et al., 2023). In addition, according to Liu et al. (2021), the use of biochar in rice cultivation can improve soil quality by reducing soil bulk density, increasing soil organic carbon content, and improving nutrient availability. These improvements in soil properties can improve rice productivity and nitrogen use efficiency.

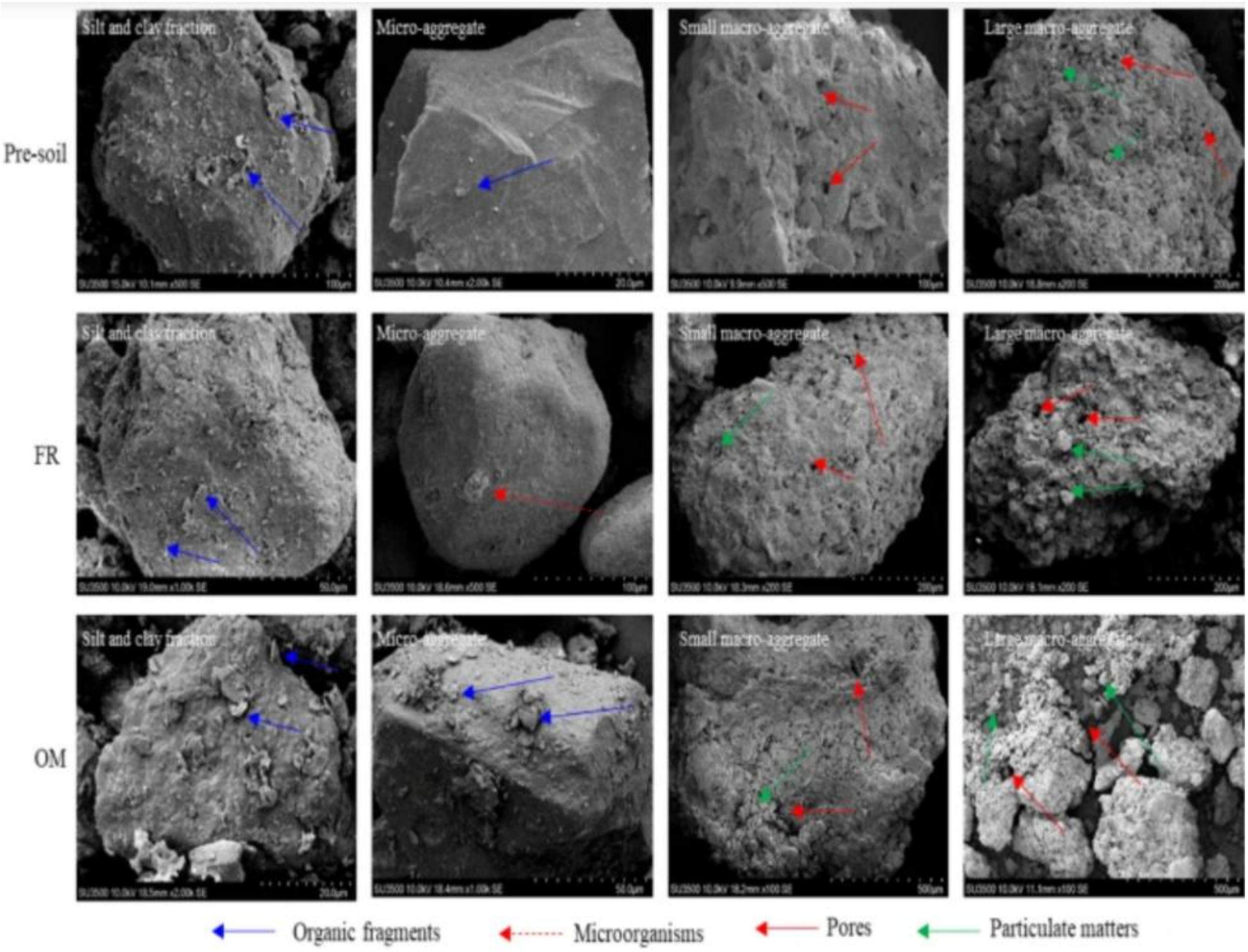

Figure 3 Scanning electron micrograph of water-able aggregates in different treatments (Adopted from Zhao et al., 2023)

4.3 Driving factors of dynamic changes of organic nitrogen

Climatic factors play a crucial role in the dynamic changes of organic nitrogen in rice cultivation. Temperature, precipitation, and humidity can influence soil microbial activity, nitrogen mineralization rates, and overall soil nitrogen dynamics. For instance, the study on paddy soils in China highlighted that soil microbial carbon and nitrogen showed similar patterns with total nitrogen, suggesting that climatic conditions, along with paddy management practices, significantly impact SON composition and mineralization (Wang et al., 2017).

Agricultural management practices, such as fertilization, flooding, plowing, and organic material incorporation, are key drivers of changes in soil organic nitrogen. The continuous application of organic materials, such as milk vetch, rice straw, and poultry manure, has been shown to improve soil nitrogen fractions and enhance soil fertility (Yu et al., 2020b). Additionally, the incorporation of rice straw and the use of biochar have been found to reduce nitrogen leaching and improve nitrogen use efficiency, contributing to better soil health and crop productivity.

The findings from the provided research papers align with existing literature on the effects of long-term rice cultivation on soil organic nitrogen dynamics. Previous studies have consistently shown that organic material incorporation and proper fertilization practices can enhance soil nitrogen content and improve soil health (Ku et al., 2019). The observed decline in grain yield due to nitrogen bonded to aromatic compounds in soil organic matter is also supported by earlier research, which highlights the importance of managing soil nitrogen availability for sustainable crop production (Schmidt-Rohr et al., 2004).

Long-term rice cultivation has both positive and negative effects on soil organic nitrogen dynamics. While it can enhance soil nitrogen accumulation and improve soil health through proper management practices, it can also lead to challenges such as soil acidification and reduced nitrogen availability. Understanding the driving factors, including climatic conditions and agricultural practices, is essential for optimizing soil nitrogen dynamics and ensuring sustainable rice production.

5 Concluding Remarks

The long-term effects of rice cultivation on soil organic nitrogen (SON) dynamics have been extensively studied, revealing several key findings. Firstly, rice cultivation significantly increases soil total nitrogen (TN) and SON fractions, such as amino acid N, ammonium N, amino sugar N, and hydrolyzable unknown N, which stabilize within approximately 100 years of cultivation. The application of organic materials, such as milk vetch, rice straw, and poultry manure, has been shown to enhance soil aggregate mass and improve the concentration of organic carbon (C) and nitrogen (N) in both light and heavy soil fractions. Additionally, long-term organic fertilizer substitution not only increases rice yield but also improves soil properties and regulates soil bacterial communities, which are crucial for maintaining soil health and fertility. However, intensive rice cropping can lead to a decline in grain yield due to the decreased availability of soil nitrogen, particularly nitrogen bonded to aromatic compounds in soil organic matter.

To sustain and improve soil fertility and rice yield, several agricultural practices are recommended. The continuous application of organic materials, such as compost, rice straw, and green manure, is highly effective in increasing soil organic carbon and nitrogen fractions, thereby enhancing soil structure and fertility. Combining organic and inorganic fertilizers can also sustain high rice yields and improve soil chemical and bacterial properties, which are essential for long-term soil health. Additionally, incorporating rice straw or amending manure to paddy soils is a preferred practice for maintaining soil organic carbon content and ensuring sustainable rice production. These practices not only improve soil fertility but also contribute to the stabilization and fixation of carbon and nitrogen in rice fields.

Future research should focus on understanding the long-term impacts of different organic and inorganic fertilizer combinations on soil health and crop productivity. Studies should investigate the specific mechanisms through which organic materials influence soil microbial communities and their role in nutrient cycling and soil fertility. Additionally, research should explore the effects of different rice cultivation practices on the formation and stabilization of nitrogen-bonded aromatics in soil organic matter, which have been linked to yield declines in intensive rice cropping systems. Long-term field experiments and modeling studies are needed to evaluate the sustainability of various agricultural practices and their impact on soil organic carbon and nitrogen dynamics over extended periods. Finally, the development of innovative soil management strategies that integrate organic and inorganic inputs to optimize soil health and crop yield should be a priority for future research.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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