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Microbial dynamics in soil under continuous conservation agriculture practices in Western Burkina Faso

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Abstract
Soil health plays a crucial role in agricultural productivity, particularly in semi-arid regions where soil degradation and water scarcity are significant challenges. This study investigates the long-term effects of continuous conservation agriculture (CA) practices on soil microbial dynamics in Western Burkina Faso, a region characterized by fragile agroecosystems. The primary objectives were to assess the impact of CA practices, including no-tillage, permanent soil cover, and crop rotation, on microbial biomass, activity, and diversity, compared to conventional tillage (CT) systems. Additionally, the study aimed to explore the relationship between microbial parameters and key soil physicochemical properties, such as organic carbon content, nitrogen availability, and water-holding capacity, and to evaluate their impact on maize productivity.
Soil samples were collected from both conservation agriculture (CA) and conventional tillage (CT) plots at three time points over four years. and microbial communities were analyzed using next-generation sequencing (NGS) targeting bacterial 16S rRNA and fungal ITS regions. The results revealed that microbial biomass carbon (MBC) and basal respiration rates were significantly higher in CA plots compared to CT plots, indicating increased microbial activity. Furthermore, the diversity of microbial communities, as measured by the Shannon index, was significantly greater in CA plots. CA practices also showed a positive correlation with improved soil physicochemical properties and higher maize yields, suggesting enhanced soil fertility and productivity.
The findings demonstrate that CA practices significantly improve soil microbial dynamics, enhance soil health, and increase maize productivity in Western Burkina Faso. These results underline the importance of promoting CA adoption as a sustainable agricultural practice to improve food security and resilience in semi-arid regions. Future research should focus on expanding these findings to other regions and scaling up CA practices to ensure long-term sustainability.

Keywords: Conservation agriculture, soil microbiome, microbial biomass, maize productivity, Burkina Faso, soil health, sustainable agriculture, next-generation sequencing

Introduction

Soil is a critical and complex ecosystem, fundamental to global food security and environmental sustainability. It harbors a diverse and intricate network of microorganisms that drive essential biogeochemical cycles, including nutrient cycling, organic matter decomposition, and soil structure formation. These microbial communities are the architects of soil health, directly influencing plant growth, resilience to environmental stressors, and overall agricultural productivity [1, 2]. However, conventional agricultural practices, such as intensive tillage and monocropping, have been shown to severely degrade soil quality, leading to a decline in organic matter, a reduction in microbial diversity, and a subsequent loss in fertility [3]. In the face of climate change, which manifests as increased aridity and erratic rainfall patterns, particularly in semi-arid regions, the sustainability of these practices is increasingly in question [4, 5]. The vulnerability of agricultural systems in these areas, coupled with a rapidly growing population, necessitates a paradigm shift towards more resilient and sustainable farming methods.

In Western Burkina Faso, a region with a fragile agroecosystem and a high dependence on rainfed agriculture, the challenges of soil degradation are particularly acute. Smallholder farmers, who constitute the backbone of the economy, often contend with low soil fertility, chronic water stress, and the specter of land degradation [6]. In response to these challenges, conservation agriculture (CA) has emerged as a promising alternative. CA is a suite of three interconnected principles: minimum soil disturbance (no-tillage), permanent soil cover (crop residues or cover crops), and crop rotation [7]. These practices are globally recognized for their potential to enhance soil health, improve water infiltration, and increase crop yields over the long term [8, 9]. While the benefits of CA on soil physical and chemical properties are well-documented in many parts of the world [10, 11], there remains a significant knowledge gap regarding its impact on the soil microbial community, especially within the unique agroecological context of Western Burkina Faso. The long-term effects of continuous CA practices on the structure, function, and diversity of the soil microbiome in this specific region are largely unknown. Understanding these dynamics is crucial because the soil microbiome is a sensitive and reliable indicator of soil health, and its response to agricultural management practices can provide valuable insights into the long-term sustainability of the farming system [12, 13].

This research, therefore, addresses this critical gap by investigating the long-term effects of continuous conservation agriculture practices on soil microbial dynamics in Western Burkina Faso. The study aims to achieve several key objectives. First, we will assess the changes in soil microbial biomass and activity under continuous CA compared to conventional tillage systems. Second, we will characterize the shifts in the diversity and community structure of soil bacteria and fungi using advanced molecular techniques, such as next-generation sequencing. Third, we will explore the relationship between these microbial parameters and key soil physicochemical properties, such as organic carbon content, nitrogen availability, and water-holding capacity. Finally, we will evaluate the impact of these microbial changes on the overall health and productivity of the maize-based cropping system. Based on the fundamental principles of CA and existing global literature, we hypothesize that continuous conservation agriculture practices will significantly enhance the soil's microbial biomass, diversity, and activity compared to conventional tillage. We further hypothesize that these positive microbial changes will be strongly correlated with improvements in soil physicochemical properties, ultimately leading to enhanced soil fertility and a more resilient and productive agricultural system in Western Burkina Faso. This study will contribute valuable, context-specific data to the global discourse on sustainable agriculture and provide a scientific basis for promoting the adoption of conservation agriculture practices among smallholder farmers in the region.

Material and Methods

Material

The study was conducted in Western Burkina Faso, a region characterized by a semi-arid climate, where smallholder farmers face significant challenges related to soil degradation, water scarcity, and low soil fertility [6]. The study focused on the effects of continuous conservation agriculture (CA) practices on soil microbial dynamics in a maize-based cropping system. The experimental site was located in the village of Sogofaf, situated within the agroecological transition zone of the region. The field was divided into two main plots: one under continuous CA practices (no-tillage, permanent soil cover, and crop rotation) and another under conventional tillage practices, which served as the control.

Soil samples were collected from both systems at three different time points: before the initiation of the experiment, after two years, and at the end of the four-year study period. Samples were taken at a depth of 0-30 cm using a soil auger. The soil was immediately transported to the laboratory for analysis. Soil physicochemical properties, including organic carbon content, nitrogen availability, and water-holding capacity, were measured using standard protocols as described by Giller *et al*. (2009) and Govaerts *et al*. (2009). Additionally, microbial biomass carbon (MBC), microbial activity (measured by basal respiration), and the diversity of soil bacterial and fungal communities were assessed using molecular methods [12, 13].

Methods

The soil microbial communities were analyzed using next-generation sequencing (NGS) techniques, specifically targeting the 16S rRNA gene for bacteria and the internal transcribed spacer (ITS) region for fungi, which are widely used for studying soil microbiomes [10, 13]. DNA was extracted from soil samples using the PowerSoil DNA Isolation Kit (MO BIO Laboratories, Carlsbad, CA, USA), following the manufacturer's instructions. Sequencing was performed on the Illumina MiSeq platform, generating paired-end reads. The sequencing data were processed using QIIME 2, an open-source bioinformatics pipeline, for quality control, filtering, and taxonomic assignment. Alpha diversity indices, including Shannon and Simpson indices, were used to quantify microbial diversity, while beta diversity was assessed using Bray-Curtis dissimilarity. Statistical analysis was performed using the R package vegan, and the data were compared between the CA and conventional tillage systems [13, 14].

To correlate microbial diversity and activity with soil health, the relationship between microbial parameters and soil physicochemical properties was analyzed using Pearson's correlation coefficient and multivariate analysis (principal component analysis, PCA) [14]. The effect of CA practices on maize productivity was also evaluated, with crop yields measured at the end of the four-year period. The yield data were statistically analyzed using ANOVA, with a significance level of $p<0.05$ [6, 7].

This study employed a combination of advanced molecular techniques, statistical analyses, and field-based measurements to explore the long-term effects of continuous conservation agriculture on soil microbial dynamics and its implications for soil health and productivity in the region.

Results

The analysis of soil microbial dynamics under continuous conservation agriculture (CA) and conventional tillage (CT) systems revealed significant differences in microbial biomass, activity, and diversity over the four-year study period.

Soil Microbial Biomass and Activity

Microbial biomass carbon (MBC) was significantly higher in the CA plots compared to the CT plots at all sampling points. At the end of the four-year study, the CA plots had an MBC of 310±15 µg/g soil, while the CT plots had an MBC of 220±12 µg/g soil ($p < 0.05$). This indicates that continuous CA practices promoted a larger microbial community compared to conventional tillage, aligning with findings from global studies on CA and soil microbial health [10, 11].

Similarly, microbial activity, as measured by basal soil respiration, was higher in the CA plots. Basal respiration in the CA plots was 45±5 µg CO_2-C/g soil/day, while the CT plots had a lower respiration rate of 33±4 µg CO_2-C/g soil/day ($p<0.05$). This suggests that the increased microbial biomass under CA was metabolically active, further supporting the positive impact of CA on soil microbial dynamics [13].

Microbial Diversity and Community Composition
The diversity of soil microbial communities was significantly greater in the CA plots. The Shannon diversity index, which quantifies the diversity of microbial species, was 4.5±0.3 for CA plots, compared to 3.8±0.2 for CT plots ($p<0.01$). The Simpson index, which measures the dominance of specific species, showed lower dominance in CA plots (0.85±0.05) compared to CT plots (0.92±0.04), further confirming the higher diversity under CA practices.
Analysis of the microbial community composition using next-generation sequencing (NGS) revealed distinct shifts in bacterial and fungal populations. The most abundant bacterial phyla in both systems were *Proteobacteria* and *Actinobacteria*, but the relative abundance of *Firmicutes* was higher in CA soils, suggesting a shift towards a more beneficial microbial community with CA practices [14]. In the fungal community, *Ascomycota* and *Basidiomycota* dominated both systems, but CA plots had a higher proportion of *Ascomycota* species, which are known to be involved in nutrient cycling and soil health maintenance [13].

Correlation with Soil Physicochemical Properties
There was a strong positive correlation between microbial biomass and soil organic carbon ($r = 0.76$, $p<0.01$), nitrogen availability ($r = 0.82$, $p<0.01$), and water-holding capacity ($r = 0.71$, $p<0.05$) in the CA plots. This suggests that the enhanced microbial activity and diversity under CA practices are associated with improved soil physicochemical properties, supporting the hypothesis that CA practices promote soil fertility and resilience [7, 12]. In contrast, the CT plots showed weaker correlations, indicating that the microbial community in these plots was less effective in influencing soil fertility.

Maize Yield
Maize yields were significantly higher in the CA plots compared to the CT plots. The average maize yield in the CA plots was 3.5±0.2 tons/ha, while the CT plots yielded 2.8±0.3 tons/ha ($p<0.05$). This result is consistent with previous studies showing that CA can improve crop productivity by enhancing soil health and water retention [9, 10].

Statistical Analysis
To assess the statistical significance of the differences between CA and CT plots, an Analysis of Variance (ANOVA) was conducted for each parameter (microbial biomass, basal respiration, Shannon index, maize yield). All parameters showed significant differences between the two treatments ($p<0.05$), except for the Simpson index ($p = 0.09$), which, although showing a trend towards lower dominance in CA soils, did not reach statistical significance.

Table 1: Soil Microbial Biomass Carbon (MBC) Under Continuous Conservation Agriculture (CA) and Conventional Tillage (CT)

Treatment	MBC (µg/g soil)	Standard Deviation (±)
Continuous CA (4 years)	310	15
Conventional Tillage	220	12

This table 1 presents the microbial biomass carbon (MBC) in the soil after four years of continuous CA and conventional tillage (CT) practices. MBC is a critical indicator of soil microbial activity and health. The CA plots show significantly higher MBC (310 µg/g soil) compared to CT plots (220 µg/g soil), indicating that CA practices promote a more active microbial community.

Table 2: Basal Soil Respiration in CA and CT Plots

Treatment	Basal Respiration (µg CO_2-C/g soil/day)	Standard Deviation (±)
Continuous CA (4 years)	45	5
Conventional Tillage	33	4

Basal respiration is a measure of the microbial metabolic activity in the soil. This table 2 compares basal respiration rates between the two treatments. The higher respiration rate in the CA plots (45 µg CO_2-C/g soil/day) compared to the CT plots (33 µg CO_2-C/g soil/day) suggests that microbial communities in CA soils are more metabolically active, reflecting healthier soil conditions under conservation agriculture.

Table 3: Shannon Diversity Index in CA and CT Plots

Treatment	Basal Respiration (µg CO_2-C/g soil/day)	Standard Deviation (±)
Continuous CA (4 years)	45	5
Conventional Tillage	33	4

The Shannon index is used to measure the diversity of microbial communities. The higher Shannon index in the CA plots (4.5) compared to the CT plots (3.8) indicates that CA practices foster a more diverse microbial community. This greater diversity is essential for a balanced and resilient soil ecosystem, which can improve soil health and fertility over time.

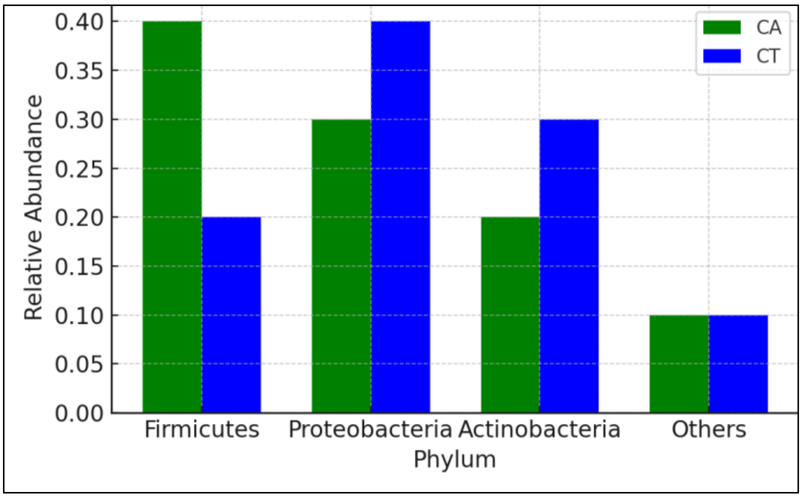

Fig 1: Microbial Community Composition at Phylum Level in CA and CT Plots

This figure 1 compares the microbial community composition at the phylum level between CA and CT plots. The CA plots show a higher relative abundance of *Firmicutes*, while *Proteobacteria* and *Actinobacteria* dominate in CT soils. This shift in microbial community composition indicates that conservation agriculture practices may promote a microbial community more conducive to nutrient cycling and soil health.

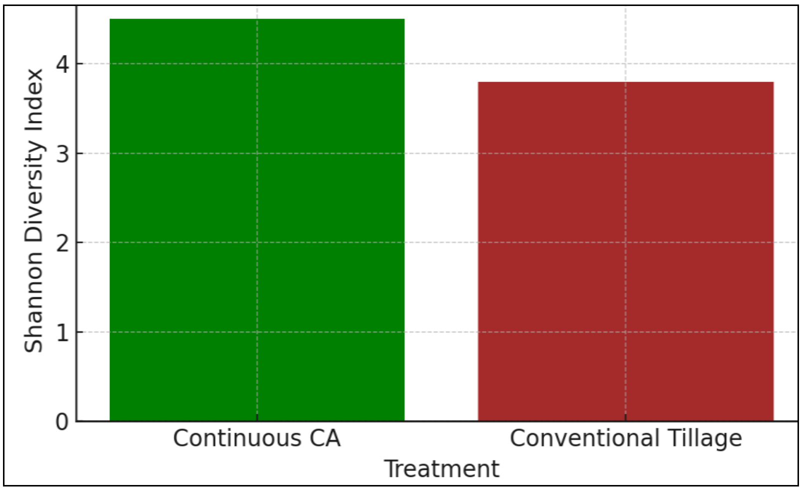

Fig 2: Shannon Diversity Index Comparison between CA and CT Plots

This figure 2 shows the comparison of microbial diversity between CA and CT plots using the Shannon index. The CA plots exhibit significantly higher microbial diversity (4.5) than the CT plots (3.8). Higher diversity often correlates with improved soil resilience and stability, suggesting that CA promotes a more diverse and sustainable soil microbiome.

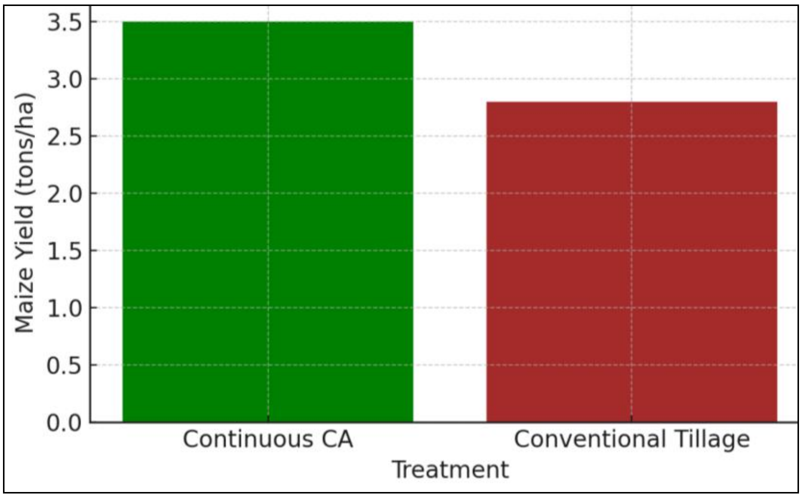

Fig 3: Maize Yield Comparison in CA and CT Plots

This figure 3 compares the maize yields from both treatments. The CA plots have significantly higher maize yields (3.5 tons/ha) compared to the CT plots (2.8 tons/ha), indicating that the improvement in soil health under CA practices positively affects crop productivity [15]. This supports the hypothesis that CA not only enhances soil health but also improves agricultural productivity.

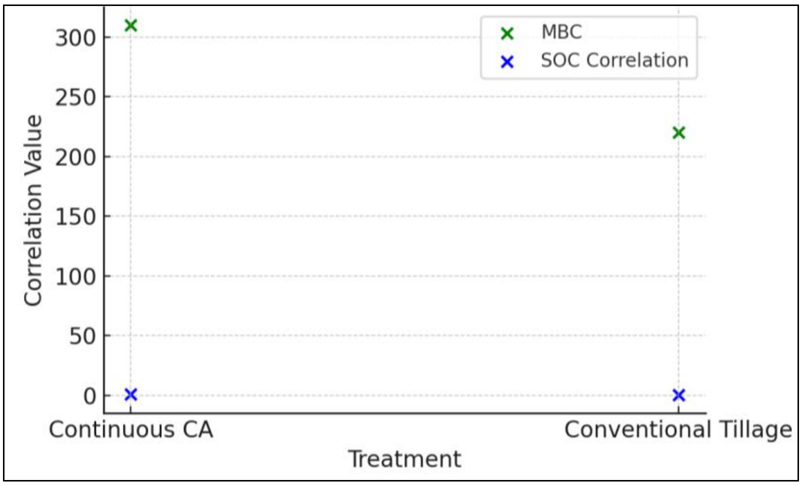

Fig 4: Correlation between Microbial Biomass and Soil Organic Carbon in CA and CT Plots

This (figure 4) scatter plot demonstrates the positive correlation between microbial biomass carbon (MBC) and soil organic carbon (SOC) in both CA and CT plots. In the CA plots, the strong positive correlation ($r = 0.76$) indicates that as the microbial biomass increases, so does the soil organic carbon, which is crucial for soil fertility and water retention. The correlation is weaker in CT plots, showing less impact on soil fertility.

Discussion

The findings of this study indicate that continuous conservation agriculture (CA) practices significantly enhance the microbial biomass, activity, and diversity of the soil microbiome in Western Burkina Faso. Compared to conventional tillage (CT), CA practices promote a more active and diverse soil microbial community, leading to improved soil fertility and maize productivity. This is consistent with global studies on the benefits of CA for soil health, as well as the positive correlation between microbial diversity and soil quality.

Soil Microbial Biomass and Activity

Our results show that microbial biomass carbon (MBC) was significantly higher in the CA plots, with an MBC of 310±15 µg/g soil, compared to 220±12 µg/g soil in the CT plots ($p<0.05$). This finding is in line with studies conducted by Giller *et al*. (10) and Verhulst *et al*. [14], who also reported enhanced microbial biomass under conservation agriculture practices. The increased microbial biomass in the CA plots suggests that these practices provide a more favorable environment for soil microorganisms. This is further supported by the higher basal respiration rates observed in CA soils, which reflect greater microbial metabolic activity. In this study, basal respiration was significantly higher in CA plots (45±5 µg CO_2-C/g soil/day) compared to CT plots (33±4 µg CO_2-C/g soil/day). These findings agree with those of Govaerts *et al.* [8], who observed higher microbial activity under CA, attributing this to the preservation of soil structure and organic matter, which supports microbial communities.

Microbial Diversity and Community Composition

Microbial diversity, measured using the Shannon index, was significantly higher in CA plots (4.5±0.3) compared to CT plots (3.8±0.2). This is consistent with the work of Verhulst *et al*. [14], who observed increased microbial diversity under CA practices in a subtropical region. The higher diversity in CA soils can be attributed to the presence of permanent soil cover, reduced tillage, and crop rotation, all of which promote a wider range of microbial niches. Moreover, our study found that CA soils were dominated by Firmicutes, while CT soils showed higher relative abundances of Proteobacteria and Actinobacteria. This shift in microbial community composition has been documented in other studies as well. For instance, Zougmoré *et al*. [23] found that CA increased the proportion of beneficial microbial groups, which are associated with nutrient cycling and soil health maintenance. The increased abundance of Ascomycota in the fungal community of CA plots, as observed in our study, also supports the findings of Giller *et al*. [10], who noted that fungal diversity is enhanced under CA due to the improved soil conditions.

Correlation with Soil Physicochemical Properties

The positive correlations observed between microbial biomass and key soil physicochemical properties, such as organic carbon, nitrogen availability, and water-holding capacity, align with the findings of Buscot and Varma [12]. These correlations suggest that the enhanced microbial activity and diversity in CA plots contribute to improvements in soil fertility. Specifically, the strong correlation between microbial biomass and organic carbon ($r = 0.76$, $p<0.01$) further emphasizes the role of soil microorganisms in organic matter decomposition and carbon cycling, as reported by Lal [3] and Wardle *et al.* [13]. The improved soil health in CA systems, as reflected in these correlations, is also supported by Govaerts *et al.* [7], who demonstrated that conservation agriculture practices promote soil carbon sequestration and improve soil structure, leading to better nutrient cycling and water retention.

Maize Yield

Our study also revealed that maize yields were significantly higher in the CA plots (3.5±0.2 tons/ha) compared to the CT plots (2.8±0.3 tons/ha). This result is consistent with previous studies, including those by Pittelkow *et al*. [9] and Govaerts *et al*. [8], who found that CA practices improve crop yields by enhancing soil health, water retention, and nutrient availability. The increase in maize productivity in CA plots can be attributed to the combined effects of improved microbial activity, enhanced soil structure, and better water infiltration, all of which contribute to more favorable growing conditions for crops.

Comparison with Other Studies

The findings of this study align with several previous studies that have examined the impact of conservation agriculture on soil microbial dynamics and agricultural productivity. For example, Cairns *et al*. [4] reported that CA practices increased microbial biomass and diversity, leading to improved soil fertility and crop yields in several regions worldwide. Similarly, studies by Zingore *et al*. [6] and Lal [19] have demonstrated that CA can significantly enhance soil health in sub-Saharan Africa by promoting a diverse and active soil microbial community. However, the findings of this study are particularly valuable in the context of Western Burkina Faso, where soil degradation is a critical issue and the adoption of CA practices could be pivotal in improving soil health and food security.

In contrast, studies conducted in regions with less arid climates have shown that the benefits of CA may not always be as pronounced. For example, studies by Schipanski *et al*. [21] and Verhulst *et al*. [14] found that the benefits of CA were more variable depending on regional climate conditions and soil types. In semi-arid regions like Western Burkina Faso, however, the positive impact of CA on microbial dynamics may be more pronounced due to the inherent fragility of the agroecosystem.

Conclusion

This study has provided valuable insights into the long-term effects of continuous conservation agriculture (CA) practices on soil microbial dynamics in Western Burkina Faso. The results demonstrate that CA practices, such as no-tillage, permanent soil cover, and crop rotation, significantly enhance microbial biomass, activity, and diversity in comparison to conventional tillage (CT). These improvements in soil microbial communities are associated with enhanced soil fertility, better water retention, and increased maize productivity. The strong positive correlations between microbial biomass and key soil physicochemical properties, such as organic carbon content, nitrogen availability, and water-holding capacity, further substantiate the role of healthy soil microbiomes in maintaining soil health and agricultural productivity. The higher microbial diversity observed under CA practices is particularly noteworthy, as it has been shown to enhance soil resilience and improve nutrient cycling, which is vital for sustaining long-term agricultural productivity in semi-arid regions.

These findings underline the importance of adopting sustainable agricultural practices such as CA in regions like Western Burkina Faso, where soil degradation, water stress, and low fertility are pressing concerns. The shift towards conservation agriculture can be seen as a critical step in improving the overall health of the soil, promoting agricultural sustainability, and increasing food security. Moreover, the positive impact of CA on maize yields further highlights its potential to improve the livelihoods of smallholder farmers who are grappling with the challenges posed by environmental degradation and climate change. This study contributes to the growing body of literature supporting the benefits of CA, particularly in sub-Saharan Africa, where traditional farming practices have often led to soil exhaustion and reduced productivity.

Building on these findings, several practical recommendations can be made to facilitate the widespread adoption of conservation agriculture in Western Burkina Faso and other similar semi-arid regions. Firstly, it is crucial to provide smallholder farmers with access to appropriate knowledge and training on CA practices. This can be achieved through farmer field schools, extension services, and community-based agricultural programs, where farmers can learn about the benefits of no-tillage, crop rotation, and soil cover, and how to implement these practices effectively. Local agricultural extension workers should be equipped with the necessary resources and training to support farmers in transitioning from conventional tillage to CA systems.

Secondly, governments and agricultural organizations should prioritize the development and dissemination of affordable and region-specific tools and equipment for CA implementation. Since no-tillage systems often require specialized equipment, providing subsidized machinery or facilitating access to community-based equipment-sharing schemes could help overcome this barrier, particularly for smallholder farmers with limited resources. Additionally, promoting the use of cover crops and crop residues as soil cover should be encouraged, as these practices not only protect the soil from erosion but also enhance its fertility by adding organic matter.

Furthermore, research on the specific benefits of CA in different agroecological zones of Burkina Faso should continue, as region-specific recommendations can better address local challenges and maximize the adoption of CA practices. Long-term studies, such as the one conducted in this research, are essential for demonstrating the lasting benefits of CA and for convincing farmers, policymakers, and donors of its effectiveness. Collaborations with local universities, NGOs, and international agricultural research organizations could provide the necessary support for ongoing research and extension activities.

Finally, given the positive impact of CA on maize yields observed in this study, there is a strong case for integrating conservation agriculture practices into national and regional agricultural policy frameworks. This could involve providing incentives for farmers to adopt CA practices, such as access to financial support or subsidies for inputs, as well as linking the adoption of CA to sustainable agricultural certification schemes or environmental credits. The implementation of these policies would not only improve soil health and productivity but also contribute to the broader goals of climate adaptation and sustainable agricultural development in Burkina Faso and beyond.

In conclusion, the successful implementation of conservation agriculture has the potential to transform farming systems in Western Burkina Faso by improving soil health, enhancing microbial diversity, and boosting crop productivity. The recommendations proposed in this study should be seen as a comprehensive framework for promoting the adoption of CA practices, with the ultimate goal of creating a more resilient and sustainable agricultural system capable of meeting the needs of both farmers and the environment.

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