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Review

Conservation Agriculture for Sustainable Soil Health Management: A Review of Impacts, Benefits and Future Directions

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Abstract

Conservation agriculture (CA) is widely recognized as the cornerstone of sustainable agriculture. It prioritizes minimizing soil disturbance, maintaining permanent soil cover, and diversifying crop species to restore soil health and ecosystem resilience. This review synthesizes the effects of CA on the soil's physical–chemical and biological properties. It demonstrates its effectiveness in improving soil structure, enhancing organic carbon sequestration, promoting microbial activity, increasing water-use efficiency, and reducing erosion and nutrient losses. The paper then highlights the broad environmental, economic, and social benefits of CA. These include biodiversity conservation, reduced greenhouse gas emissions, improved yields, and increased food system resilience. The review explores the synergistic role of technological innovations such as precision agriculture, remote sensing, and digital tools in scaling CA for higher productivity and sustainability. The review then examines how socioeconomic conditions, institutional frameworks, and policy interventions shape CA adoption and impact. Despite its growing adoption, CA's successful implementation will require strategies adapted for local needs, capacity-building, and supportive, inclusive policies. Finally, the review identifies key CA research gaps and future directions. This provides a comprehensive foundation to advance CA as a climate-smart, resilient, and sustainable pathway to ensure global food security and environmental stewardship.

Keywords: precision agriculture; crop diversification; no-till farming; permanent soil cover; soil management; digital agriculture; sustainability; socioeconomic and policy considerations

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1. Introduction

Sustainable agriculture is crucial for meeting the increasing global food demand while safeguarding the environment and natural resources [1]. Conservation Agriculture (CA) is a sustainable farming approach that prioritizes soil health, increased productivity, and climate resilience through practices like minimal soil disturbance, crop residue retention, and crop rotation [2]. It offers a paradigm shift from conventional extractive farming to one that regenerates soil functions and fosters environmental sustainability. CA practices improve soil structure, enhance water infiltration and retention, and increase carbon sequestration, ultimately making farms more adaptable to climate change impacts [3–5]. Thus, it contributes to achieving key Sustainable Development Goals, especially in ensuring food security, land restoration, and climate action [6].

The impact of CA in improving soil health and promoting sustainable farming is context specific. It notably incorporates soil organic carbon, thereby significantly improving soil health by enhancing its structure, water retention, nutrient availability, and microbial diversity [7]. Its success is influenced by local agroecological conditions, farming practices, and socioeconomic factors [8]. In cold, wet regions with poorly drained soils, CA may not be the most appropriate approach because it can worsen waterlogging, delay planting, slow nutrient cycling, and increase risks from weeds, pests, and diseases [7].

The evolution of Conservation Agriculture is being driven by technological advancements that boost both productivity and sustainability. Precision agriculture tools, such as remote sensing and variable rate applications, boost crop yields while minimizing environmental footprint [9]. Digital technologies like AI, IoT, and machine learning can transform CA by improving crop monitoring, soil health assessment, and resource management [10,11]. Advanced technologies such as Global Positioning System (GPS), drones, and sensors facilitate high-throughput phenotyping and enable the use of automated agricultural robots (AgroBots) for tasks like harvesting and weed detection [10]. Concurrently, biotechnological advancements, including genetic engineering and genome editing, are developing crop varieties that are more stress-tolerant and yield higher outputs [12]. These innovations can work synergistically with CA practices to enhance soil health, conserve water, and reduce greenhouse gas emissions (GHG) [13]. CA benefits from specialized equipment and robotics designed to optimize resource utilization, minimize soil disturbance, and maximize crop yields while minimizing environmental impacts [14].

Adoption of CA is influenced by socioeconomic factors and policy support. Labor-intensive CA practices are more likely to be adopted in regions with abundant, cheap labor, while capital-intensive methods are favored where capital is relatively inexpensive [15]. To promote widespread adoption, it is crucial to understand CA's economic, social, and environmental benefits [2]. Successful implementation requires a change in stakeholder behavior. Farmers should be provided with social mechanisms for experimentation and adaptation to local conditions [8]. Sustained policy and institutional support, incentives and motivations form a key component of CA adoptions and improvements [2,8].

Despite CA's increasing worldwide adoption, its impacts on soil health are debatable. This is due to agroecological zone variations, farming systems, and socioeconomic conditions. Understanding how CA impacts soil properties is crucial for its effective implementation, continued improvement and addressing emerging limitations. This will lead to the development of effective technological innovations, policy frameworks, and capacity-building strategies to enhance its application on both smallholder and mechanized farming systems.

This review focuses on summarizing current understanding of the effects, benefits and future directions of CA within the framework of sustainable soil management. The aim is to provide a comprehensive overview of CA's role in promoting long-term soil health and productivity. Drawing from studies across diverse regions, it explores how CA practices affect soil health. It then identifies key research gaps and highlights innovative tools and policy considerations essential for its successful scaling. It finally provides a comprehensive foundation for researchers, practitioners, and policymakers in advancing conservation-based farming systems for long-term sustainability.

This review advances existing literature by bringing together and integrating various findings on how conservation agriculture contributes to sustainable soil management. It involved a broad literature search across major academic databases including Scopus, Web of Science, and Google Scholar, covering publications from 2000 to 2025. The search process emphasized studies addressing CA's impacts on soil health, climate resilience, and sustainability, with particular attention to recent contributions from the last seven years. Only peer-reviewed works directly relevant to CA were considered. Studies unrelated to soil health were excluded.

In terms of novelty, this review builds upon earlier works by integrating emerging technological innovations, policy frameworks, and context-specific adoption challenges into the discussion of CA impacts. Unlike prior reviews, it provides a more comprehensive and forward-looking analysis by linking updated empirical findings with practical scaling tools. Special attention is given to digital integrations such as Artificial Intelligence (AI) for predictive soil health modeling, the Internet of Things (IoT) enabled real-time monitoring, drone-based phenotyping, and automated agro-robots; areas largely absent from earlier syntheses. Additionally, it expands on the socioeconomic and policy dimensions, with a focus on inclusive strategies such as targeted incentives for smallholder farmers in developing regions, and highlights machinery access challenges that shape CA adoption.

2. Conservation Agriculture

2.1. Principles and Practices

CA is defined by three core principles: minimal soil disturbance (often through no-till practices), maintaining permanent soil cover with crop residues or cover crops, and implementing diverse crop rotations [8,16]. These methods focus on enhancing soil health, promoting carbon sequestration, and building resilience in agroecosystems [8]. Research has demonstrated that CA significantly improves soil health, leading to various benefits, including reduced pesticide use and enhanced water use efficiency [16]. The use of surface mulch helps regulate soil temperature, encourages biological activity, and suppresses weed growth [17]. By mimicking natural ecosystems, CA provides farmers worldwide with benefits in productivity, economic returns, and environmental sustainability.

2.1.1. Minimum Soil Disturbance

Minimum soil disturbance, often implemented via reduced or no-tillage practices, is crucial for maintaining and improving soil health by minimizing disruption to soil and surface residues. These practices contribute to sustainable agriculture and environmental protection by preserving soil structure, enhancing biological activity, and increasing soil organic carbon [18]. CA, and particularly no-till farming, offers significant benefits for soil health and productivity. They include improved water retention, porosity, and macropore development [19].

2.1.2. Permanent Soil Cover

This is the creation of a lasting soil cover using mulches and crop residues and permanent cover crops within tree orchards. It is a vital practice for building healthy, productive, and resilient agricultural systems. Soil cover suppresses weeds, supplies and retains nutrients, conserves soil moisture, interrupts pest and disease cycles, and prevents erosion [20]. Surface mulch and plant roots contribute carbon and essential nutrients to the soil and crops, regulate water movement, and inhibit weed growth through physical barriers or allelopathic effects [21].

2.1.3. Crop Rotation

Crop rotation is a proven strategy that enhances agroecosystem biodiversity by boosting soil health and reducing pest and disease problems [22]. Its effectiveness is influenced by crop selection, rotation duration, farmland history, crop sequence, and soil characteristics [23]. Cereal–legume cover crop mixtures can be combined to enhance weed control and crop robustness through increased biodiversity [24]. Enhancing plant residue return to the soil through crop rotation and reduced monoculture practices is indeed linked to higher soil organic carbon levels in CA systems [20].

2.2. Key Types of Conservation Agriculture Practices

2.2.1. No-Tillage (NT)

Although some studies have reported increased bulk density and soil compaction after long term adoption of no-till practices [4], they are generally sustainable, since they keep the soil undisturbed. This approach requires less energy and reduces equipment depreciation, making it a resource-efficient and low-carbon method of farming [25]. In arid climates, NT improves soil phosphorus, potassium, and organic matter [26]. Research by Adil et al. [27] demonstrated that combining no-tillage with straw cover in winter wheat significantly increased grain yield and precipitation use efficiency compared to traditional tillage methods. Key benefits of NT include better soil erosion control, improved water retention, lower energy costs, and increased production, particularly in areas with gentle slopes. However, this practice may experience hardening and soil stratification due to increased herbicide use for weed management [28].

2.2.2. Reduced Tillage (RT)

Reduced tillage is the practice of limiting how much the soil is disturbed before planting [8]. Also known as minimum or shallow tillage, RT can lower CO_2 emissions and improve soil organic carbon. Within rainfed perennial cropping systems utilizing continuous no-till, strategic tillage every five to ten years may be necessary to correct soil compaction and nutrient stratification issues [29].

2.2.3. Mulching

Mulching involves applying materials such as crop residues, plastic, manure, sand, or rocks to the surface before, during, or after seeding [30]. This technique reduces soil evaporation, enhances rainwater infiltration, and modifies the microclimate [31]. By covering the soil surface, mulching moderates soil temperature fluctuations, improves soil structure, enhances organic matter and moisture content, and increases porosity. It also improves chemical characteristics like cation exchange capacity and electrical conductivity.

2.2.4. Cover Cropping

This is an eco-friendly farming method that entails cultivating particular plants, mainly to safeguard and enhance soil health [32]. Cover cropping offers multiple benefits, including enhanced soil fertility, reduced soil erosion, increased microbial biodiversity, and improved nutrient cycling. Cover crops increase soil organic carbon, improve aggregate stability, enhance water infiltration, and reduce bulk density [33]. They enhance the levels of nitrogen, phosphorus, and potassium in the soil and promote a healthier, more active microbial community [34]. Beyond preventing wind and water erosion, cover crops stabilize crop yields and serve as a source of animal feed or biofuel use [35].

3. Effects of CA on Soil Properties

3.1. Effects of CA on Soil Physical Properties

3.1.1. Soil Structure

Soil structure influences its physical, chemical, and biological processes and their susceptibility to water erosion [36]. To improve soil structure, practices that reduce disturbance, increase organic matter, support plant life, and enhance overall fertility should be prioritized. Conventional tillage degrades soil structure by depleting organic matter [37]. Conversely, CA methods strengthen topsoil structure by increasing the stability of soil aggregates [38]. This is attributed to organic matter in the top acting as a protective barrier, reducing the erosive forces of raindrops. Thus, it prevents the breakdown of soil aggregates and prevents compaction [39]. A long-term experiment showed CA with maize cultivation can improve soil structure by altering its hydraulic properties [40].

3.1.2. Bulk Density

Bulk density is a proxy of soil compaction and its ability to support seedling growth, root development, and ultimately, crop yields [41]. Research on conservation agriculture's impact on soil bulk density has yielded mixed results. Some studies report higher bulk density relative to intensive tillage [4]. Others have found no significant difference [42] or even lower bulk density with CA [43]. No-tillage systems with residue incorporation demonstrated a small 1.4% increase in soil bulk density compared to conventional tillage [44]. Notably, the maximum compaction values in conservation tillage (CT) practices remained below the critical limit that hinders plant growth. Thus, CA, can help reduce soil bulk density.

3.1.3. Water Infiltration and Retention

Conservation Agriculture practices boost water infiltration and preserve soil moisture [7,33,44]. It lessens the effects of seasonal droughts, contributing to greater crop output and farm income [45]. Typically, it takes two to five cropping seasons for the observed yield improvements and increased profitability to become substantial. Subsoiling combined with straw incorporation, a conservation tillage practice, was reported by [46] to enhance soil structure and improve water infiltration and retention by reducing soil compaction. Furthermore, less intensive tillage promotes soil structural stability by improving aggregate distribution and increasing porosity. This, in turn, boosts infiltration, reduces the soil's susceptibility to erosion, enhances soil fertility, and ultimately leads to better agronomic productivity [47]. Studies in Brazil and Paraguay have reported that CA significantly reduces both soil erosion and runoff compared to conventional tillage [48]. This reduction is mainly due to the enhanced biological activity under crop residues, which increases soil porosity.

3.1.4. Reduced Erosion

Studies demonstrate CA's effectiveness in lowering soil loss rates [49]. Examples from Italy, Mexico, Ecuador, and Egypt reveal reductions of between 7.5% and 56% [50]. In sloped terrain, CA practices demonstrate significant effectiveness in safeguarding and enhancing soil health [51]. In Mediterranean rainfed uplands, CA systems that retain crop residues and incorporate cover crops significantly curb soil erosion. These practices safeguard the soil surface from rainfall, reducing erosion (the detachment, transport, and deposition of soil particles) and preventing the formation of surface seals and crusts [2]. Cover crops and their residues minimize erosion by slowing runoff and increasing water infiltration [52]. Compared to bare soils, fields with residue levels of 1.5 to 4.5 tons per hectare experience significantly less water runoff (around 50% reduction) and soil erosion (around

80%). Similarly, cover cropping, a key conservation strategy, significantly reduces surface runoff and erosion, by an average of 67% and 80%, respectively, relative to conventional methods [53].

Increases in soil organic carbon (SOC) under CA practices are often associated with improved soil aggregate stability [44]. A global meta-analysis indicates that using no-tillage in conjunction with residue retention generally leads to a 1.4% increase in soil bulk density [44]. In cases where bulk density decreases, this is often associated with higher incorporation of organic materials, which stimulates soil fauna activity [54]. Studies show significant improvements in soil texture, aggregate stability, and the soil's ability to hold water following reduced or no-tillage. For example, no-till and reduced tillage farming methods in Manitoba, Canada, led to observable improvements in soil bulk density, porosity, and water retention. In another study, Powlson et al. [55] found that increasing SOC in California topsoil benefited soil properties and resilience, though it did not guarantee increased crop yields. By improving the physical, chemical, and biological characteristics of the soil, CA is a promising approach for sustainable agriculture and environmental protection [56].

3.2. Effects of CA on Soil Chemical Properties

3.2.1. Soil Organic Carbon

Utilizing cover crops and reduced tillage boosts biomass production and forms a soil-protecting residue layer [57]. This builds organic matter in the soil, significantly influencing microorganism activity and populations [58]. CA practices significantly enhance soil health by boosting organic matter and nutrient availability [59]. Thus, they contribute to improved soil chemical properties, promote carbon sequestration, boost microbial activity, and stabilize nitrogen content [60]. CA outcomes are influenced by the duration of implementation, soil type, and adopted management strategies [8]. Compared to conventional tillage, CA practices reported to increase SOC in the 0–30 cm soil layer by 20–40% over 5–7 years [61,62]. Enhanced organic matter input in CA systems is indicated by the development of coarse particulate organic matter (cPOM) [62]. Zero tillage with residue retention can sequester approximately 2 Mg ha^{-1} of SOC in the upper 15 cm over six years [61]. The effect of CA on carbon sequestration depends on root development, baseline soil C content, climate, and erosion history [4].

In addition, CA influences how SOM is distributed vertically in the soil [63]. It accumulates in the upper soil layers as a result of reduced tillage and the continued presence of surface residue mulch [64]. Furthermore, CA promotes microbial activity, particularly through no-till systems with residue retention. These conditions have been shown to increase soil microbial carbon and nitrogen pools in soil [65]. This boost is primarily driven by sustained organic matter inputs and reduced disruption to the soil ecosystem.

3.2.2. Soil pH

Soil pH is a critical factor in determining the productive capacity of soil. It impacts nutrient availability for plant uptake. CA practices increase SOC and improve soil pH relative to traditional tillage. The ability of cover crops to promote organic matter accumulation and enhance soil structure contributes significantly to soil pH stability [7]. The breakdown of plant residues generates organic acids that can modify pH levels [42]. Contradictory results where CA systems heighten nitrogen mineralization have been reported. They result in nitrate leaching, thereby influencing pH balance [55,66]. An example occurs in no-till systems, where the concentration of roots on topsoil can cause localized acidification due to increased root exudation [66]. Other studies have demonstrated that maintaining crop residues in permanent beds lead to higher pH levels compared to systems where residues were removed [67]. An example is in Ethiopia where minimum tillage with residue retention acidified the soil more than conventional tillage in the top 7.5 cm [68].

Another study by Nunes, et al. [69] revealed that moldboard plowing notably affected soil pH in the surface layer (0–7.5 cm). In contrast, no-till and sub-till systems, which retain organic material at the surface, exhibited lower pH values than moldboard plowing across all depths. In general, conservation agriculture (CA) affects soil pH by promoting the accumulation of organic matter and facilitating nitrogen cycling. However, long-term implications of these effects are dependent on soil type, climatic conditions, and residue management strategies [70].

3.2.3. Cation Exchange Capacity (CEC)

CA practices which increase soil SOC, have been linked to variations in CEC [71]. While the exact details of these connections are not fully understood, numerous studies have confirmed that as SOC levels rise, so does CEC. The soil's organic material has a natural ability to hold and exchange nutrients [42]. Thus, it improves soil fertility by minimizing nutrient leaching and bolstering nutrient retention. Soils with higher CEC are also less prone to nutrient imbalances, which can adversely affect plant growth and limit crop yields. Besides making nutrients available, CEC is essential for keeping the soil structure sound, maintaining stable fertility, and buffering soil pH [72]. Despite this, studies have shown contrasting results. In some, CA increases aggregate stability and CEC in the topsoil. Others report decreases [42], while some have found no significant changes [73].

3.2.4. Nutrients Cycling

Through improved soil aggregation and water infiltration, CA practices decrease surface runoff and nutrient losses [71,74–76]. Their ability to increase SOM enhances soil microbial activity and protects the soil, enhancing nutrient cycling and retention within the system [32]. Organic matter on the soil surface decomposes gradually, releasing nutrients in a controlled manner synchronized with plant uptake [75]. These residues provide food for soil organisms, boosting their numbers [77,78]. These microbial communities, including bacteria and fungi, are essential for breaking down organic materials and converting nutrients into forms accessible to plants. Arbuscular mycorrhizal fungi (AMF) are particularly beneficial because they enhance phosphorus uptake by extending root access beyond the nutrient depletion zone [79].

A unique aspect of CA is the tendency for nutrients to accumulate in layers near the soil surface due to the combination of no tillage and consistent residue application [80,81]. This stratification benefits microbial activity and carbon cycling in the upper soil layers [81]. However, it may also necessitate strategies such as cultivating deep-rooted crops or fostering symbiotic relationships like mycorrhizal fungi to access nutrients located deeper in the soil. By integrating cover crops and crop rotations, CA improves soil organic matter and nitrogen fixation [82]. However, it initially may increase nitrogen limitation due to immobilization by microbial decomposition of surface residues [83]. To address this, adaptive nitrogen management strategies are crucial [83]. CA enhances the soil-microbe-plant relationship to make both organic and inorganic nutrients more accessible to plants through improved biological processes [82]. CA systems are associated with a greater abundance of soil mineral nitrogen than conventional tillage [84].

Overall, tailored management approaches are necessary to optimize the effects of CA on soil health, crop production, and environmental benefits [82,83]. The use of leguminous cover crops improves nitrogen cycling through their biological nitrogen fixing capabilities [85]. These plants convert atmospheric nitrogen into forms that other crops can utilize, thereby decreasing reliance on chemical fertilizers. In addition, the mulch layer and undisturbed soil help stabilize temperature and moisture levels. This minimizes nitrogen loss caused by volatilization and denitrification [86].

CA also improves phosphorus availability [87]. Phosphorus is often immobilized by binding aluminum and iron compounds. The decomposition of organic residues in CA practices releases organic acids that can bind with these compounds, making phosphorus more accessible to plants [88]. In soils lacking nutrients, mycorrhizal fungi aid in dissolving and absorbing phosphorus. Besides nitrogen and phosphorus, CA helps retain vital cations like potassium, calcium, and magnesium by boosting the soil's CEC through increased SOC [82]. This enhanced nutrient retention reduces leaching and improves the soil's long-term fertility.

Crop diversification and rotation within CA significantly enhance nutrient cycling by utilizing the distinct nutrient demands and rooting depths of various crops. Deep-rooted plants cycle nutrients from deeper soil to the topsoil, improving overall nutrient availability [82]. This method naturally enhances soil structure and fertility by stimulating biological activity and increasing organic matter. By fostering a diverse and dynamic soil ecosystem, CA reduces dependence on external inputs like synthetic fertilizers and pesticides, supporting sustainable farming systems [89]. The long-term effects of these benefits include improved crop productivity and healthier ecosystems, achieved through sustained soil resilience and nutrient availability.

3.2.5. Mitigating Climate Changes and Greenhouse Gas Emissions

CA is gaining recognition as a valuable strategy for addressing climate change and minimizing greenhouse gas (GHG) emissions within the agricultural sector. These practices promote carbon sequestration by accumulating SOC stocks and lower mineralization [6]. No-till or reduced tillage practices can decrease N_2O emissions by 11% compared to conventional tillage, especially in humid climates and low-carbon soils [90]. CA minimizes denitrification by enhancing soil structure, water infiltration, and erosion control [91]. Integrating cover crops and varied crop rotations can lead to further reductions in N_2O emissions, particularly in soils that are not overly acidic or alkaline and have a balanced amount of organic matter [90].

3.3. Effects of CA on Soil Biological Properties

CA practices have been demonstrated to enhance soil health and the activity of beneficial microorganisms. By increasing SOC and improving soil structure, CA creates an environment that supports higher microbial biomass and activity—a positive indicator of soil health [92]. These microbial diversities include bacteria and fungi and are influenced by specific conditions and management practices [93].

A global meta-analysis by Li et al. [65] concluded that no-tillage farming, with residue retention, increased the abundance, variety, and overall mass of soil microbes compared with conventional tillage practices. By boosting soil organic carbon, these practices are key to healthy soil function. They support their physical, chemical, and biological characteristics [8,94].

CA, alongside its benefits for microbes, greatly helps soil fauna including earthworms, insects, and predatory spiders by providing improved habitat and food sources through reduced disturbance and organic residues [77,95]. Through their natural processes, soil fauna actively decomposes organic matter, facilitate nutrient cycling, and enhances soil structure [41]. Soil microflora, including bacteria and fungi, thrive under CA, where they facilitate nutrient cycling through the decomposition of the continuously supplied SOM [96]. Thus, soil fauna is critical to the maintenance of soil fertility and enhanced plant growth. Studies have indicated that CA improves soil enzyme activity, a key determinant of soil health and fertility [97,98]. Increased enzyme activity accelerates SOC decomposition and nutrient cycling processes, which are fundamental for sustaining crop productivity and soil health [99]. An example is the increases of β-glucosidase and arylsulfatase enzyme activities which are associated with improved SOM content and nutrient availability under CA practices [97,98]. These results reveal the significant advantages of implementing CA to maintain a healthy soil, enhance biological processes within the soil, and contribute to overall agricultural sustainability."

The implementation of CA practices affects soil emissions of gases and aerosols, carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) [100,101]. By enhancing soil health, particularly through improved structure and increased organic matter, CA practices can boost carbon sequestration, potentially lowering greenhouse gas emissions and improving crop resilience to climate fluctuations [6]. Improved nitrogen management under CA further helps lower N_2O emissions [102]. CA can reduce CO_2 emissions through decreased fuel consumption and lower soil organic matter mineralization [6,103]. It can also help mitigate CH_4 emissions in rice cultivation and potentially reduce N_2O emissions with proper fertilizer management [101,102,104]. CA positively influences soil biological properties by enhancing microbial diversity, activity, and biomass. Improved SOC and soil structure support soil fauna, which have an influence on greenhouse gas emission from soil [101].

4. Potential Benefits of CA for Promoting Soil Health

4.1. Soil Carbon, Soil Health and Climate Resilience

By implementing CA practices, farmers can enhance soil structure, reduce erosion, and promote sustainable agriculture. A recent global study by Xiao et al. [3] provides new insights into how CA affects carbon cycling in the context of soil erosion. The study found that while CA did not greatly reduce runoff compared to conventional tillage, it significantly decreased sediment loss and boosted SOC in the topsoil. Conservation practices reduced SOC loss and increased SOC concentration in eroded sediments, with straw mulching proving especially effective for erosion control and carbon retention. Table 1 summarizes the impacts of CA on soil physico–chemical and biological properties.

Table 1. Effects of conservation agriculture on soil physico-chemical and biological properties.

	Category	Effect	References
	Soil Structure	Improves aggregate stability, especially in topsoil, due to residue retention and reduced disturbance.	[36,39,40,42]
Physical Properties	Bulk Density	slight increases (~1.4%) with residue retention; decreases linked to higher residue incorporation and fauna activity.	[4,44,54]
	Water Infiltration & Retention	Enhanced infiltration and moisture retention due to improved structure, porosity, subsoiling further improves retention.	[7,44,46,54]
	Reduced Erosion	Significantly reduces erosion by 7.5–80% compared to conventional tillage, especially with residue retention and cover crops.	[49,50,53,105]
	Soil Organic Carbon	Increases SOC by 20–40% in topsoil over 5–7 years; enhances carbon sequestration, especially with zero tillage and residue retention.	[57,61,62]

Table 1. *Cont.*

	Category	Effect	References
Chemical Properties	Soil pH	Stabilizes or increases pH, particularly with cover crops and residue retention; effects vary with depth and management.	[7,42,67,69]
	Cation Exchange Capacity (CEC)	Increases CEC in topsoil due to higher SOC, improving nutrient retention and soil fertility.	[42,72]
	Nutrient Cycling	Enhances nutrient cycling by improving aggregation, reducing runoff/leaching, and increasing organic matter and microbial activity.	[60,72,74,76]
	Microbial Activity	Increases microbial biomass carbon and nitrogen, boosts microbial activity due to sustained organic matter inputs and reduced disturbance.	[59,60,65]
Biological Properties	Soil Fauna	Higher residue retention and reduced tillage stimulate soil fauna activity, improving soil structure and nutrient cycling.	[54,59]
	Biodiversity	Promotes greater soil biodiversity by providing stable habitats and food sources through organic matter and minimal disturbance.	[41,59,60]

In Boset Woreda, Ethiopia, farmers who implemented soil bunds, contour cultivation, mulching, afforestation, and no-till practices to conserve water experienced significantly reduced soil loss compared to those who did not [106]. This indicates that adopting these measures is crucial for controlling soil erosion and promoting sustainable land management in the region. Another large-scale comparative study [53] confirmed that conservation management practices greatly reduce soil erosion and surface runoff compared to traditional tillage. These methods boost soil health and water absorption, helping to prevent erosion and maintain crop productivity.

Crop residues enhance soil health by increasing organic matter, which improves soil structure, water retention, and nutrient availability [5]. In tropical and subtropical regions, biochar application raised SOC by 25.4%, while conservation tillage and cover crops increased SOC by 18.8% and 15.8%, respectively [45]. In Mediterranean and humid subtropical climates, conservation agriculture improved SOC by 0.21–0.48 megagrams per hectare per year—effects that were more pronounced in soils with low initial carbon [107]. In semi-arid regions, zero-till combined with residue retention raised SOC by 22.6% in the upper 15 cm [108]. One study observed a loss (−0.74 megagrams per hectare per year) with cover cropping in Northeast Italy, a context-specific finding [109]. In other studies, SOC gains ranged from 15.8% to 78% or 0.21 to 2.5 megagrams per hectare per year—depending on the conservation practice, soil properties, climate, and duration of management [110].

CA enhanced SOC stocks by about 0.3 to 1.2 tons of carbon per hectare annually (t C/ha/yr) in contrast to conventional tillage systems [111]. According to Powlson et al. [55], combining no-till farming with residue retention resulted in an average annual increase of 0.57 tons of SOC per hectare compared to conventional tillage. This positive impact was particularly noticeable in regions with wetter climates. Compared to conventional tillage, CA practices have been shown to increase SOC stocks in surface soil layers 12.9–19.4% [112] Adopting multiple practices could potentially mitigate up to 2861 kg CO_2e ha^{-1} yr^{-1} [113]. While increased SOC may lead to higher N_2O emissions in some cases, the climate benefits of SOC storage are generally not fully offset, except for reduced tillage [114]. Each tillage operation can release up to 300 kg CO_2e ha^{-1}, and soil erosion can contribute an additional 300 kg CO_2e ha^{-1} annually [115]. Consistent implementation of all CA principles, along with complementary measures, has the potential to significantly decrease agriculture's carbon footprint and potentially achieve carbon neutrality [115].

A 12-year study (2010–2022) comparing no till, minimum tillage, and conventional tillage for durum wheat showed that all systems experienced yield decreases. However, no till had the smallest decline and the best yield stability. No till also stored about 13% more soil moisture than conventional tillage. This enhanced resilience to precipitation variability, particularly during autumn and late spring. This helped maintain yields under drought conditions with a 28–35% advantage over conventional tillage and minimum tillage in dry years [116]. Despite some reductions in plant height and grain weight, no till maintained grain quality and soil carbon levels. This highlights its importance for sustainable agriculture and climate resilience.

Sharma and Singh [117]'s field experiment, spanning three years, assessed the potential of CA practices for sodic soil reclamation in a rice-wheat system. The study compared a CT approach with several CA practices, including zero tillage, mungbean rotation, residue mulch, and subsurface drip irrigation (SDI). Results indicated that a combination of CA and SDI strategies demonstrated a significant reduction of soil pH by 2.16%, 2.16%, and 1.33% compared to CT systems across three soil layers (0–5 cm, 5–15 cm, and 15–30 cm). There was a reduction of 2.9%, 11.2%, and 14.9% in the exchangeable sodium percentage under CA practices with residue management. Furthermore, the concentration of extractable anions decreased, while soil organic carbon and cation concentrations increased in CA-based SDI plots, highlighting the effectiveness of these integrated practices in improving sodic soil conditions.

4.2. Reduction in Input Dependence

While CA may entirely not eliminate the need for chemical inputs (fertilizers and pesticides), it significantly reduces their use by promoting natural soil fertility and biological pest control mechanisms [118,119]. CA can reduce synthetic fertilizer use by up to 50% and pesticide use by up to 50%, depending on the system and local conditions. These reductions are achieved through improved soil fertility, crop rotation, and enhanced biological pest control. Studies have shown that CA practices can reduce the need for nitrogen fertilizers by 20–50% compared to conventional tillage, especially when combined with legume rotations and residue retention [120]. Beneficial soil organisms like earthworms, termites, mycorrhizal fungi, other microbes, and soil organisms improve nutrient cycling and boost plant health, lessening the need for synthetic inputs [121,122]. Additionally, diversified cropping systems improve pest and disease resistance, decreasing the frequency and intensity of outbreaks (He et al. [103]).

Weed growth is suppressed through residue mulching and the use of cover crops, which limits sunlight penetration and physically obstructs weed emergence. This natural weed control reduces the need for chemical herbicides, potentially lowering herbicide use by 20–40% [123]. Nikolić et al. [124] studied the effect of maize and wheat residues on weed seedling emergence in no-till systems. They tested three residue levels—half, equal to, and 1.5 times the typical field rate—on eight weed species over two years. Results showed that standard and higher residue rates reduced weed emergence by 20% and 44%, respectively, while low residue increased emergence by 22%.

4.3. Long-Term Economic Benefits

Transitioning to CA is financially advantageous in the long run, despite requiring initial investment in equipment and knowledge. Farmers can enhance profitability by adopting practices like minimal tillage, which conserves fuel and labor, coupled with reduced reliance on fertilizers and pesticides, and improved crop yields. Furthermore, CA promotes sustainable land use, ensuring continued productivity for future generations. Studies in Malawi showed CA systems increased crop yields by 22–31% and income by 50–83% in relation to conventional tillage [125,126]. CA reduced labor requirements by 28–39 days/ha, leading to greater net benefits [126]. A long-term study (1996–2019) found no significant yield differences between no-till and conventional tillage for corn, soybean, and wheat. However, it demonstrated that no-till generated greater profits because of reduced operational expenses [127]. This approach offers farmers considerable advantages in terms of fuel and machinery maintenance costs [128]. With less tillage, land preparation becomes less time-consuming and labor-intensive, a major benefit in areas with limited labor availability. In general, CA enhances farming efficiency by delivering greater productivity with reduced input requirements. Figure 1 shows the summary of the potential benefits of CA for promoting soil health

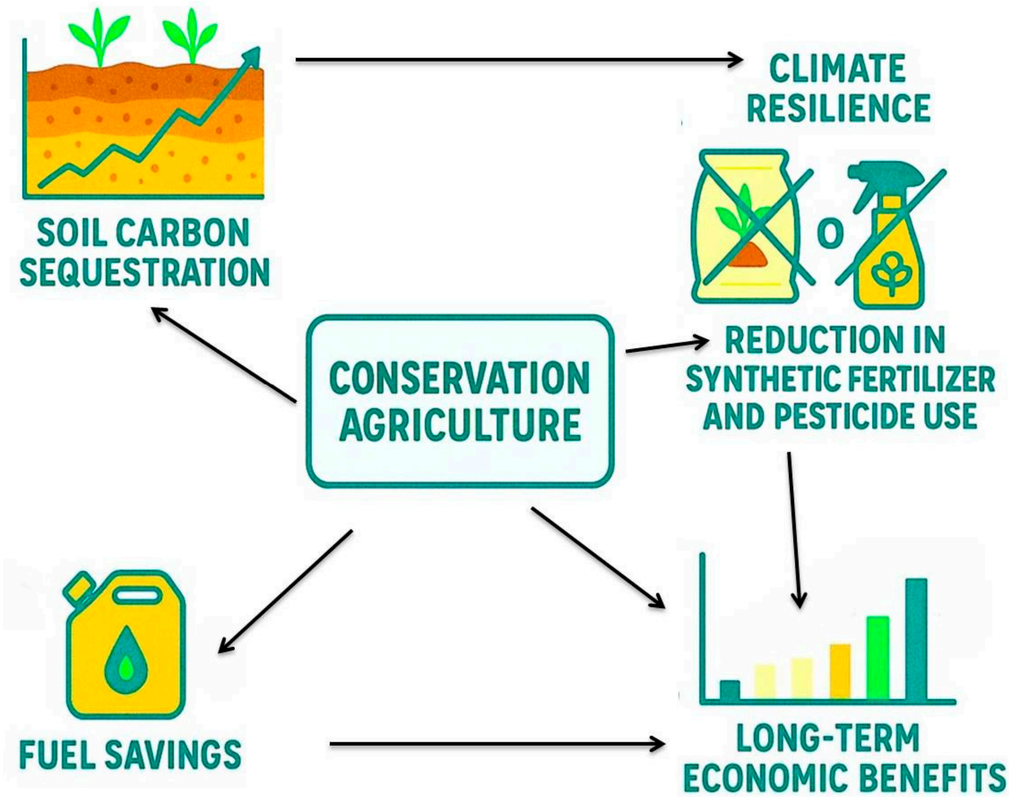

Figure 1. Potential benefits of conservation agriculture for promoting soil health.

5. Future Directions and Technological Innovations in CA

Through the adoption of advanced technologies, CA is experiencing rapid evolution, resulting in enhanced productivity, sustainability, and resilience. Key innovations include precision agriculture and digital tools, low-disturbance machinery and seeding technologies, and bio-based agricultural inputs.

5.1. Precision Agriculture and AI Digital Tools

Precision agriculture utilizes technology to observe, measure, and respond to variations within a field, allowing for more targeted and efficient management. By using these technologies, farmers can apply inputs like seeds, fertilizers, and pesticides to specific areas that need them, increasing crop yield and quality while saving on costs [129,130]. Precision farming utilizes a suite of technologies that include Global Positioning System (GPS), remote sensing, drones, geographic information system (GIS), and Variable Rate Technology among others (Table 2).

Machine learning and artificial intelligence are increasingly incorporated into sensor systems to facilitate observation and control of crops without being physically present in the field [10,131]. By offering real-time data on soil, crops, and weather, these technologies facilitate better decision-making for farmers. For instance, farmers can apply fertilizers and water precisely where and when needed, thereby reducing overuse, minimizing environmental damage, and enhancing crop productivity. This mirrors the core principles of CA, which advocates minimal soil disturbance and reduced chemical use.

Continuous monitoring through soil sensors and satellite imagery provides farmers with the data needed for optimizing farm inputs, enhancing crop yields, and reducing environmental impact [132,133]. Mobile applications and Information and Communications Technology (ICT) platforms deliver localized weather forecasts, market data, and pest and disease diagnostics directly to farmers, improving farm management efficiency [134]. Artificial Intelligence (AI) and machine learning analyze large datasets to predict yields, detect early crop stress, and optimize resource allocation, supporting precise interventions that conserve resources [134]. The Internet of Things (IoT) connects sensor networks to automate smart irrigation and nutrient management, reducing water waste and fertilizer overuse [135]. GIS and digital mapping tools facilitate creation of maps and analysis of spatial data, like land use to plan conservation efforts, and monitor their success [136].

High-throughput phenotyping and automated agricultural robots (AgroBots) further improve efficiency and reduce environmental impacts [10]. Digital twins provide virtual representations for simulation and optimization of farming practices. Additionally, digital platforms enhance market access and traceability through blockchain technology, promoting transparency, food safety, and sustainable value chains [137]. While these technologies offer significant benefits for sustainable agriculture, challenges remain in ensuring inclusivity for small-scale farmers, addressing ethical concerns, and overcoming connectivity issues in rural areas [10]. Collectively, these digital innovations empower farmers to adopt sustainable practices, improve productivity, and conserve natural resources, thereby advancing the goals of conservation agriculture.

Precision agriculture and digital tools are revolutionizing farming by boosting sustainability, efficiency, and environmental quality. This transformative power was demonstrated by a U.S. case study in Mississippi that used Unmanned Aerial Vehicle (UAV) systems to enhance crop management by (i) assessing crop damage from herbicides; (ii) estimating yields and (iii) monitoring fields from different altitudes [138]. The use of variable rate technology (VRT) allowed for targeted application of inputs to only areas where they were needed. This practice offers several benefits, such as reduced environmental impact, improved soil health, and enhanced profitability [139]. Similarly, in India, smallholder farmers use digital platforms like Kisan Suvidha to make data-driven decisions [140]. The platform customizes agronomic recommendations based on satellite data and weather forecasts. This technology allows farmers to more efficiently adopt conservation methods such as crop rotation and mulching [140]. A study by Sarvestan et al. [141] employed UAVs to capture aerial images and map dominant weeds in maize fields. This demonstrated the importance of precision agriculture in enhancing weed control efforts. Images taken with multispectral and RGB sensors were processed into an orthomosaic and classified into soil, maize, and two main weed species using both unsupervised (K-means, ISO-data) and supervised (SVM, Neural Network, Maximum Likelihood, Minimum Distance) algorithms. The results showcased the effectiveness of supervised approaches, with Neural Networks and Support Vector Machines demonstrating high accuracy (over 95%) and reliable kappa coefficients, while unsupervised methods were less effective. The accurate weed maps generated enabled the creation of prescription maps for targeted herbicide application. It demonstrated a practical approach to reduce herbicide use and environmental impact during critical weed management periods, thus embodying the synergy between digital agriculture and CA.

The study by Moghadam et al. [142] presents the Digital-Twin Orchard concept, which creates a detailed virtual replica of every tree and its environment in large-scale orchards. The system utilizes advanced technologies like spinning 3D LiDAR and cameras integrated into farm vehicles (AgScan3D+). It continuously monitors tree canopy structure, health, stress, fruit quality, and disease in real time. This digital twin, powered by AI, enables dynamic prediction of stress, disease, and yield gaps, supporting precise and timely orchard management decisions. Solar-powered smart irrigation systems, incorporating sensors and Global System for Mobile Communications (GSM) modules, are being implemented in Pakistan and Nigeria to manage water resources for agriculture. This approach enhances water use efficiency and promotes sustainability by reducing reliance on conventional power sources and enabling remote monitoring and control [143,144].

5.2. Low-Disturbance Machinery and Seeding Technologies in CA

Achieving minimal disturbance requires the use of specialized low-impact machinery and advanced seeding technologies that enable precise planting without disrupting the soil excessively [145,146]. These innovations drive sustainable farming, improving soil health and productivity to protect the environment and maintain crop yields [146,147].

Low-disturbance machinery refers to agricultural equipment specifically designed to minimize or completely avoid soil tillage. This preserves soil structure and maintains organic matter levels [148]. Traditional tillage methods like plowing can lead to the deterioration of soil structure, resulting in a loss of soil organic matter and negative effects on the soil organisms [58,147]. In contrast, low-disturbance tools like no-till planters, strip-till equipment, and direct seeders enable farmers to sow seeds directly into undisturbed crop residues, preserving soil structure and enhancing soil health [148]. For instance, no-till drills are equipped with narrow openers that slice through crop residues and place seeds at a precise depth while causing minimal soil disturbance. This agricultural approach prevents soil from eroding, helps the soil retain water, and encourages the growth of beneficial microorganisms [147].

A good example can be found in India, where farmers widely use zero-till seeders equipped with disc openers that slice through crop residue with minimal soil inversion. These machines allow continuous cropping while reducing fuel usage, conserving moisture, and improving soil structure [149]. Another example is strip-till machinery, which tills narrow strips of soil where seeds are planted while leaving the areas between rows undisturbed [44]. This method strikes a balance between conventional tillage and no-till farming by creating a warm, loose seedbed that promotes early plant growth while preserving soil cover and maintaining biological activity in the undisturbed inter-row zones. In the United States, maize and soybean farmers incorporate GPS-guided precision equipment within their strip-till systems [150]. This version emphasizes the integration of the technologies within the strip-till approach. By enabling the precise placement of seeds and fertilizers, these technologies lead to greater efficiency and less soil compaction.

Modern seeding technologies increasingly integrate smart sensors and automation to enhance planting accuracy and reduce the number of field operations. Precision planters, often equipped with GPS and Variable Rate Technology (VRT), can adjust seeding depth, spacing, and input application in real time according to soil and environmental conditions. This real-time adjustment optimizes resource use and crop performance [151,152].

For smallholder farmers in sub-Saharan Africa, simpler low-disturbance equipment adapted for animal traction or small tractors is becoming available. For example, in Zambia and Tanzania, CA programs have introduced ripper tines and ox-drawn direct seeders that allow farmers to plant without plowing, thus conserving soil moisture and improving drought resilience [153]. These tools aid in crop survival in semi-arid regions by helping to maintain crucial soil cover and moisture levels. Similarly, CA no-till techniques can be implemented with basic tools or animal-powered equipment [154]. Two-wheel tractors with direct seeders are emerging as viable options for smallholders, reducing time and labor for crop establishment [153]. By manufacturing equipment such as jab planters, rippers, and sprayers locally, communities can ensure they are suited for their specific conditions and drive rural development.

5.3. Bio-Based Inputs in Conservation Agriculture

Within conservation agriculture, eco-friendly bio-based inputs like biofertilizers, biopesticides, and biochar are becoming viable replacements for chemical inputs, supporting sustainable practices and ecological balance [155,156]. These bio-based inputs are essential for advancing sustainability and ecological balance within conservation agriculture [157]. Sourced from natural materials and biological processes, these inputs offer environmentally friendly alternatives to traditional synthetic fertilizers and pesticides. They boost soil vitality and crop productivity while decreasing reliance on synthetic agrochemicals, thereby reducing harmful effects on ecosystems and supporting long-term agricultural resilience [155,158].

Biofertilizers consist of living microorganisms that enhance plant growth by increasing nutrient availability or uptake. For example, *Rhizobium* species fix atmospheric nitrogen in legumes, while *Azospirillum* and *Azotobacter* support non-leguminous crops by improving nitrogen supply [159]. Improved yields and better soil nitrogen balance have been achieved in India's rice-wheat system by integrating *Azospirillum* biofertilizers with reduced synthetic nitrogen application [160]. Additionally, phosphate-solubilizing bacteria (PSB) convert insoluble phosphorus in the soil into forms accessible to plants, potentially lessening the application of chemical phosphate fertilizers [161].

Recent studies confirm that biofertilizers can increase crop yields by 10–40%, partially replacing chemical fertilizers, promoting sustainable agriculture and reducing environmental pollution [162]. Biofertilizers improve soil fertility by mobilizing nutrients like nitrogen and phosphorus, producing growth-promoting biomolecules, and enhancing microbial activity. They also reduce reliance on synthetic inputs, thereby lowering greenhouse gas emissions and minimizing soil and water contamination [163]. For instance, *Bacillus*-based biofertilizers have shown significant contributions to sustainable crop production by improving nutrient cycling and plant resilience [164].

Unlike traditional chemical pesticides, biopesticides, which originate from plants, bacteria, and minerals, offer a natural and eco-friendly method for controlling pests while preventing the accumulation of harmful residues. For instance, *Bacillus thuringiensis* (Bt) offers selective pest control by producing toxins that kill certain insect larvae but spare beneficial insects [165]. In Kenya, smallholder maize farmers using Bt-based biopesticides have successfully controlled stem borers, lowering chemical pesticide use and associated environmental risks with improved economic returns [166]. When combined with precision technologies like digital twins and smart sensors, biopesticides can be applied more effectively and only when needed. This reduces their environmental impact but supports sustainable resource use. For instance, digital twin technology can simulate pest outbreaks and optimize biopesticide application timing and dosage. It offers effective pest management that also safeguards soil and environmental health [167].

Biochar, a charcoal-like material made from plant biomass via pyrolysis, is seeing increased adoption in CA. It is added to soil to enhance its quality, specifically to improve its structure, increase its water-holding capacity, and store carbon [156].

Further, biochar improves soil fertility by boosting its cation exchange capacity. This enhances nutrient retention, making nutrients more available to plants, thus supporting healthier crop growth and reducing fertilizer use [156]. Biochar application demonstrably enhanced soil fertility and maize yields in a Nigerian study, particularly in degraded lands [156]. This highlights biochar's potential to rehabilitate degraded soils, a key objective of CA.

5.4. Challenges and Limitations in Adopting Technological Innovations in Conservation Agriculture

Despite the advantages of technology, its widespread adoption faces several challenges and limitations. These include high upfront costs, limited availability in local markets, necessity for farmer training, and the need to adapt equipment to diverse cropping systems [168]. Access to such technology is often restricted, particularly for smallholder farmers who lack the financial means or technical support to operate and maintain advanced machinery [168]. Other barriers are data ownership concerns, insufficient locally adaptable CA equipment, technological complexity and compatibility, and socio-economic factors like farmers' focus on short-term yields over long-term sustainability.

Farmers' desire to innovate is influenced by their perception of the usefulness of technology and their willingness to take on the risks associated with change. Addressing these issues requires enhanced extension services, policy, and financial support. Strengthening knowledge and information-sharing mechanisms and fostering collaboration between researchers, extension services, and manufacturers can accelerate technology transfer [49,169].

Table 2. Technological innovation areas and their contributions to conservation agriculture.

Innovation Area	Description	Technological Examples	Benefits to Conservation Agriculture (CA)	References
Precision Agriculture and AI Digital Tools	Use of real-time, site-specific data and AI for crop and resource management	GPS, GIS, remote sensing, drones, IoT, AI/ML, soil sensors, mobile apps, digital twins, blockchain	Enhances input efficiency, reduces environmental damage, supports data-driven decisions	[130,133–135]
		UAVs for weed/pest mapping and crop monitoring; mobile platforms for advisory	Targeted input use, reduced herbicide usage, better crop monitoring	[139–143]
Low-Disturbance Machinery and Seeding Technologies	Machinery that minimizes soil disruption while allowing effective crop establishment	No-till drills, strip-till equipment, precision planters with GPS/VRT, two-wheel tractors, jab planters	Preserves soil structure, reduces erosion, maintains soil health and moisture	[8,49,145,148,150]
Bio-based Inputs in CA	Use of natural products to enhance soil fertility, pest control, and ecosystem balance	Biofertilizers (e.g., *Rhizobium*, *Azospirillum*), biopesticides (e.g., Bt), biochar from plant biomass	Reduces chemical input dependency, improves soil fertility, promotes resilience	[156,159,166,167]

6. Socioeconomic and Policy Considerations for CA Adoption

6.1. Incentive Structures and Subsidies for CA Adoption

Incentive programs and subsidies play a critical role in encouraging farmers to adopt CA practices, especially given the initial costs and risks associated with transitioning to new farming methods. Financial incentives such as direct payments, cost-sharing schemes, tax credits, equipment subsidies, and machine rental support help lower the upfront investment barriers that often deter farmers from adopting CA [170]. Incentives with immediate economic returns are more likely to be adopted than those promoting only ecological benefits. For example, subsidies for practices like residue mulching and intercropping can increase their adoption. However, care must be taken to avoid crowding out other CA components such as zero tillage [171].

In many cases, incentives reduce the perceived risk of adopting unfamiliar technologies. These benefits offer financial stability and easier access to information, which is vital for small-scale and low-income farmers. [168,172]. A study by El Bakali et al. [173] demonstrated that financial incentives could create a tipping point in CA adoption among small-scale farmers. Uptake was heavily influenced by the adoption behavior of one's neighbors. Incentive packages that combine short-term productivity support (e.g., improved seeds, organic fertilizers) with long-term ecosystem service rewards are particularly effective in sustaining adoption. However, to maximize impact, incentive programs must be tailored to local socio-economic contexts and farmer characteristics, balancing economic, environmental, and social outcomes [171].

Studies show that payments for ecosystem services and input subsidies significantly increase CA uptake [173]. Farmers' risk aversion and the uncertainties associated with conservation tillage payoffs mean they often need more than just compensation for expected profit losses to adopt it. While incentives can promote CA adoption, they may also create perverse consequences, leading to partial compliance or crowding out certain practices [174]. Tailoring insurance policies to address new risks associated with adoption of CA may be more effective than subsidies alone [175].

6.2. Capacity Building and Extension Services

Effective capacity building and extension services are necessary to achieve widespread adoption of CA. This is particularly important in developing countries where access to information and technical support remains a major constraint [176]. CA often involves a paradigm shift from conventional practices to knowledge-intensive systems that require an understanding of soil cover management, minimal tillage, and crop rotations. Therefore, building farmers' knowledge and skills through training, demonstrations, farmer field schools, and peer-to-peer learning is essential for sustained adoption [177]. Moreover, extension agents serve as the vital link between research institutions and farming communities. When properly trained, they help adapt CA innovations to local agro-ecological and socio-economic contexts [178].

Successful implementation of CA relies on the interplay of financial incentives and the vital support provided by technical assistance and extension. Through these services, farmers acquire the foundational knowledge, practical skills, and necessary confidence to implement CA effectively [129,179]. This dismantles barriers related to lack of information, technical know-how, and management skills, which are often cited as major constraints to CA adoption [171]. While financial incentives can encourage initial adoption [180], long-term success depends on farmers perceiving benefits for their farms and the environment [171]. Complementary practices, such as appropriate nutrient management and improved stress-tolerant varieties, are critical for enhancing CA system functionality [179]. Additionally, mechanization services can support smallholder farmers in overcoming equipment-related barriers to CA adoption [181]. Tailoring these approaches to local contexts and considering farmer characteristics is essential for effective policy design and implementation [171,179].

Digital tools and mobile platforms are also enhancing the reach and effectiveness of extension services. For example, platforms like Digital Green and Farmerline use videos and mobile SMS services to disseminate information on CA practices in local languages across Africa and South Asia [117,182]. These innovations overcome barriers of literacy and remoteness, ensuring timely and context-specific advice. As climate change intensifies the vulnerability of traditional farming systems, integrating robust capacity-building strategies and dynamic extension services is key to empowering farmers [129]. This will ensure adoption of CA farming practices and help achieve their ecological and economic benefits.

6.3. Gender Inclusiveness and Support for Smallholder Farmers

Gender inclusiveness is crucial in conservation agriculture (CA) adoption, as women face distinct barriers. Gender disparities in access to productive resources, including land, machinery, inputs, extension services, and credit facilities, contribute to reduced adoption and increased dis-adoption of sustainable farming practices among women farmers [183,184]. Women often bear a disproportionate burden of on-farm labor, which can make labor-intensive CA practices unsustainable [184]. Achieving gender equity in agriculture involves strategically supporting women as beneficiaries, engaging men to understand women's needs, and ensuring women have direct access to agricultural inputs [182,185]. Ensuring that CA programs are gender-sensitive will improve equity and enhance overall adoption and impact. These barriers can be addressed by tailored extension services, women-focused training, and facilitating women's access to inputs and technologies [186].

The successful implementation and widespread adoption of CA practices extend beyond technical innovations and agronomic benefits. Socioeconomic factors and policy frameworks play a pivotal role in shaping farmers' willingness and ability to adopt CA practices.

7. Areas for Further Research and Innovation

Despite the growing adoption of CA worldwide, several areas still require focused research and innovation to enhance their effectiveness, scalability, and adaptability under diverse agroecological conditions. One critical area is the context-specific adaptation of CA practices. Current CA models often follow generalized principles. Site-specific solutions tailored to local soil types, climate variability, cropping systems, and socio-economic realities are essential. For example, more research is needed to develop region-specific crop residue management techniques that prevent residue removal for fuel or fodder without compromising soil health. This is especially needed in smallholder farming systems in Sub-Saharan Africa and South Asia [70,187]. The success of initiatives such as the Conservation Agriculture in Crop-Livestock Systems (CLCA) project in North Africa and Latin America provides a good example of this [188,189].

The development and testing of low-cost, low disturbance seeding equipment suitable for smallholder farmers is another important research frontier. Most mechanized CA tools are designed for large-scale farms, leaving smallholders with limited access. Participatory engineering innovations and public–private partnerships can help bridge this gap and improve affordability and usability.

To better grasp the advantages and disadvantages of adopting CA, especially regarding labor dynamics, gender equity, and land tenure systems, more socioeconomic and behavioral research is essential. Multidisciplinary studies combining agroecological and social sciences can provide insights into farmer decision-making and inform policies and extension services that are responsive to local realities [190].

Lastly, innovations in bio-based inputs such as microbial consortia tailored to CA systems, biochar, and biopesticides deserve greater attention. This is necessary to enhance nutrient cycling and pest resilience while maintaining ecological balance. They work synergistically with crop residues and soil organisms to enhance soil health and reduce reliance on synthetic chemicals.

8. Conclusions

CA represents a transformative and holistic approach to sustainable farming.

Beyond soil health, CA offers broad environmental, economic, and social benefits. It enhances water retention, promotes biodiversity, reduces greenhouse gas emissions, enhances resource utilization, thereby boosting and stabilizing crop yields. Economically, CA can lower input costs and improve profitability, especially over the long term. However, realizing these benefits at scale requires addressing several challenges. Looking ahead, the future of CA lies in advancing context-specific adaptations tailored to diverse agroecological and socio-economic conditions. Integrating innovative technologies such as precision agriculture tools, sensor-based monitoring, digital twins, and affordable low-disturbance equipment can optimize CA implementation and management. Innovations in bio-based inputs like biofertilizers, biopesticides, and biochar further enhance soil health and sustainability. Improved farmer capacity building, extension services, and participatory learning are crucial for equipping farmers with the knowledge and skills for effective adoption. Crucially, supportive policies including targeted incentives, subsidies, shared machinery services, and inclusive frameworks are essential to overcome adoption barriers and ensure equitable access.

By combining scientific evidence with technological, economic, and policy perspectives, this review offers a more nuanced understanding of CA's potential. It identifies underexplored gaps including context-specific AI applications, long-term microbial resilience under climate stress, and cross-sector policy alignment. Collectively, this integrated approach provides researchers, practitioners, and policymakers with a timely and actionable foundation to advance CA as a climate-smart and sustainable pathway for global food security and environmental stewardship.

In summary, Conservation Agriculture offers a viable and promising pathway toward resilient, productive, and climate-smart agricultural systems. To achieve sustainable food production and environmental protection for today and tomorrow, CA needs to prioritize the combination of ecological principles, technological innovation, and socio–economic inclusiveness.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
AMF	Arbuscular Mycorrhiza Fungi
CA	Conservation Agriculture
CEC	Cation Exchange Capacity
CLCA	Conservation Agriculture in Crop-Livestock Systems
GHG	Greenhouse Gases
GIS	Geographic Information System
GSM	Global System for Mobile Communications
GPS	Global Positioning System
ICT	Information and Communications Technology
IoT	Internet of Things
NT	No tillage
PA	Precision Agriculture
RT	Reduced tillage
SDI	Subsurface Drip Irrigation
SOC	Soil Organic Carbon
VRT	Variable Rate Technology

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