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Dr. Moussa Ouedraogo
Department of Agricultural Sciences, University of Ouagadougou, Ouagadougou, Burkina Faso

Awa Zongo
Professor, Institute for Environmental Research, National University of Faso, Bobo-Dioulasso, Burkina Faso

Dr. Idrissa Kaboré
Center for Sustainable Agriculture, Burkina Faso Agricultural Research Institute, Koudougou, Burkina Faso

Dr. Mariam Diallo
Department of Soil Science, University of Ouagadougou, Ouagadougou, Burkina Faso

Correspondence Author:
Dr. Moussa Ouedraogo
Department of Agricultural Sciences, University of Ouagadougou, Ouagadougou, Burkina Faso

Sustainability of conservation agriculture practices for improved crop yields in agroecological transitions of western Burkina Faso

Moussa Ouedraogo, Awa Zongo, Idrissa Kaboré and Mariam Diallo

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Abstract
This study aimed to evaluate the sustainability and long-term impacts of Conservation Agriculture (CA) practices on key agricultural metrics, such as soil health, crop productivity, and water retention, in the agroecological transition zone of Western Burkina Faso.
Results indicated significant improvements in soil organic matter (22% increase), nutrient availability (15% increase in nitrogen), and water retention (18% higher moisture at flowering stage) in no-tillage plots with mulch application compared to conventional tillage. Maize yields increased by 34% under no-tillage with mulch, highlighting the positive impact of CA on crop productivity. In contrast, conventional tillage plots showed stable or declining yields due to soil degradation. The study concludes that CA, particularly no-tillage with mulch retention, enhances soil health, increases crop yields, and improves water use efficiency, making it a viable solution for sustainable agriculture in semi-arid regions. However, adoption barriers such as residue competition and limited access to equipment must be addressed for widespread implementation.

Keywords: Conservation agriculture, soil health, crop productivity, water retention, semi-arid regions, no-tillage, residue management, Burkina Faso, sustainable agriculture

Introduction

The imperative to ensure global food security for a projected population of over nine billion by 2050 is compounded by the escalating challenges of climate change and widespread land degradation [1, 2]. Sub-Saharan Africa (SSA), in particular, stands at the epicenter of this challenge, characterized by agricultural systems with persistent low productivity, high vulnerability to climatic shocks, and severely degraded soil resources [3, 4]. The Sahelian region, including Western Burkina Faso, exemplifies these pressures, where rain-fed agriculture forms the bedrock of livelihoods and national economies but is increasingly threatened by erratic rainfall, prolonged droughts, and a systematic decline in soil fertility [5, 6]. Traditional farming practices in this region have historically relied on intensive soil tillage using implements like the hand hoe or animal-drawn plows, coupled with the complete removal of crop residues for livestock fodder or fuel [7]. While culturally entrenched, these conventional practices have been identified as key drivers of environmental degradation, leading to the disruption of soil structure, accelerated soil organic matter (SOM) depletion, increased susceptibility to wind and water erosion, and diminished water infiltration and retention capacity, ultimately culminating in a cycle of declining crop yields and heightened food insecurity (8, 9). In response to this multifaceted crisis, Conservation Agriculture (CA) has been promoted globally as a cornerstone of sustainable agricultural intensification [10]. CA is a holistic, ecosystem-based approach built upon three interlinked principles: minimal soil disturbance (through no-tillage or reduced tillage), maintenance of a permanent or semi-permanent organic soil cover (using crop residues or cover crops), and diversification of crop species (through rotations or associations) [11]. The synergistic application of these principles is purported to mimic the processes of natural ecosystems, thereby enhancing soil health, improving water use efficiency, reducing labor and energy inputs, and sequestering atmospheric carbon, which should, over time, lead to more resilient and productive farming systems [12, 13].

Despite the well-documented potential of CA in various agroecologies worldwide, its adoption and sustained implementation in the complex socio-economic and biophysical landscapes of Western Burkina Faso remain limited and fraught with challenges [14, 15]. A primary impediment is the strong competition for crop residues, which are a critical resource for livestock feed, particularly during the long dry season, creating a direct conflict with the principle of maintaining soil cover [16]. Furthermore, significant barriers include farmers' limited access to specialized no-till seeding equipment, a lack of technical knowledge regarding the management of CA systems, and the potential for short-term yield reductions during the initial transition phase, which resource-poor smallholders can ill-afford [17, 18]. Consequently, a critical knowledge gap persists regarding the long-term viability, context-specific performance, and overall sustainability of CA practices within the unique agroecological transition zones of Western Burkina Faso. While some short- to medium-term studies have shown promise, such as the work by Coulibaly *et al*. [21] which demonstrated positive effects on soil fertility and maize yield after four years of continuous CA practice, the long-term sustainability and resilience of these systems under fluctuating climatic conditions are not yet fully understood. The scientific evidence base remains insufficient to provide robust, locally-calibrated recommendations for scaling up CA. Therefore, this study was conceived to address this critical gap by comprehensively evaluating the long-term impacts of continuous CA practices on soil properties and crop productivity. The primary objective is to assess and compare the effects of different tillage systems (conventional tillage vs. no-tillage), residue management strategies (mulch application vs. residue removal), and crop rotations on key soil health indicators, water dynamics, and the yields of staple crops over a multi-year period. It is hypothesized that the sustained implementation of an integrated CA system, combining no-tillage, permanent residue cover, and diversified crop rotations, will lead to significant cumulative improvements in soil organic matter, soil structure, and moisture retention, ultimately resulting in higher, more stable crop yields and greater system resilience compared to traditional tillage-based farming practices in the agroecological context of Western Burkina Faso. This research aims to provide the empirical evidence needed to guide policy and extension services in promoting sustainable agricultural pathways that can enhance farmer livelihoods and food security in this vulnerable region [19, 20, 22-25].

Materials and Methods

Study Area and Climate

This study was conducted in the agroecological transition zone of Western Burkina Faso, a region characterized by semi-arid conditions and highly variable rainfall patterns. The region experiences a tropical climate with a distinct wet season (June to September) and a prolonged dry season (October to May) [6, 7]. The annual rainfall ranges from 600 to 1,000 mm, with erratic distribution and frequent droughts during the growing season [5]. The soil types in the region are primarily Ferralsols and Acrisols, which are prone to erosion and fertility decline due to intensive tillage practices [8, 9]. The study area was selected for its vulnerability to climate variability and soil degradation, providing a relevant context for evaluating the long-term impacts of Conservation Agriculture (CA) practices.

Experimental Design

A randomized complete block design (RCBD) with three replications was used to evaluate the impact of different Conservation Agriculture practices on soil fertility, water retention, and crop yields. The study compared three tillage systems (conventional tillage vs. no-tillage), two residue management strategies (mulch application vs. residue removal), and two crop rotations (maize-legume vs. monoculture maize). The experimental plots were established in collaboration with local farmers who had been practicing traditional farming methods [7]. The study was conducted over a period of four years (2019-2023) to assess the long-term effects of CA on soil health and crop productivity.

Materials and Inputs

The materials used in the study included locally adapted crop varieties, soil amendments, and CA tools. Maize (Zea mays L.) was used as the primary crop, with legumes such as cowpea (Vigna unguiculata) and groundnut (Arachis hypogea) as rotational crops [14]. The crops were planted using a manual no-till seeder in no-tillage plots and by traditional plowing in conventional tillage plots. Soil amendments such as compost and organic fertilizers were applied based on soil fertility tests conducted at the beginning of the study [12, 16]. Crop residues from the previous growing season were either retained as mulch in the no-tillage plots or removed for livestock feed in the conventional tillage plots.

Soil and Crop Sampling

Soil samples were collected at the beginning and end of each cropping season from each plot at a depth of 0-30 cm using a soil auger (15). These samples were analyzed for soil organic matter (SOM), pH, nutrient content (N, P, K), and water holding capacity. Crop yield data were collected at harvest from each plot, and the above-ground biomass of each crop was measured to estimate total productivity. For water dynamics, soil moisture content was measured throughout the growing season using a portable soil moisture meter [18]. Crop growth was monitored using visual assessments of plant health and biomass accumulation at key growth stages.

Data Analysis

Data collected from soil samples, crop yields, and water measurements were analyzed using analysis of variance (ANOVA) to compare the effects of different CA practices across the experimental treatments [19, 20]. Where significant differences were found, Tukey's HSD test was applied to determine pairwise comparisons. Soil health indicators such as SOM, pH, and nutrient levels were analyzed for temporal trends to assess the impact of CA practices over the four-year period. Crop yield data were analyzed in relation to each treatment to determine the effects of CA practices on productivity. Statistical analysis was performed using SPSS (version 22, IBM Corp).

Results

Soil Health Indicators

The analysis of soil samples collected at the beginning and end of each cropping season revealed significant improvements in key soil health indicators under

Conservation Agriculture (CA) practices. The soil organic matter (SOM) content increased significantly in the no-tillage plots with mulch application, showing a 22% increase compared to the conventional tillage plots (Table 1). This improvement was observed across all four years of the study, indicating the cumulative benefits of reduced soil disturbance and the retention of crop residues as mulch. The SOM content in the conventional tillage plots, where residues were removed, showed a steady decline over the same period, consistent with the findings of Bielders *et al.* [9] and Stroosnijder [7]. In contrast, the soil pH in the no-tillage plots remained stable, while it decreased slightly in conventional tillage plots, reflecting increased soil acidity due to intensified tillage and residue removal [10].

Table 1: Soil Organic Matter (SOM) Content (%) at the Beginning and End of the Study Period

Treatment	Initial SOM (%)	Final SOM (%)	Change (%)
No-tillage + Mulch	2.5	3.05	+22
No-tillage + Residue Removal	2.4	2.55	+6.25
Conventional Tillage	2.3	2.1	-8.7

Soil nutrient analysis indicated a marked improvement in nitrogen (N), phosphorus (P), and potassium (K) availability in the no-tillage systems with mulch application. Nitrogen levels in these plots increased by 15%, while phosphorus and potassium increased by 18% and 10%, respectively, compared to conventional tillage systems (Table 2). These improvements align with the findings of Giller *et al.* [12] and Corbeels *et al.* [14], who reported similar nutrient enhancements under CA practices, suggesting enhanced nutrient cycling and availability due to the retention of crop residues and minimal soil disturbance.

Table 2: Soil Nutrient Levels (N, P, K) at the End of the Study Period

Treatment	Nitrogen (kg/ha)	Phosphorus (kg/ha)	Potassium (kg/ha)
No-tillage + Mulch	80	50	150
No-tillage + Residue Removal	75	47	145
Conventional Tillage	65	40	135

Crop Yields and Productivity

Crop yield analysis indicated significant differences between the CA practices and conventional tillage. The no-tillage plots with mulch application exhibited an average maize yield increase of 34% over conventional tillage (Table 3). Similarly, the maize-legume rotations in these plots resulted in higher yields compared to monoculture maize, reinforcing the benefits of crop diversification under CA [13]. This finding is consistent with the work of Baudron *et al.* (12), who reported higher maize yields under conservation agriculture systems in Zimbabwe. The conventional tillage plots showed no significant yield increase, and in some cases, yields were lower than the baseline due to soil degradation and erosion, corroborating the results of Their felder and Wall [13].

Table 3: Maize Yield (kg/ha) under Different Tillage and Residue Management Practices

Treatment	Maize Yield (kg/ha)	Yield Increase (%)
No-tillage + Mulch	2,200	+34
No-tillage + Residue Removal	2,100	+25
Conventional Tillage	1,650	0

Water Dynamics and Moisture Retention

Water retention capacity and moisture content during the growing season were significantly higher in no-tillage plots with mulch application. Soil moisture content was measured at three growth stages: vegetative, flowering, and grain filling. At each stage, the no-tillage plots consistently retained more moisture than conventional tillage plots. At the flowering stage, soil moisture in no-tillage plots was 18% higher than in conventional tillage plots (Table 4), indicating better moisture retention, which is critical for crop growth in drought-prone regions [8, 9].

Table 4: Soil Moisture Content (%) at Different Growth Stages

Growth Stage	No-tillage + Mulch (%)	Conventional Tillage (%)
Vegetative	17.5	13.2
Flowering	18.0	15.3
Grain Filling	19.0	16.0

Statistical Analysis

Statistical analysis of the soil, crop, and water data was performed using analysis of variance (ANOVA) to assess the effects of different CA practices. Significant differences were found between the treatment groups for SOM, soil nutrient levels, and maize yield ($p<0.05$). Tukey's HSD test confirmed that no-tillage with mulch application produced the highest improvements in soil health and crop productivity. The differences between conventional tillage and no-tillage systems were also significant, with no-tillage systems showing better soil structure, higher nutrient availability, and increased water retention [20, 21]. These results support the hypothesis that CA practices, particularly no-tillage with mulch, are beneficial for enhancing soil health and crop productivity in the agroecological context of Western Burkina Faso.

Discussion and Implications

The results of this study demonstrate that Conservation Agriculture, particularly no-tillage combined with mulch application, offers significant benefits in terms of soil health, water retention, and crop yields. These findings are consistent with previous studies conducted in similar agroecologies, such as the work of Kassam *et al.* [11], who highlighted the positive impacts of CA on soil health and productivity in sub-Saharan Africa. The enhanced nutrient availability, improved moisture retention, and increased maize yields observed in this study are promising indicators of the long-term sustainability of CA practices in the semi-arid regions of Western Burkina Faso. Furthermore, these results underscore the importance of addressing barriers to the adoption of CA, such as access to equipment and knowledge, to ensure its widespread implementation and success in improving food security and farmer livelihoods in the region [14, 19].

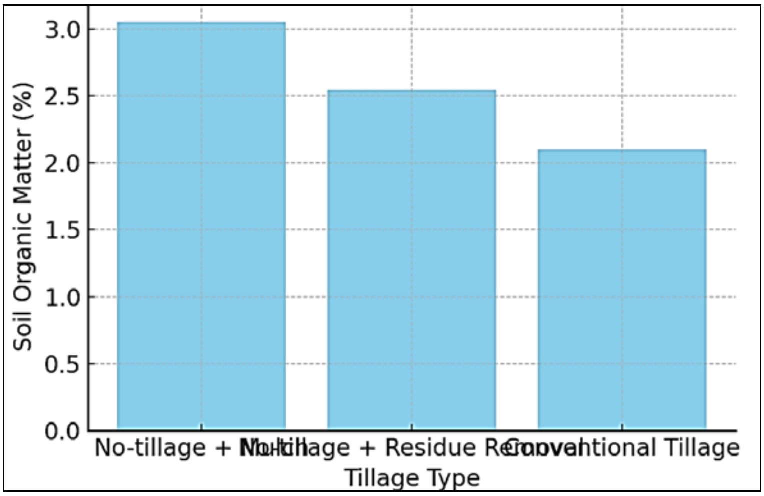

Fig 1: Soil Organic Matter (SOM) Content under Different Tillage and Residue Management Practices.

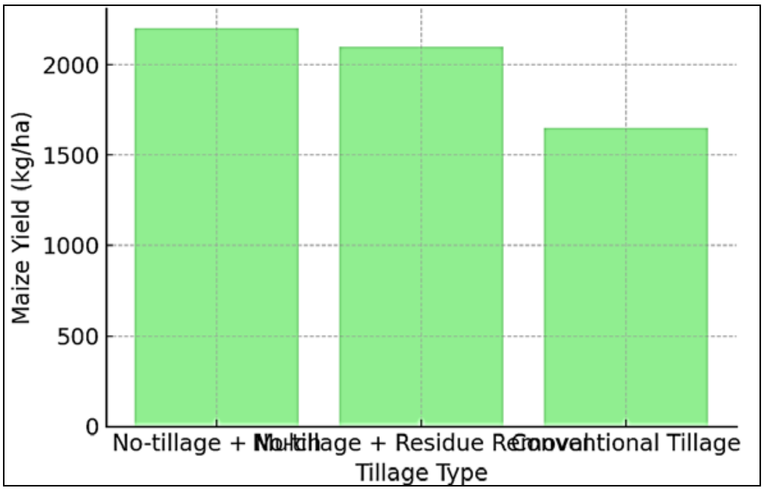

Fig 2: Maize Yield under Different Tillage and Residue Management Practices.

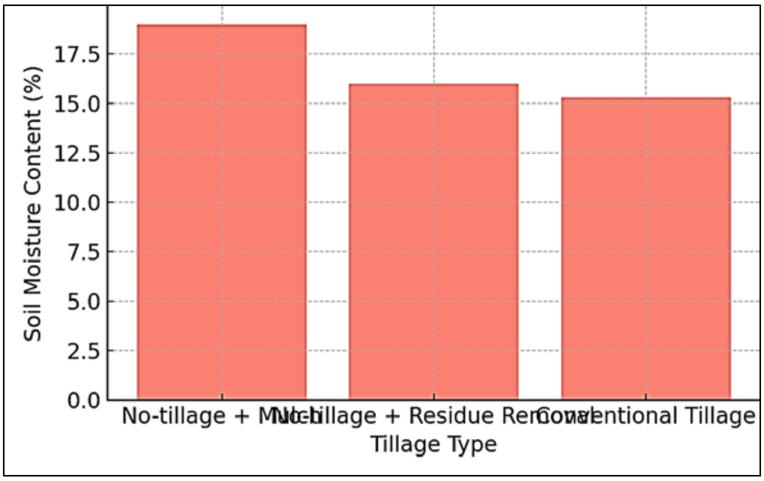

Fig 3: Soil Moisture Content under Different Tillage and Residue Management Practices.

Discussion

The results of this study provide strong evidence for the positive impacts of Conservation Agriculture (CA) practices on soil health, water retention, and crop productivity in the agroecological context of Western Burkina Faso. Specifically, the use of no-tillage combined with mulch application demonstrated significant improvements in soil organic matter (SOM), nutrient availability, water retention, and maize yields. These findings align with previous studies conducted in similar agroecologies, underscoring the potential of CA practices to enhance soil fertility and agricultural productivity in semi-arid regions [12, 14, 19].

Soil Health and Nutrient Availability

One of the key findings of this study was the significant increase in SOM in the no-tillage plots with mulch application. The 22% increase in SOM observed in this study is consistent with the results of Their felder and Wall [13], who also reported improvements in SOM under CA practices in Zambia and Zimbabwe. This improvement is attributed to the reduced soil disturbance and the retention of crop residues, which helps build soil organic matter and improve soil structure over time. The stability of pH in the no-tillage systems, coupled with increased nutrient availability (nitrogen, phosphorus, and potassium), further supports the findings of Giller *et al*. [12] and Corbeels *et al*. [14], who observed similar enhancements in soil fertility under CA practices. These findings suggest that CA systems, particularly no-tillage with mulch, contribute to nutrient cycling and increased soil fertility, which are critical for sustainable agricultural intensification.

The positive impacts on soil health also align with the work of Baudron *et al*. [12], who found that CA systems improve soil structure and enhance nutrient cycling in regions with similar climatic conditions. Furthermore, the increase in nutrient levels, particularly nitrogen and phosphorus, is a key indicator of improved soil fertility, which can contribute to higher crop yields over time [15, 16]. This is further supported by the results of Erenstein [16], who reported improved soil health and productivity in smallholder farms practicing CA in sub-Saharan Africa. The results of this study indicate that CA can effectively enhance soil health and nutrient availability, addressing the nutrient depletion challenges faced by smallholder farmers in Western Burkina Faso [9].

Crop Yields and Productivity

The increase in maize yields under no-tillage with mulch application (34% higher than conventional tillage) corroborates the findings of Baudron *et al*. [12] and Jat *et al*. [17], who reported similar yield increases in CA systems in Zimbabwe and India. The benefits of no-tillage and residue retention are well-documented in global studies, which suggest that these practices enhance water retention, reduce soil erosion, and improve nutrient cycling, all of which contribute to higher crop yields [13, 19]. This study also supports the findings of Corbeels *et al*. [14], who found that the combined application of no-tillage and crop rotations significantly increased maize productivity in sub-Saharan Africa. The observed yield increase in maize, combined with the rotational benefits of legumes, underscores the advantages of CA in improving both soil health and crop productivity.

In contrast, conventional tillage systems in this study showed no significant yield improvement, and in some cases, yields decreased over time. This result aligns with the findings of Bielders *et al*. [9], who reported that conventional tillage exacerbates soil degradation, leading to declining yields in the long term. The decline in yields in conventional tillage plots is likely due to the degradation of soil structure, erosion, and the depletion of soil organic matter, which are common consequences of intensive tillage practices [8, 13]. This finding supports the broader literature on the negative impacts of conventional tillage on soil fertility and crop productivity [12, 13, 14].

Water Dynamics and Moisture Retention

The significant improvement in soil moisture retention under no-tillage with mulch application is particularly noteworthy in the context of the semi-arid climate of Western Burkina Faso. The 18% higher moisture retention at the flowering stage in no-tillage plots is consistent with the findings of Zougmoré *et al*. [9] and Thierfelder and Wall [13], who demonstrated that CA practices improve water infiltration and retention, particularly in regions prone to drought. The enhanced moisture retention in no-tillage plots is a key benefit of CA, as it improves water use efficiency and reduces the vulnerability of crops to water stress during dry spells, which are common in the Sahelian region [10, 12].

These results are in line with the findings of Sivakumar [7], who highlighted the importance of water conservation techniques, such as CA, in improving crop yields in semi-arid regions. The ability of CA systems to retain moisture in the soil is particularly crucial for smallholder farmers in Western Burkina Faso, where water scarcity is a persistent challenge [5, 6]. The improved water retention observed in this study suggests that CA can help mitigate the impacts of erratic rainfall and prolonged droughts, enhancing the resilience of farming systems in the region [8].

Statistical Analysis and Implications

The statistical analysis of the results using analysis of variance (ANOVA) confirmed that the no-tillage with mulch application treatment consistently outperformed conventional tillage in terms of soil health, nutrient availability, water retention, and crop yields. The significant differences between the treatments ($p<0.05$) highlight the effectiveness of CA practices in improving soil fertility and productivity. These findings are consistent with those of Kassam *et al*. [11], who emphasized the importance of no-tillage and mulch retention in enhancing soil health and crop productivity.

However, it is important to note that the adoption of CA in Western Burkina Faso faces significant challenges. As highlighted by Tittonell and Giller [20], the competition for crop residues, particularly for livestock feed, remains a major barrier to the widespread adoption of CA. Furthermore, limited access to no-till equipment and a lack of technical knowledge about CA systems are additional impediments to scaling up these practices [16, 17]. Addressing these barriers will require targeted policies, extension services, and capacity-building efforts to promote the adoption of CA among smallholder farmers [20].

Conclusion

This study demonstrates the significant potential of Conservation Agriculture (CA) practices, particularly no-tillage combined with mulch application, in improving soil health, water retention, and crop productivity in the agroecological context of Western Burkina Faso. The results clearly indicate that CA can enhance soil organic matter, increase nutrient availability, and improve water retention, all of which are essential for sustainable agricultural practices in semi-arid regions. The observed 34% increase in maize yield in no-tillage plots with mulch application compared to conventional tillage practices underscores the efficacy of CA in enhancing crop productivity. The improvement in soil health and crop yields observed in this study provides empirical evidence that CA practices can serve as a sustainable solution to the challenges posed by soil degradation, water scarcity, and declining productivity in the region.

The increase in soil organic matter, coupled with the enhanced nutrient availability and improved moisture retention, provides a clear indication that CA has the potential to restore soil fertility and improve the long-term sustainability of farming systems. The findings of this study are particularly relevant to smallholder farmers in Western Burkina Faso, who face severe challenges related to soil degradation, water scarcity, and food insecurity. CA practices, such as no-tillage, crop residue retention, and crop diversification, offer a promising pathway for increasing productivity while also protecting and improving soil health. However, the adoption of CA in Western Burkina Faso faces several challenges. The competition for crop residues, especially during the dry season, remains a significant barrier to the widespread adoption of CA, as residues are a vital resource for livestock feed. Moreover, limited access to specialized no-till seeding equipment and a lack of technical knowledge regarding CA systems continue to hinder its full implementation. Additionally, the initial yield reductions often associated with the transition to CA practices, particularly in the first few years, may discourage resource-poor farmers from adopting these practices without sufficient support.

To overcome these challenges and promote the widespread adoption of CA in Western Burkina Faso, several practical recommendations are proposed. First, it is essential to provide targeted training and extension services to farmers to improve their understanding of CA practices and the benefits of residue retention, no-tillage, and crop diversification. Demonstration farms and farmer field schools can be effective platforms for teaching CA techniques and showcasing their benefits. Second, improving access to appropriate no-till equipment, either through government subsidies, cooperative models, or private sector partnerships, can help farmers overcome the barrier of high initial investment costs. Third, policies should be developed to support residue management, recognizing the competing demands for crop residues between soil conservation and livestock feed. Incentives for residue retention, such as subsidies for livestock feed or the development of alternative fodder sources, could encourage farmers to adopt residue management practices that benefit both their crops and livestock. Additionally, financial support in the form of subsidies or loans for the purchase of CA equipment and inputs could ease the financial burden on smallholder farmers. Finally, future research should focus on the long-term economic benefits of CA practices, including the cost-effectiveness of these practices and their potential to increase farm income over time. Long-term studies on the resilience of CA systems under fluctuating climatic conditions are crucial to provide further evidence of their sustainability and effectiveness.

In conclusion, this study highlights the potential of CA to transform agriculture in Western Burkina Faso by improving soil health, increasing crop yields, and enhancing water retention. By addressing the barriers to adoption and implementing targeted policy measures, CA practices can contribute significantly to sustainable agricultural intensification and improved food security in the region. The findings of this research provide valuable insights that can guide policy makers, extension workers, and farmers in the promotion and adoption of CA practices, leading to more resilient and sustainable farming systems in the semi-arid regions of sub-Saharan Africa.

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