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REVIEW ARTICLE

Conservation agriculture: A pathway to achieving sustainable development goals

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Abstract

Conservation agriculture (CA) is an approach to optimize farm and watershed performance. It integrates local and national economic systems while considering societal, environmental and institutional frameworks. This approach engages value chains supported by public, private and civil sectors. CA seeks to harmonize the use of natural resources with population needs, employing sustainable intensification to meet human demands effectively and preventing the loss of arable land. Conservation agriculture directly influences all sustainable development goals (SDGs) by leveraging the core principles of minimum soil disturbance, permanent soil cover and crop rotation. Conservation agriculture can prove to be a viable option for meeting the targets of the sustainable agenda. This practice supports environmental, social and economic justice, which creates a holistic developmental route that supports the burgeoning population. Conservation agriculture relies on a knowledge-based strategy to reduce production costs, enabling farmers to adopt new technologies more readily. While CA demonstrates significant benefits across scales, its adoption remains constrained by socioeconomic factors and limited mechanization in the smallholder context. Advancing CA requires a multidisciplinary, participatory research paradigm coupled with policy support, institutional support and capacity building for farmers. CA offers a sustainable framework that ensures sustainable intensification and environmental stewardship in the long term.

Keywords

conservation agriculture; food security; risk aversion; sustainable intensification; zero tillage

Introduction

Conservation agriculture is a resource-safeguarding approach that includes minimum tillage, direct sowing technologies and crop rotation (1). Conservation agriculture maintains soil health by utilizing natural resources while minimizing soil disturbance (2). Agriculture and farm management practices in cultivated fields are often related to CA. Therefore, different soil moisture retention conditions are developed in CA systems, influencing cultivation practices. The CA system manages soil and water through crop residue mulching, mixed cropping, cover crops and delayed planting (3). It promotes ecosystem multifunctionality (4) by enhancing, regulating and supporting services that include biodiversity preservation, soil and water quality and climate change mitigation (5, 6). Conservation agriculture offers a framework to address food security challenges while mitigating environmental degradation caused by conventional methods (7, 8). Thus, CA is considered a promising sustainable agricultural development approach (6). The global population is growing at 1.1 % annually and is projected to reach 9.8 billion by 2050 (9). Notably, 42 % of the world's poor, earning less than USD 1.90 per day, reside in South Asia, where 21 % of the population is underweight and over 41 % of children are undernourished. Southern Asia is the global hotspot for contemporary and future vulnerability (10). To ensure food security via sustained intensification, CA system presents itself as a necessity. International research centers have significantly promoted CA research and adoption, including CIMMYT, ICRISAT, CIRAD, ICARDA and ICRAF. Regional organizations like the African Conservation Tillage Network (ACT), the New Partnership for Africa's Development (NEPAD) and the South African Development Community (SADC) have also contributed to advancements in the field (11, 12). Key drivers for CA adoption include improved input productivity, yields, farm output and sustainability. Additional benefits such as increased income, timely cropping, reduced labor and enhanced ecosystem services (e.g., clean water, erosion control, carbon sequestration and land rehabilitation) further support its adoption (13, 14).

Principles

The challenges of transitioning from conventional agriculture to CA have marked a significant shift toward the future of sustainable agriculture (15). The key distinctions between conventional and CA practices include i) intensive tillage causing significant soil disturbance, ii) monocropping systems, iii) clean cultivation leaving soil exposed, iv) excessive use of pesticides and herbicides and v) reliance on energy-intensive farming methods (3). However, the CA system functions on the postulates of i) minimal mechanical soil disturbance in continuity, ii) maintenance of permanence of biomass as soil cover and iii) crop diversification (16), as shown in Fig. 1. These practices have increased biological outputs, productive efficiency, resilience and eco-systemic stability. These principles can establish synergy between global needs and production capacity (2). Conservation agriculture practices integrate physical, biological, chemical and hydrological processes to enhance biological output, improve ecosystems and regenerate land productivity. Conservation agriculture practices integrate physical, biological, chemical and hydrological processes to enhance biological output, improve ecosystems and regenerate land productivity. A comparative analysis between conventional and conservation practices is necessary to quantify the effect of the extent of soil disturbance on different parameters of agriculture (Table 1).

Table 1. A comparative analysis of traditional tillage, conservation tillage and conservation agriculture for various issues (17)

Issues	Traditional Tillage (TT)	Conservation Tillage (CT)	Conservation Agriculture (CA)
Practice	Disturbs the soil and leaves a bare surface.	Soil is covered and minimal disturbance is there due to permanent cover.	Minimal soil disturbance and soil surface permanently covered.
Erosion	Wind and soil erosion: maximum.	Wind and soil erosion: reduced significantly.	Wind and soil erosion.
Soil physical health	The lowest of the three.	Significantly improved.	The best practice of the three.
Compaction	Reduces compaction and is induced by destroying biological pores.	Reduced tillage is used to reduce compaction.	Compaction is a problem, but using mulch and promoting biological tillage helps to reduce the problem.
Soil biological health	The lowest of the three, owing to frequent disturbance.	Moderately better soil biological health.	Diversified biological properties and populations.
Water infiltration	Lowest after soil pores are clogged.	Good water infiltration.	Best water infiltration.
Soil organic Matter	Oxidation of soil organic matter and causes its loss.	Soil organic increases in the surface layers.	Soil organic increases in the surface layers even greater than CT.
Weeds	controls weed and causes more weed seeds to germinate.	Reduced tillage controls weed and exposes other weed seeds for germination.	Weeds are a problem in the early stages of adoption but are reduced with time and residues can help to suppress weed growth.
Soil temperature	More variable.	Intermediate in variability.	Moderated the most.
Diesel uses and costs	Diesel use: high.	Diesel use: intermediate.	Diesel use: much reduced.
Production costs	Highest costs.	Intermediate costs.	Lowest costs.
Timeliness	Operations can be delayed.	Intermediate timeliness of operations.	Timeliness of operations more optimal.
Yield	It can be lower where the planting is delayed.	Yields the same as TT.	Yields the same as TT but can be higher if planting is done more on time.

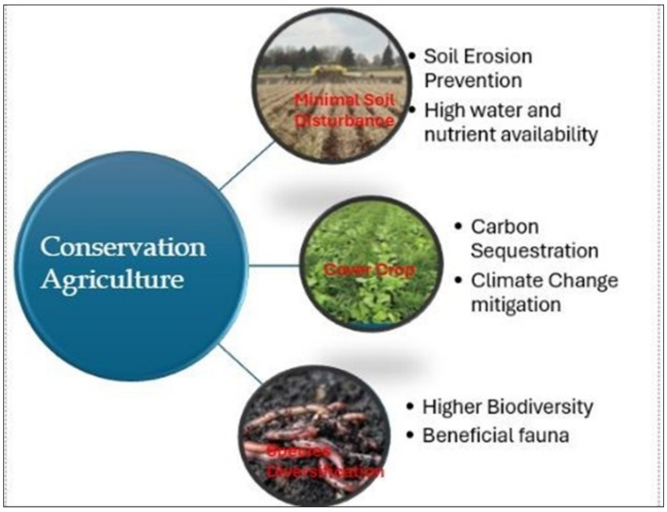

Fig. 1. Principles of Conservation Agriculture.

History of CA

The practice of tillage was questioned for the first time in the 1930s. This eventually led to the commencement of the 'Dust Bowl Era" between 1931 and 1939, exposing the devastated topsoils in the plains of southern USA. The exposed vulnerability of topsoil resulted in land degradation and raised other environmental concerns. To combat this, reduced tillage and biomass retention was introduced as a measure of erosion control. Edward Faulkner, often regarded as the first true conservationist, criticized the widespread use of the moldboard plow in his book *Plowman's Folly* (18). Fukuoka gave more than 65 years of his life for this purpose (19). Montogomery and Smith's award-winning book 'Dirt - The Erosion of Civilization' (20) emphasized non-inversion tillage and its negative linearity with soil degradation. The historical context of soil conservation practices has significantly influenced the global adoption of CA (Table 2).

Advantages and disadvantages of CA

Although it is challenging to substantiate, CA is recognized as a low-input, self-sustaining system capable of supporting sustainable intensification and enhancing food security. Its adherence to principles entails the very foundation of the multifunctionality that CA poses. Tables 3 and 4 outline the advantages and disadvantages of CA, providing a basis for its evaluation as a sustainable farming system.

Why CA?

Assessing agricultural systems in terms of productivity and economic performance highlights the multifunctionality of agroecosystems and the environmental services they provide. Conservation agriculture is vital in efficient energy usage and soil quality preservation (43, 44), as in Fig. 2. Sustainable management in synergy with CA has led to 1.7 times higher multifunctionality than conventional systems, which incentivizes the adoption of CA in the future (4). Conservation agriculture practices contribute significantly to climate change mitigation by sequestering 100 - 150g CO_2 e m^{-2} annually (45). In addition to that, eutrophication potential can be reduced by 4-9 %, soil erosion by 5-32 % and global warming potential by 3-8 % (46). Therefore, all these factors present a well-supported argument in favor of

Table 2. History of conservation agriculture

Year	Development	Reference
1930	Great Dust Bowl and the start of conservation agriculture in the USA.	(17)
1940	Development of first no-till sowing and direct seeding.	(21)
1943	Book on no-till in modern agriculture entitled "Plowman's Folly".	(18)
1950	No-till, direct-sowing of crops was first successfully demonstrated in the USA.	(22)
1956	Experiments on various combinations of tillage and herbicides were initiated.	(23)
1960	Commercial adoption of no-till in the USA.	(21, 23)
1962	Paraquat was registered as the first herbicide for broad-spectrum weed control.	(23)
1962	Long-term no-till experiments were started in Ohio, USA; the experiments are still running.	(24)
1964	First, no-till experiments in Australia.	(25)
1966	Demonstration of direct drill trials in Germany.	(26)
1967	Demonstration trials on direct drilling systems in Belgium.	(27)
1968	First no-tillage trials in Italy.	(28)
1969	Introduction of CA in West Africa.	(29, 30)
1970	First no-till demonstration in Brazil.	(31)
1970	Long-term no-till experiments were started in France.	(32)
1970	First report on the development of herbicide resistance in weeds.	(33)
1973	Phillips and Young published the book "No-Tillage Farming" This publication was a milestone in no-tillage literature, being the first one of its kind in the world.	(34)
1974	First no-till demonstration in Brazil and Argentina.	(21)
1975	Book on CA entitled "One Straw Revolution" by Fukuoka.	(19)
1976	Glyphosate was registered as a general broad-spectrum herbicide.	(23)
1980	Introduction and on-farm demonstration of CA in the sub-continent.	(22)
1980	Introduction of CA in Zimbabwe.	(23)
1981	The first National No-till Conference was held in Ponta Grossa, Paraná, Brazil.	(34)
1982	Introduction of no-till in Spain.	(35)
1982	Development of first glyphosate-resistant transgenic crops.	(36)
1990	Development and commercial release of reliable seeding machines.	(23)
1990	Commercial adoption of CA in southern Brazil, Argentina and Paraguay.	(21)
1990	Introduction of CA in South Asia, India, Pakistan and Bangladesh.	(21)
1992	Start of CA research in China.	(37)
1996	Commercial launch of transgenic glyphosate-resistant soybean.	(38)
1997	Commercial launch of transgenic glyphosate-resistant crops in China.	(39, 40)
1998	Identification of weed (rigid ryegrass) resistant to glyphosate.	(41)
2002	Introduced no-tillage systems in Kazakhstan.	(38)

Table 3. Advantages of CA

Parameter	Factor	Advantage
Resource utilization		
	Fuel	Few operations account for less fuel utilized (Up to 80 % savings).
	Time	Operation times and fewer field trips required (1-3 trips in CA compared to 5-10 trips in the conventional system) are flexible.
	Labour	Up to 60 % fewer man-days required in CA.
	Weed Control	The absence of soil disturbance and surface residue retention reduces weed incidence.
	Fertilizer Requirement	Improved soil fertility accounts for less fertilizer. Requirement.
	Irrigation requirement	Less water is used due to moisture conservation.
Environmental Welfare		
	Air Pollution	Reduced fossil fuel consumption thereby lowers emissions.
	Water Pollution	Reduced chemical runoff from agricultural landscapes into water bodies.
	Temperature regulation	Lower canopy temperature, thereby avoiding terminal heat stress.
	Greenhouse gas (GHG) emission	Use of climate-resilient technologies, lowering GHG emissions.
	Reduced Carbon footprint	Overall, the carbon footprint was reduced due to in situ resource utilization and lowered reliance on external outputs.
Economics and Energy productivity		
	Lower Costs	The total capital investment required in tillage operation can be reduced by up to 50 %.
	Improvement amalgamation	Newer technologies can easily combine with existing CA practices.
	Increased yields	Yield benefits, along with sustainable intensification, can be achieved.
	Lower replacement rates	Less use of machinery leads to lower requirements to replace machinery parts.

Modified from (42)

Table 4. Disadvantages of CA

Parameter	Limitation
Requirement of new machinery	Novel machinery needs to be purchased or hired.
Development of new pest and disease cycle	Retained crop residues may encourage new pest and disease cycle formation and act as alternate hosts.
Requirement of skills	Precision is required to gain increment in yields, which requires the implementation of skills.
Requirement of on-hand expertise	Specific requirements must be catered to and quality advice is needed to form tailored approaches.
Increased usage of chemicals	The reliance on chemicals, especially herbicides, is the tip of the scale towards environmental degradation.
Untidy fields	Fields look trashy and observations become somewhat difficult.
Risk of crop failure	Without appropriate measures for disease and weed control, the risk of crop failure increases.
Difficulty in intercultural operations	Retained residues interfere with the functioning of intercultural operations.

Modified from (42)

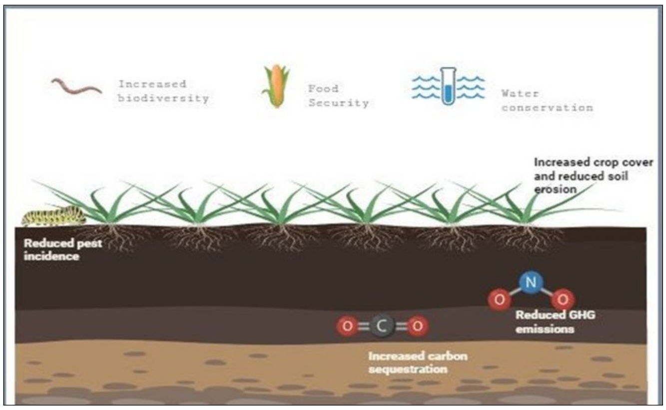

Fig. 2. Implications of CA: Reduction in erosion and gaseous emission, food security and better utilization of resources.

CA.

Yield profitability

A notable yield benefit is observed under the CA system due to considerable soil health and input quality improvement. Conservation agriculture facilitates better crop establishment with increased moisture use efficiency and reduced unanticipated heat stress due to aberrant climate conditions. Crop residue retention leads to a stable regime of temperature, i.e., warmer temperatures in cold climates will lead to better crop establishment and increased yields. Conservation agriculture unwaveringly leads to increased mechanization of the farm, which leads to greater resource utilization efficiency and thereby, a larger yield percentage. Compared to the conventional methods, the wheat production system demonstrates a 113 % and 55 % efficiency advantage in ZT and no-till systems, respectively, indicating a significantly higher profit margin (47). Crops like barley, chickpea (43 %), lentil and wheat (62 %) performed far more superiorly with greater yield stability under CA management system (48). Hence, there is an untapped potential for changing the agricultural system to a sustainable practice without compromising yields.

Soil health management

Soil health is crucial for sustainably intensifying agricultural productivity. Due to its innovative practices, CA represents a paradigm shift in soil health management. While soil health and quality are often used interchangeably, soil quality refers to the soil's functional capacity, whereas soil health emphasizes its dynamic, living nature. A 100-year modeling study has concluded that carbon equilibrium in the case of conventional agriculture practices was lost by 9 % of its carbon. The CA scenario gained a considerable 14 % of soil carbon when administered with cover crops alone and 26 % when cover crop were coupled with composting (49). A combination of soil quality indicators (visual and standard field) indicated increased soil fauna numbers, better consistencies and chemical compositions, stipulating a positive trend for soil preservation (50). Conservation agriculture is directly involved in conserving and improving natural resource use efficiency and integrating soil, water and biological resources in a unified way.

Soil physical health in CA

Soil physical health reflects a soil system's resilience to accommodate plant and ecosystemic requirements of water, aeration and strength over prolonged periods. When exposed to different stresses, soil structure and aggregation are crucial in maintaining its physical integrity. Conservation agriculture reduces soil disturbances such that soil aggregates become more stable, implying structural stability, thereby making them less prone to deterioration. Zero tillage (ZT) prevents aggregate breakage, while residue retention protects soil particles from erosion, particularly raindrop impact. Residual mulching decreased soil bulk density by 4.3 % in the top 15 cm of soil, 5.1 % in 15-30 cm and 2.7 % in 30-45 cm. Although soil electrolyte conductivity remained unaffected by crop waste and green manures, subabul and sun hemp decreased the soil reaction (51, 52). Soil loss and runoff were significantly reduced when plants like dolichos and sorghum were incorporated (53). No-tillage and retention residue were vital in improving soil moisture profile, such as when incorporated with maize stovers (54). At the same time, porosity was increased over time with practices such as ZT with biomass incorporation and strip planting (55, 56). Capillary continuity and residue retention enhanced soil moisture distribution and reduced evaporative losses.

Soil chemical properties in CA

CA practices significantly modify the soil microenvironment, improving chemical properties to support sustained intensification. Key improvements in soil chemical properties include changes in pH, electrical conductivity (EC) and exchangeable sodium percentage (ESP). Permanent Raised Beds (PRB) with full residue retention increased soil organic matter content compared to conventional agriculture, followed by straw incorporation (57). Nutrient use efficiency, particularly in micronutrients, was improved due to enhanced nutrient-supplying capacity (58, 59). Mixed effects were observed on soil pH directly correlating with residue management (60-62). Particulate organic carbon and nitrogen were increased, reflecting enhanced carbon storage and nutrient status (63). Conservation agriculturedemonstrates how specific practices can enhance the overall functionality of the agricultural system.

Organic carbon storage in CA

The soil carbon balance and storage in agricultural systems is determined by the net difference between carbon inputs and outputs and crop biomass production (64) (Fig. 3). Carbon inputs include endogenous and exogenous organic matter. In contrast, outputs result from leaching, erosion, crop uptake, mineralization and decomposition, occurring over both short- and long-term scales (65). The variability in soil organic carbon (SOC) sequestration depends upon climatic conditions, initial SOC level, crop types and duration of the crop and the management practice employed (66). Worldwide, SOC rates range from 0.28 to 0.39 t C ha^{-1} year^{-1}. Crop rotation and increasing the number of crops in rotation enhances the SOC sequestration by 0.15 ± 0.11 t C ha^{-1} (67). Further analysis revealed that complex rotations with legumes increase SOC by 18 % compared to systems without rotation or legumes.

In comparison, SOC decreased by 6 % in long rotations and 3-5% in short rotations with legumes (68, 69). The increase in SOC was more pronounced in semiarid climates (11 %) than in humid and sub-humid climates. Additionally, adopting crop diversification increases SOC by 28 % within 2-10 years (70). Therefore, under different land management systems, different levels of carbon sequestration can be observed, as shown in Table 5. Hence, CA can be treated as a viable option for sequestering carbon in the agricultural system and can lead to efficient cycling.

Soil biological health in CA

The CA system enhances the biological properties of soil by improving the carbon pools and enzymatic activities, rendering a conducive environment for soil flora and fauna subsistence (71). A two-year study found that potentially mineralizable nitrogen content increased from 3.6 mg kg^{-1} to 8.9-12.1 mg kg^{-1}, significantly exceeding levels in conventional systems. Additionally, higher microbial populations were observed under ZT soils, ultimately increasing carbon and nitrogen cycling (72). Contrary to conventional agriculture, increasing ZT increased soil microbial biomass in carbon and nitrogen cycling by more than 100 % (73). This is due to the

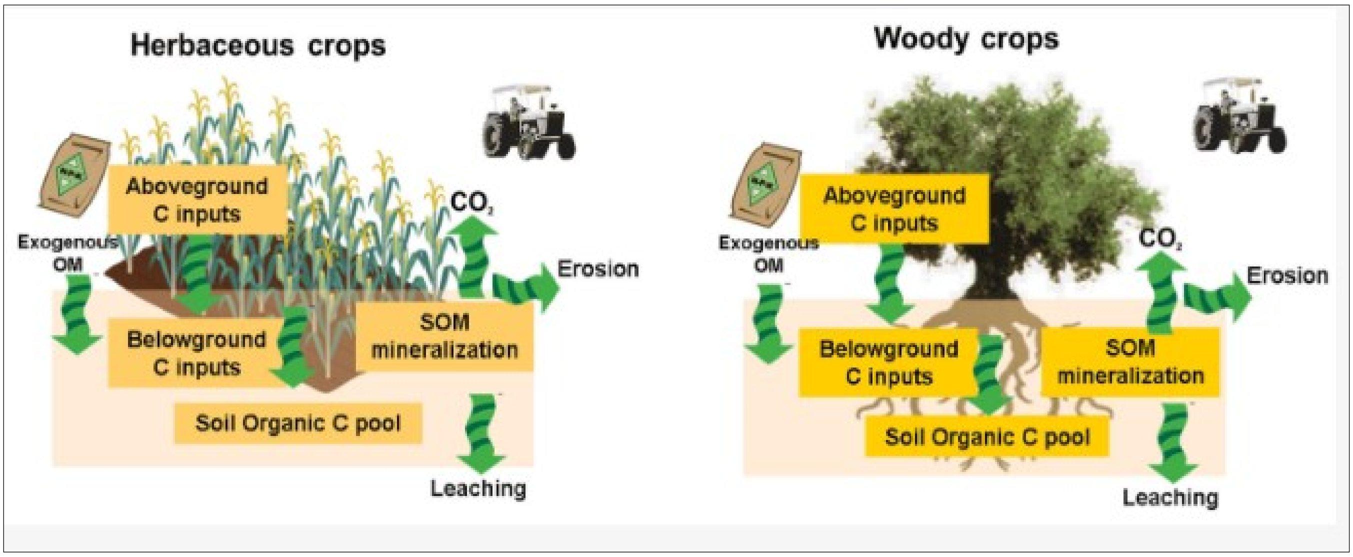

Fig. 3. Comparison of soil carbon balance in herbaceous and woody plants in cropping systems (64).

Table 5. SOC sequestration under different land use management (70)

Agriculture activity	Management practice	Carbon sequestration (t ha^{-1}yr^{-1})
Cropping	Increasing soil fertility	0.05 - 0.15
	Improve rotations	0.10 - 0.30
	Irrigations	0.05 - 0.15
	Eliminate fallows	0.10 - 0.30
Conservation tillage	Retain stubble	
	Reduce tillage	0.40
	Use no-till systems	
Addition of organic amendments	Add animal manure	0.10 - 1.10
	Add biosolids	1.00
Land conversion	Convert degraded cropland to pasture	0.80 - 1.10
Grazing	Use fertilizers	0.30
	Manage grazing time	0.35
	Irrigation	0.11
	Introduce legumes	0.75

higher enzymatic activities, including dehydrogenase, urease, protease, phosphatase and beta-glucosidase, under ZT, which promote increased microbial density in the soil (74). Conservation agriculture practices significantly improved the soil microbial communities with respect to their population, diversity, food web and carbon dynamics (16). Residue retention significantly changed the carbon and nitrogen levels, especially in the soil's top 0-10 cm layer (75). The CA system also showed higher organic matter decomposition, microbial biomass carbon and nitrogen (up to 31 %) and increased enzyme activity (76). The cropping sequence has also considerably impacted the soil microbial biomass accumulation (8, 10). Maize-wheat-maize and maize-oat-maize had increased soil biological activity and respiration rates than their fallow counterparts (71). These residues impact soil physio-chemical properties, leading to better soil microbial biomass and healthier soil.

Weed management in CA

A linear negative relationship between weed density and crop yields makes weed management critical for increasing yield. Conservation agriculture offers significant benefits in addressing resource scarcity and promoting efficient utilization, but it also poses challenges for weed management. Conservation agriculture can prove to be profitable; namely, i) inducing dormancy in weed seed and altering the process of natural loss of viability, ii) disruption of weed establishment via various cultural interventions and iii) hindering weed seed dispersal and proliferation (76). These practices impact both weed ecology and distribution (77). Weed seeds are buried deep within the soil layers, increasing their chances of survival (78). When brought closer to the surface, these seeds are subjected to climatic aberrations and desiccation (79). In ZT practices, weed seeds accumulate in the top 0-5 cm of soil, enabling control through methods like the stale seedbed approach, which promotes uniform emergence and can be particularly effective against seeds present in the topsoil, having low initial dormancy and light-activated germinating seeds. ZT also prevents deep proliferation of roots of weeds owing to its higher penetration resistance, ultimately leading to lethal germination (80). However, the ZT system may favor perennial weeds, which can dominate under such conditions (81). Zero tillage also favored more diversity once the weed seed bank was compared with conservation practices (82). Weed emergence is also hampered due to residue retention, which increases the feasibility of losses in establishment rates of weeds (83). Crop establishment, cultivar selection, sowing time and planting geometry influence weed establishment (84). Early planting with dense geometry provides a competitive advantage over the weeds via the smothering effect (85). Integrated weed management strategies are crucial to counter herbicide resistance and shift (86). Crop rotation, in combination with allelopathy and altered resource demands, increases weed control efficiency. In the case of wheat, adopting cover crops reduces the weed density and biomass growth in subsequent crops by 10% and 5% respectively (85, 87). In rice-based systems, integrated weed management systems become particularly challenging in rainfed scenarios, often requiring herbicide interventions (88). Decision-making models such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchic Process (AHP) were used to conclude that CA is not only a better practice for soil conservation but for weed management as well (89). Rainfed ecologies, herbicide applications and cultural practices are integrated to manage diverse flora and weed shifts. Incorporating mung bean and stale seed beds during the fallow period has been shown to reduce the population of major weeds, such as *Dactyloctenium aegyptium,* in the subsequent crop by 84 % and 40 % respectively (90). The mustard-rice system entails a reduced density of weeds as compared to transplanted and puddled rice. Weeds had reduced yields of 21.88 % in zero till rice and 44.87 % in DSR-zero till rice (91). Therefore, weed control is necessary in CA systems as it affects crop yield and nutrient dynamics.

Energy dynamics in CA

Agriculture is a process of conversion of solar energy into chemical energy for biomass production. A terrestrial plant's highest photosynthetic efficiency is approximately 6 %, whereas farmed crops can only achieve 0.15 to 0.20 % of the total energy received. Efficient resource utilization, particularly in energy consumption, is a key criterion for sustainable intensification (92). Energy demand in agriculture varies over time, aligning with critical operations such as transplanting, plowing and harvesting. India accounts for about 200 million agricultural workers, contributing 43000 T of human energy, with 80 million draught animals providing 81000 T of animal energy (93). Both sources have shown a decreasing trend over the years, necessitating increased reliance on machinery. The farm power requirement is about 0.77 kWha$^{-1,}$ primarily met through mechanization (7). The computation of energy input and output is essential to determine the efficiency of a system under defined conditions. Different machinery can be evaluated based on suitability and efficacy as the major criteria. In CA, the energy requirement is far less due to a smaller number of overall operations in the field (94). Although ZT reduces energy requirements, this is offset by the higher energy demands for water and nitrogen inputs (12).

Energy forms can be partially interchangeable within certain defined limits. Tillage before planting, which requires one-third of the total energy input, can be entirely avoided in the case of ZT. Crop residues even contributed about 167995 MJ ha^{-1}, around 76 % of the total energy expended during the process (93). The cropping system decreased energy usage compared to the 11800 MJ required by mustard, followed by cowpea (9553 MJ ha^{-1}) (91). A study showed that soybeans have the lowest energy requirement under ZT, NT and ZT with SR (95). ZT lowers the overall energy requirement when compared to other practices. Thus, CA practices provide a pathway for developing energy-smart agricultural systems.

Challenges in CA adoption

The adoption of CA is influenced by socioeconomic variability, demography and institutional considerations. Key drivers include income, age, education, social capital, land security, land holding size, technology extension, market access and government support, contributing to a 25 % adoption rate in Sub-Saharan Africa. A well-educated, informed individual with enough institutional and government assistance will adopt CA practices more readily than their peers. On the contrary, poor technical expertise, a lack of finance and access to financing restrict the adoption of these technologies. Effective dissemination of information is crucial to encourage farmers to adopt CA, a traditional technique refined over time (96, 97). Risk aversion is also a prominent factor to consider when analyzing the context of CA adoption. The impact of risk aversion and impatience on adoption intensity was approximately 12 % for impatient farmers and 18 % for risk-averse farmers. (98). Risk and time preferences influence farmers' decision to adopt CA. Farmers are more likely to make cautious and informed decisions When informed about the risks and time frames associated with CA adoption (99). Smallholders, however, perceive CA as riskier due to the possible yield penalties during the initial period of adoption (100). When farmers encounter high uncertainty, they are expected to strive to reduce risk by investing less in m odern technologies (101). This risk perception is pivotal in determining the adoption of CA rates. Risk-averse farmers were more inclined to adopt drought-tolerant maize varieties over local maize but were less likely to adopt other improved ones (102). Similarly, a study found that loss-averse farmers were more willing to adopt risk-reducing seed varieties but tended to adopt Bt cotton later than their counterparts (103). It is attributed to the fact that farmers' risk preferences are closely linked to their chosen livelihood strategies. These findings highlight the significance of risk perception and aversions in adopting CA as a standard practice (104, 105).

Harnessing CA for the fulfillment of sustainable development Goals

Over years of agricultural development, various approaches have been proposed to produce sufficient food sustainably, including the 'doubly green revolution' (106), 'alternative agriculture' (107), 'evergreen revolution' (108), 'agroecological intensification' (109), 'green food systems' (110), 'greener revolutions' (111) and 'evergreen agriculture' (112). Implementing sustainable practices and the global food security demands has emphasized the need for sustained intensification (113). Conservation agriculture plays a poignant role in this area. Conservation agriculture addresses natural resource degradation issues, escalating production costs and climate change (114). A shared blueprint for sustainable development was proposed by the United Nations in 2015. The fulfillment of the 2030 agenda is a succession of Millenium Development Goals, which ended in 2015 (115). Agriculture is pivotal in fulfilling SDG. Compared to conventional practices, CA offers significant agricultural, environmental and economic benefits (116). CA aligns with the overarching priorities of SDGs as it increases the overall productivity of the agricultural system with the juxtaposition of poverty, hunger, sanitation and education as its key challenges, as shown in Table 6. Conservation agriculture holds the potential to mitigate the ill effects of climate change imposed by the continual exploitation in agriculture as it reduces pollution to an appreciable extent such that common health benefits of the environment can be reaped (42, 117). Thus, implementing novel technologies in conventional agriculture will be instrumental in increasing overall productivity (Fig. 4).

In the Indian context, considerable efforts are being made to achieve these goals. The vision of the Government of India aligns with the 2030 agenda by ensuring food security and enhanced nutrition levels (119). A Vision 2030 by the Department of Agriculture Cooperation and Farmers Welfare, Government of India encompasses utilizing natural resources in such a way that they are non-degrading, environmentally non-hazardous and socially acceptable for promoting sustainable agriculture (118). Land pooling is presented as another option so that economic scales are optimized (101). Leasing out land without compromising the original rights and title of the tenants is a major advantage of this system. Producing enough food to maintain long-term food security as the population's purchasing power increases and the modified targeted subsidy establishes a streamlined venture for affordable food products (119) (Fig. 4). Supply chain management for agricultural goods is vital. Agro-diversification can alleviate pressure on conventional crops. Reviving climate-resilient technologies will create better prospects for the agricultural sector (120). Although CA is an age-old cultivation technique, it integrates new technologies, enabling breakthroughs in sustainable intensification.

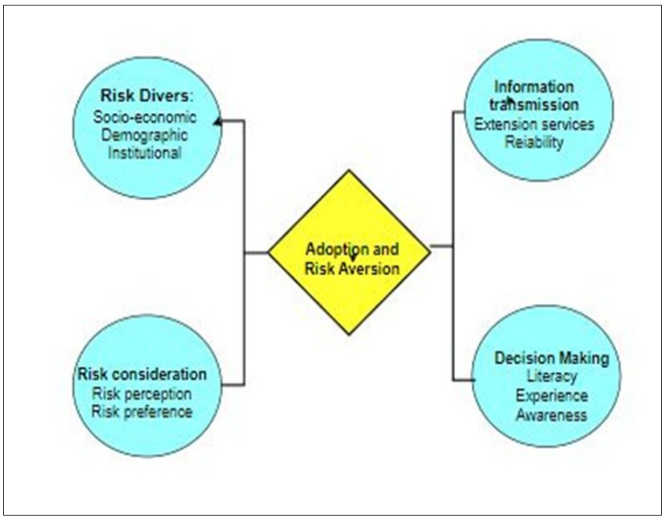

Fig. 4. Risk aversion strategies in the adoption of CA.

Table 6. Conservation Agriculture in fulfilment of SDGs

SDG No.	Goal	Aim/Target	Contribution of Conservation Agriculture
1	No Poverty	End of poverty in all its forms.	The majority of the poor population (70 %) depends on agriculture; therefore, agriculture entails more scope in poverty reduction than any other sector.
2	Zero hunger	End hunger, achieve food security and end nutritional imbalances in a sustained way.	Achievement of sufficient food for the population along with nutritional fortifications is one of the primary objectives of agriculture.
3	Good health and well-being	Ensure healthy lives and promote well-being of every age strata.	Indirectly linked
4	Quality education	Ensure quality and lifelong learning opportunities.	Improved extension renders farming communities to harpoon the modern technologies, inputs and the capacity to implement it.
5	Gender equality	Equal cerebral opportunities for all genders and promotion of inclusivity and empowerment.	Women farmers face a 20-30 % disparity in production compared to their male counterparts. Reducing this gap would mean better production capacity to minimize world hunger.
6	Clean water and sanitation	Ensure availability of water and sanitation for all, along with effective management.	As the water demand doubles by 2030, all sectors, including agriculture, will face scarcity, reducing production capacity.
7	Affordable and clean energy	Ensure access to affordable, reliable, sustainable and non-polluting energy for all.	Biofuel crops can be an alternative to fossil fuels with a cleaner residue.
8	Decent work and economic growth	Promote sustained economic growth with productive employment and decent work opportunities for all.	Developing mechanization in the farming industry will reduce the physical manpower needed, therefore expelling the former laborers to resort to gaining skill sets for better job opportunities.
9	Industry, innovation and infrastructure	Build resilient infrastructure, promote Indirectly related inclusive and sustainable industrialization and foster innovation.	Indirectly related.
10	Reducing inequality	Reduce inequality within and among countries.	Indirectly related.
11	Sustainable cities and communities	Make human settlements safe, resilient and sustainable, making them highly inclusive.	Indirectly related.
12	Responsible consumption and production	Ensure sustainable consumption and production system.	Average consumption per capita is projected to grow exponentially by 2030.
13	Climate action	Take immediate action to counter climate change and its impacts.	Conventional agriculture releases about 17 % of greenhouse gas emissions, contributing largely to climate change. Agricultural climate mitigation will reach up to 7.5 % of global emissions.
14	Life below water	Conserve and sustainably utilize marine resources for sustainable development.	Indirectly related.
15	Life on land	Protects and promotes sustainable utilization of terrestrial ecosystems, sustainably manages forests, mitigates desertification and slows and reverses land degradation and biodiversity loss.	Efficient production system development on the existing farms will prevent land degradation and prevent further conversion of natural habitats into farmland.
16	Peace, justice and strong institutions	Promotes inclusive societies for sustained development, provides access to justice for all and builds effective and accountable institutions at all levels.	Indirectly related.
17	Partnerships for the goals	Strengthen the means of execution and revitalize the global partnership for sustainable development.	Indirectly related.

Future directive

The CA-based agricultural system offers a promising approach to meet growing food demand while ensuring agro-ecosystem sustainability. At the 8th World Congress on CA, the global community aimed to transform 50 % of the global cropland area into the CA systems by 2050. Conservation agriculture is recognized as a sustainable approach to enhance farm profitability, improve soil productivity and ensure efficient resource use. Advancements in machinery, such as turbo and happy seeders, have facilitated CA adoption by addressing challenges like crop residue management, particularly in ZT rice-wheat systems. It relies more on biologically mediated nutrient acquisition, sequestration and availability. To ensure the sustainability and resilience of the agricultural systems, CA must evolve as a transformative approach that can address contemporary and emerging challenges. The future trajectory of CA should entail i) enhancing the productivity on limited land by leveraging precision agriculture, ii) reversal of resource and environment degradation, iii) improvement in resource use efficiency, iv) adaptation to climatic aberrations and v) institutionalizing multi-disciplinary research and farmer participation. Embedding these directives in the policy framework, the development of CA practices can ensure food security while building a resilient system.

Conclusion

Conservation agriculture can easily be recognized as the upcoming avenue for conserving the ecosystem to withstand growing food demands. It is a scientifically validated pathway to sustainable intensification that addresses critical challenges of resource degradation, climate variability and food security. This readily adaptable technique is pivotal in achieving SDGs, uplifting the agricultural sector. Conservation agriculture is applicable across diverse agro-ecological and socio-economic contexts, promoting sustainable intensification to ensure food security while protecting the environment. Sustainable intensification through CA can foster environmentally- friendly economic growth and benefit related sectors. CA aligns with the essence of sustainability, which includes ameliorating poverty, equitable resource distribution, peace and prosperity and ecosystemic balance as its core values. A paradigm shifts in research that emphasizes a participatory approach and on-farm validation is vital to unlock the full potential of CA. By integrating these efforts, CA can become a global cornerstone for a resilient, sustainable and climate-smart agricultural system.

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Authors' contributions

SR, TR, AM, RU and AS collected literature. SR, TR and AM reviewed and wrote the first draft of the manuscript. MPK, SS and AS edited the manuscript. JB, DR, SKN, RJ and KS did the second revision of the manuscript. SR and AM did final revision of the manuscript. All authors have read and agreed to the published version of manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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