Plant Archives Vol. 25, No. 1, 2025 pp. 635-646 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org

DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.no.1.096

CONSERVATION AGRICULTURE: EFFECT ON CROP YIELD, SOIL HEALTH AND CARBON SEQUESTRATION IN INDIAN SOILS

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(Date of Receiving-05-12-2024; Date of Acceptance-24-02-2025)

ABSTRACT

Conservation Agriculture (CA) is an eco-friendly and sustainable agricultural practice that integrates minimal soil disturbance, permanent soil cover, and crop diversification. This review explores the impact of CA on crop yield, soil health, and carbon sequestration, particularly in Indian soils. Evidence suggests that CA enhances soil organic matter, improves water retention, and promotes biodiversity, contributing to long-term agricultural sustainability. This practice also improves the aeration and structure of soil, which makes the dependence on synthetic fertilizers decrease. Besides, CA contributes to mitigating climate change through enhanced carbon sequestration, decreased emission of greenhouse gases, and overall improved resilience of soil. Some challenges associated with CA are residue management, high adoption costs, and limited awareness of farmers. The overcoming of such barriers may depend on technological developments, government incentives and farmer training programs. This review could help one understand the gains and losses of CA while emphasizing its prospects for the future in India.

Key words : Conservation Agriculture, Soil health, Crop yield, Carbon sequestration, Indian Agriculture, Sustainable farming.

Introduction

Conservation Agriculture is an innovative approach to farming, which is both sustainable and environmentally friendly (Hobbs *et al*., 2008). It aims at enhancing agricultural productivity while maintaining ecological balance. The three core principles are minimal soil disturbance (zero or reduced tillage), permanent soil cover (through crop residues, mulches, or cover crops), and diverse crop rotations, including intercropping and agroforestry (Giller *et al*., 2015). These three principles contribute together to improved soil health, increased water-use efficiency, enhanced biodiversity, and long-term agricultural sustainability (Farooq *et al*., 2015).

In India, soil degradation, declining soil fertility, water scarcity, and climate change are emerging challenges that threaten food security and rural livelihoods (Osman, 2014). Unsustainable agricultural practices such as intensive tillage, excessive chemical input use, monocropping, and over-extraction of groundwater have led to soil erosion, loss of organic matter, and reduced productivity. CA has been recognized as a potential solution to these problems by promoting sustainable land management while maintaining or even improving yields (Padhiary and Kumar, 2024).

CA has been adopted in varying proportions in different agro-ecological regions. In the Indo-Gangetic Plains, it has been promoted widely (Islam *et al.*, 2023). This is because the conservation tillage techniques in wheat-rice systems have been shown to increase productivity and reduce input costs with zero tillage (Jat *et al.*, 2012). For semi-arid and rainfed regions, CA includes mulching and cover cropping that conserve soil moisture, prevent soil erosion, and increase drought tolerance (Pratibha *et al.*, 2022). Furthermore, in hilly and tribal areas, agroforestry-based CA models are being explored for soil conservation and sustainable livelihood opportunities.

There are several barriers that have deterred the adoption of CA, with major ones including the significantly high machine cost for technologies like a zero-till seed drill, requirement of technical knowledge, reluctance to shift from conventional practices by farmers, and limitations of policies (Bunda *et al.*, 2023). But initiatives of governments through the research programs and extension services are indeed promoting CA through promotion campaigns, incentives through finance, and demonstration trials.

Tillage operations consume nearly 30% of the energy utilized in the entire crop production process (Lal, 2004; Singh *et al.*, 2008). Intensive tillage practice enhances the production of greenhouse gas emissions, as energy is typically generated from fossil fuels (Yadav *et al.*, 2017a, b; Soni *et al.*, 2013). Thus, a paradigm shift in agricultural management is required that focuses on conservation efficiency, increased energy use efficiency (EUE) and lower GHG emissions to make food production cleaner and safer. The CA practices like NT, residue retention (mulching) and other similar methods have enormous benefits by reducing energy consumption and GHG emissions (Lal, 2004).

CA is a set of management practices that reduce soil erosion, compaction, aggregate breakdown, organic matter depletion, and nutrient leaching, all of which are exacerbated by extreme weather conditions and conventional farming practices (Hobbs *et al.*, 2008; Dalal *et al.*, 2011; Sinha *et al.*, 2019; Somasundaram *et al.*, 2020). These practices slow the rate of carbon release into the atmosphere by promoting the gradual decomposition of organic materials, which are integrated into the surface soil layer. Consequently, the soil functions as a carbon sink by sequestering significant amounts of carbon (Dalal *et al.*, 2011; Page *et al.*, 2020; Somasundaram *et al.*, 2018, 2020). This is a process that is crucial in mitigating GHG emissions from agriculture and combating the evil effects of climate change.

Table 1 : Different components and practices of conservation agriculture.

No-tillage, minimum and reduced tillage	Drip /trickle/sprinkler irrigation technology
Nutrient cycling	Crop and pasture rotation
Agroforestry	Noburningofcropresidues/retentionofcropresiduesatsoil surface
Trap cropping for insect control	Alley cropping
Biological mode of pathogen control	Bed and furrow planting
Integrated pest management (IPM)	Contour farming and strip cropping
Cover and green manure cropping	Organic and biodynamic farming
Stubble mulching	Continuous crop land use

Source: Maity *et al*. (2021).

Fig. 1 : Principle and approaches of conservation agriculture (Source, Rai *et al.*, 2023).

The positive effects of CA on the health of soils include increased structural integrity, lower compaction levels, greater levels of organic matter, greater amounts of carbon in the top layer, and constant soil temperature due to stabilized fluctuations (Cárceles Rodríguez *et al.*, 2022). Besides the economic advantages derived from time and energy saving, increased crop production through better spacing and planting time, less likelihood of pest and disease attacks since there is an increase in biodiversity and GHG emission decreases (Lamichhane *et al.*, 2015).

The paper reviewed the effects of CA on these three key domains of Indian agriculture: crop yields, soil quality, and sequestration carbon. Its rationale is to deepen understanding regarding CA practices contributing towards sustainable agricultural development, efficiency enhancement in the resource use context and climate resilience strengthening in the domain of Indian farm systems.

Principles of Conservation Agriculture

Conventional tillage practices adversely affect the pool of soil carbon (C) by increasing soil erosion and compromising the structural properties of the soil (Bhattacharya *et al*., 2016). On the other India's hilly areas are located with rich biodiversity and high potentiality for various agricultural activities, such as horticulture and livestock farming. It has huge ecological issues due to vulnerability in climatic variations and the increasing pressure on agricultural land in the Himalayan region due to food demands (Rasul, 2010). It is reported that almost two-thirds of the Himalayan population is engaged in subsistence farming, which provides sufficient food only for five to six months annually (Shrestha and Nepal, 2016).

The hilly terrain is different from the plains in both economic and social terms, due to its topographical and geographical characteristics. These regions are blessed with abundant natural resources, including fertile soil, dense forests, lush meadows, lakes and snow-covered mountain peaks. The perennial streams that sustain the plains originate from these hills (Rai *et al*., 2023). Effective utilization of these resources is essential for the sustainable development of both the region and its inhabitants. With varied agro-climatic conditions, the North-Western Himalayas (NWH) is an ideal region for growing different crops. The growth of agriculture and its related industries has contributed significantly to the development and economic growth of these regions (Sharma *et al*., 2017).

It may be surmised that agriculture is of significant importance in the North-West Hill region, with limited development in modernization. Indicators include low levels of adoption of state-of-the-art agricultural technologies, low fertilizer application and slow economic growth. Nonetheless, the most important issue contributing to this slow development is inadequate investment in system-specific and location-based technologies that are very pivotal for sustainable agricultural development (Dolman, 2024).

Effect of Conservation Agriculture

Conservation tillage reduces soil loss by as much as 50% (Fig. 2) by reducing soil compaction and retaining the natural moisture of the soil. In zero tillage, seeds are sown directly into the soil without any tillage after the previous crop has been harvested. This way, crops can use residual moisture from the previous season, saving up to a million liters of water per hectare during germination (Rai *et al*., 2023).

Effects on Crop Yield

There has been a variation in the impacts of Conservation Agriculture (CA) on crop yields in different agro-ecological zones in India. In the short term, there might be a marginal decrease in yield because of adaptation in the soil and changes in microbial dynamics; however, productivity improvements are noticeable with long-term implementation (Mohanty *et al*., 2015). These

Fig. 2 : Rational conservation approaches to restore natural resources (Source: Rai *et al*., 2023).

improvements are due to better structure in the soil, better retention of water, higher organic matter and enhanced nutrient cycling (Chatterjee *et al*., 2021).

In the Indo-Gangetic Plains, conservation tillage has been shown to offer yield advantages in major staple crops such as wheat rice, and maize. Experiments indicate that in wheat-based systems, zero tillage combined with residue retention enhances root proliferation and availability of soil moisture, which has led to stability in yields even under erratic rainfall conditions (Krishna and Veettil, 2014). Likewise, in rice systems, adoption of DSR under CA practice reduces water usage and enhances nutrient uptake efficiency and leads to sustainable productivity (Joshi *et al*., 2013).

In central and southern India, CA practices like reduced tillage and permanent soil cover have been found to enhance the yields of crops such as soybean, chickpea, and sorghum by improving soil aeration and microbial activity (Chaudhary *et al*., 2023). In semi-arid regions, where water scarcity is a major constraint, CA helps in conserving soil moisture, reducing runoff and preventing nutrient loss. These benefits are particularly important in rainfed cropping systems, where CA enhances drought resilience and supports stable yields over time (Jat *et al*., 2012).

However, the extent of yield improvement under CA is influenced by several factors, including soil type, climate variability, crop selection and management practices. Poor residue management, improper weed control, and inadequate mechanization can limit the positive impacts of CA. Additionally, farmers' awareness, accessibility to suitable machinery, and economic incentives play a crucial role in the successful adoption of CA practices (Lee and Thierfelder, 2017).

Effects on Soil Health

CA contributes to soil health through the improvement of soil structure, increase in organic matter, reduction in soil erosion and promotion of microbial diversity (Lal, 2016). While conventional tillage breaks up the soil aggregates and hastens nutrient loss, CA maintains the soil integrity, hence long-term fertility and productivity gains (Goud *et al*., 2022).

The long-term adoption of CA will lead to better soil fertility, improved water use efficiency, higher microbial diversity and reduced erosion, making it a promising approach for sustainable agriculture in India (Sharma *et al*., 2012). Though short-term challenges such as residue management and weed control are present, the long-term benefits far outweigh the initial difficulties and ensure soil health and productivity for future generations (Henry *et al*., 2018).

Table 2 : Effects of different CA practices on soil health parameters.

Soil health parameters	CA practices	Remarks	References
Bulk density and soil organic carbon	ZT+residue retention	Decrease in BD and ZT increased SOC stock up to 30 cm but residue retention increased it up to 60 cm	Bhattacharya *et al.* (2020) andModak *et al.* (2020)
Hydraulic conductivity and infiltration rate	PBB+R	Increased HC and infiltration rate in 0-15 and 15-30 cm of soil depth as compared to CT	Ghosh *et al.* (2020); Parihar *et al.* (2016)
Microbial and enzymatic properties	CA-based maize-wheat (MW)	MBC and MBN increased by 208% and 263%, whereas, dehydrogenase and alkaline phosphatase activity increased by 210 and 48%	Choudhary *et al.* (2018a)
Soil compaction and penetration resistance	CA based systems ZT and PB	Decrease in bulk density (4.3–6.9%) and penetration resistance (15.9– 30.7% as compared to CT based maize	Parihar *et al.* (2016); Saha *et al.* (2010)
Total soil N(TSN)	Zero tillage with bed planting (ZT-B) and zero tillage with flat planting (ZT-F)	15% higher TSN concentrations than conventional tillage and bed planting plots (CT-B)	Bhattacharyya *et al.* (2013)
Soil aggregation process	Minimum tillage (MT) and addition of organic matter	Enhanced soil aggregation processes and water stableaggregates and decreased long-term soil erosion on a gentle slope (~2%) in the Indian Himalayas	Ghosh *et al.* (2016)

Source: Maity *et al*. (2021).

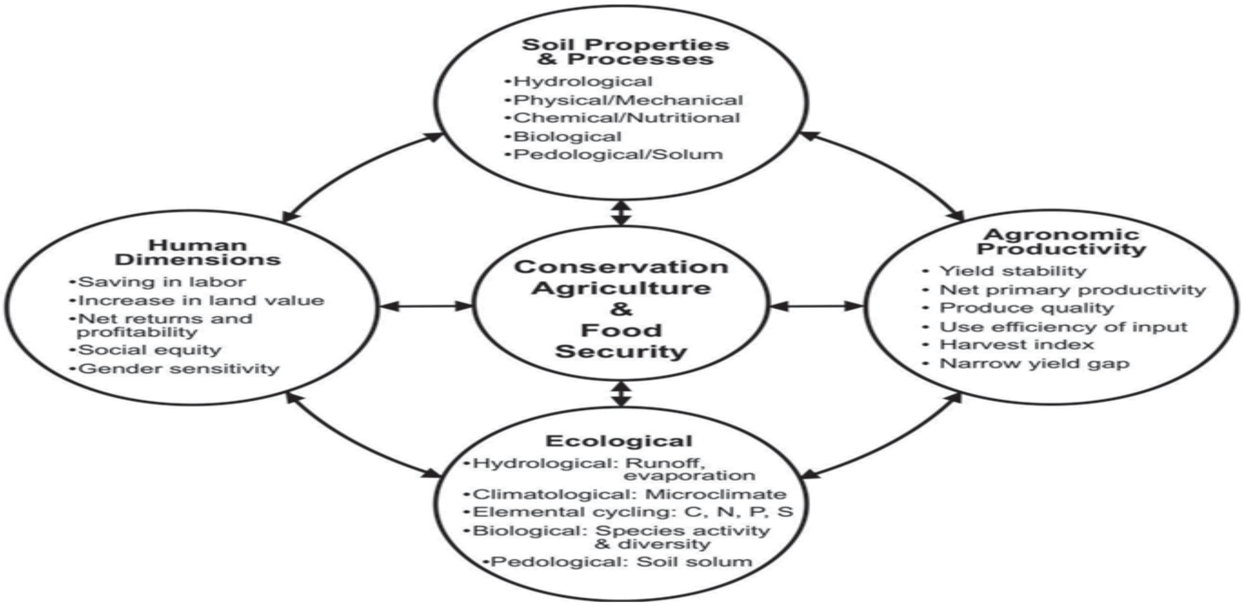

Fig. 3 : Diifrent benefit of CA for food security and sustainability in the ecosystem (Source: Srinivasarao *et al.*, 2015).

Improvement in Soil Structure and Physical properties

By minimizing soil disturbance, CA helps preserve soil aggregates, leading to improved porosity, aeration, and water infiltration (Abdallah *et al.*, 2021). The maintenance of crop residues and cover crops on the soil surface reduces the impact of raindrops, preventing soil compaction and crusting. This leads to:

Better root penetration, allowing crops to access deeper water and nutrients. Reduced surface runoff, improving water-use efficiency and mitigating soil erosion. Improved soil water holding capacity, making CA highly effective in dry lands

Soil Organic Matter and Nutrient Cycling increased

CA promotes greater organic carbon sequestration through the admittance of crop residues and cover crops into the soil (Oladele *et al.*, 2021). This leads to increased Cation exchange capacity (CEC), thereby increasing soil fertility and nutrient availability. Soil aggregation increased, which decreases soil erosion and increases stable structure. Higher microbial biomass, which leads to efficient decomposition of organic matter and increased nutrient release (Khan *et al.*, 2016). Cover crops and retained crop residues are continuous sources of nutrients, thus decreasing the dependency on synthetic fertilizers. Organic matter accumulation over time leads to a more sustainable nutrient cycle, thereby improving soil fertility without excessive chemical inputs

Enhancement of Microbial activity and Soil biodiversity

Nutrient transformation, decomposition of organic matter, and suppression of disease occur through soil microbial communities. CA promotes a lively microbial ecosystem in the following ways:

Reducing tillage would minimize the soil microbial habitat disruptions. Increasing levels of organic carbon, which could provide a consistent food source to beneficial microbes Improving the diversity of fungal and bacterial flora, thereby leading to enhanced N fixation, solubilization of phosphorus, and organic matter decomposition (Dhaliwal *et al.*, 2020; Schmidt *et al.*, 2018).

There is an increase in mycorrhizal fungi under CA, which forms symbiotic relations with the root organs of plants, thus enhancing phosphorus uptake and overall nutrient efficiency (Khaliq *et al.*, 2022). Moreover, CA decreases soil-borne pathogens by encouraging beneficial microbial competition.

Reduction in Soil Erosion and Degradation

Soil erosion is still one of the common factors affecting agricultural sustainability mainly in sloping and rain-fed areas. CA reduces erosion through:

Permanent soil cover, which keeps it from facing wind and water-induced erosion. Increased infiltration, with less surface runoff and sediment loss (Chakrabortty *et al.*, 2022). Stable soil aggregates, which resist deterioration under heavy rain or dry weather. In India, where degradation of soil is an increasing concern, CA helps in conserving topsoil and productive land for future use (Bhattacharyya *et al.*, 2023).

Soil Moisture Conservation and Drought resilience

For areas with unstable rainfall and more frequent

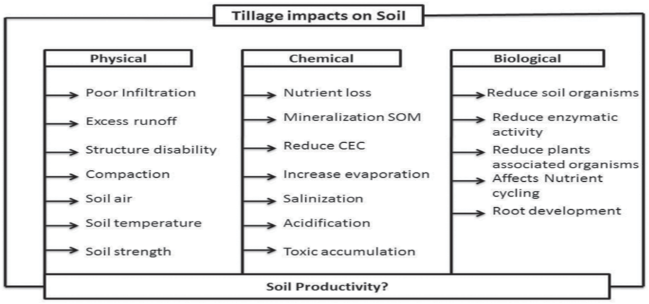

Fig. 4 : Effect of tillage on different properties of soil (Source: Srinivasarao *et al.*, 2015).

droughts, CA contributes to better conservation of soil moisture by:

Minimizing evaporation through cover of crop residue. Enhancing water infiltration, minimizing runoff losses (Liao *et al.*, 2021). Promoting deep root systems, increasing access to subsoil moisture. This makes CA particularly valuable for dryland agriculture, helping farmers sustain productivity even under water-limited conditions (Wang *et al.*, 2022).

Carbon Sequestration and Climate Change mitigation

One of the most significant environmental benefits of Conservation Agriculture lies in its carbon sequestration contribution towards climate change mitigation (Li *et al.*, 2020). Soil organic carbon (SOC) is increased as a result of CA, thus indirectly reducing atmospheric carbon dioxide (CO_2) concentration while it minimizes greenhouse gas (GHG) emissions (Holka *et al.*, 2022). In India, agriculture is a significant source of climate change through intensive tillage, excessive fertilizer use, and residue burning. CA offers an environmental-friendly option to enhance soil carbon sequestration while mitigating climate change (Neogi *et al.*, 2022).

SOC in soils is a significant indicator of soil health, and its relationship with the surface concentration in nutrients reserves, erosion control and water infiltration has significant importance. The profile distribution of SOC in soils depends on various factors, including tillage methods and the initial SOC levels. Carbon sequestration refers to the long-term storage of carbon in soils, vegetation, oceans, and geological formations. There are several factors influencing SOC sequestration, which include land use, natural vegetation, soil texture, climate conditions, topography and the initial SOC stock (Minasny *et al.*, 2017; Mondal *et al.*, 2020).

Vegetation types, irrigation practices, crop rotation, and integrated pest and nutrient management and livestock rearing also influence the rate of carbon sequestration in

Table 3 : Effect of different conservation agriculture practices on soil organic carbon sequestration.

Management practices	Erosion ($Mgha^{-1}yr^{-1}$)	Soil Organic C ($Mg/ha^{-1}yr^{-1}$)
Conventional tillage (CT)	16.5	–0.023
CT with increased fertilizer	15.0	–0.006
Ridge tillage (RT)	6.6	0.001
RT with increased fertilizer	5.9	0.027
RT with fertilizer and residues	3.5	0.086

Source: Doraiswamy *et al.* (2007).

soil (Patle *et al.*, 2013). At the field level, maintaining the positive SOC balance involves increasing the organic matter input into the soil while reducing carbon losses through mineralization, leaching, and erosion or slowing down SOC decomposition. Among the most effective agricultural practices for enhancing SOC content are CA and agroforestry (Corbeels *et al.*, 2019). This means the substitution of rice cultivation with maize under CA systems increases SOC, thereby increasing carbon stability in the humic acids.

CA and Soil Carbon sequestration

CA enhances carbon sequestration by ensuring increased organic carbon storage in the soil through reduced soil disturbance, retention of crop residues and application of organic amendments (Chowdhur *et al.*, 2021). The mechanisms are as follows:

Minimal soil disturbance (zero/reduced tillage): Conventional tilling involves the oxidation of soil organic matter, which is lost as carbon in the form of CO_2. CA, therefore, reduces carbon losses and enhances soil carbon stabilization (Hussain *et al.*, 2021).

Retention of residues and organic amendments: Retaining crop residues on the field or incorporating organic matter (such as compost, farmyard manure) into the soil increases the input of organic carbon, contributing to long-term carbon accumulation in the soil (Bolinder *et al.*, 2020).

Cover cropping and crop rotation: Cover crops help to fix atmospheric carbon and improve soil structure, whereas diversified crop rotations ensure continuous carbon inputs, thereby preventing carbon depletion over time (Zou *et al.*, 2024).

Research studies conducted in Indian agro-ecosystems, particularly in the Indo-Gangetic Plains and dryland regions, have shown that zero-tillage wheat-rice systems, with residue retention, significantly increase SOC levels as compared to conventional tillage (Naresh *et al.*, 2017).

Decrease in Greenhouse Gas (GHG) emissions

Agricultural activities release GHGs primarily through CO_2 from soil disturbance, methane (CH_4) from paddy fields, and nitrous oxide (N_2O) from excessive nitrogen fertilizer use (Chataut *et al*., 2023). CA helps to mitigate these emissions by:

Reduction of soil CO_2 emissions: CA reduces the oxidation of organic matter by preventing frequent plowing, which would otherwise be released into the atmosphere as CO_2 (Nair *et al*., 2015).

Methane emission reduction in rice systems: Traditional flooded rice systems emit enormous quantities of methane through anaerobic decomposition. AWD is a CA-friendly water management practice that reduces methane emissions by increasing the aerobic soil condition (Conrad, 2020).

Reducing N_2O emissions: Overuse of nitrogen fertilizers leads to nitrous oxide emissions, a potent GHG. CA enhances the efficiency of nitrogen use through improved nutrient cycling and microbial activity, thus reducing the application of chemical fertilizers (Dimkpa *et al*., 2020).

Climate Resilience and Adaptation

In addition to mitigation, CA enhances climate resilience by enhancing soil health and water retention, thereby making agricultural systems more adaptive to climate variability (Altieri *et al*., 2017). Key benefits include:

CA will increase the water holding capacity of soil, hence crop will resist more to water stress (Bodner *et al*., 2015). Flooding tolerance will increase as better structure and higher infiltration rates in the soil can help reduce the impact of flooding caused by excessive rain (Kaur *et al*., 2020). Crop residue cover insulates the soil from temperature variations, thereby saving soil biota from heat shock (El-Beltagi *et al*., 2022).

Long-term gains for Indian agriculture

Integrate CA into the farming systems of India and align well with both national and global goals of climate action, such as various initiatives that include India's commitment to the Paris Agreement and initiatives like NAPCC (Kumar, 2018). Scaling up CA will:

Improve the opportunity for carbon sequestration and balance out emission releases from agriculture (Hutchinson *et al*., 2007). Reduce reliance on fossil fuel-based practices by reducing energy costs. Conduct sustainable and regenerative agriculture in a manner ensuring long-term food security and sustainability of the environment (Borsari, 2020).

CA represents a climate-smart agricultural approach through carbon sequestration, reduced GHG emissions, and increased resilience to climate change (Sun *et al*., 2024). Though the uptake of CA in India is associated with limited awareness, residue management issues, and policy constraints, the long-term benefits make CA a viable strategy for sustainable and climate-resilient agriculture (Scherr *et al*., 2012). Accelerating this transition towards a greener and more resilient future requires strengthening research, farmer education, and policy support (Knickel *et al*., 2018).

Conservation Agriculture for Climate-Smart Farming

Conservation farming is now globally recognized as a vital integrated agricultural system with the potential to mitigate the environmental impact of farming, enhance and safeguard natural resources, reduce carbon emissions, address climate change challenges, and improve the social and economic well-being of farming communities worldwide (Hobbs *et al*., 2008). Growing concerns over soil degradation have driven international policies in favor of conservation farming. The connection between soil carbon sequestration, global warming and the role of conservation agriculture (CA) is now widely acknowledged by agricultural policymakers (Kimble *et al*., 2016).

CA contributes to climate change adaptation by strengthening the resilience of cropping systems, making them less susceptible to extreme climatic conditions. Enhanced soil structure and increased water infiltration capacity help mitigate flooding and soil erosion following intense rainfall events. Additionally, higher soil organic matter (SOM) levels improve the soil's water-holding capacity, ensuring crop sustainability during drought periods (Bhattacharya *et al*., 2020; Kumar *et al*., 2020). Compared to conventional agriculture, crop yield fluctuations under CA are less severe during extreme weather conditions.

Furthermore, CA helps combat climate change by reducing greenhouse gas (GHG) emissions, such as carbon dioxide and nitrous oxide, through lower fossil fuel consumption and the elimination of crop residue burning, while also promoting long-term soil organic carbon (SOC) sequestration (Parihar *et al*., 2016). In paddy cultivation, adopting no-till practices and efficient water management significantly decreases the emission of GHGs, such as methane and nitrous oxide.

Challenges and Limitations

Although, the challenges of adopting Conservation Agriculture are multiple in India, targeted policy reforms, farmer education, technology development and research support will be able to unlock its full potential. The process of scaling up CA should be multi-stakeholder and involve government agencies, research institutions, agribusinesses and farmer organizations.

By addressing residue management issues, improving financial accessibility, strengthening extension services, and developing region-specific CA models, India can successfully integrate CA into mainstream farming practices, ensuring long-term food security, environmental sustainability and economic benefits for farmers.

Although, CA has a number of agronomic and environmental advantages, its adoption in India continues to be hindered by a number of technical, economic and institutional constraints. Although, CA has been implemented in some areas with success, the large-scale adoption of CA remains somewhat restricted due to the following key challenges:

Residue Management issues

One of the major barriers to CA adoption in India, especially in rice-wheat cropping systems of the Indo-Gangetic Plains, is crop residue management.

Paddy straw and wheat stubble are left in large quantities after harvest. In the absence of proper residue management techniques, farmers burn crop residues, resulting in air pollution (stubble burning), loss of organic matter, and greenhouse gas emissions.

Mechanized options like Happy Seeder, Super Seeder, and Straw Management System (SMS) attachments can help to incorporate residues without burning but the high costs and limited access restrain their wide adoption. Residue retention can sometimes lead to nitrogen immobilization, affecting crop nutrition and may harbor pests and diseases if not managed properly.

High Initial Costs and Knowledge Gap

The adoption of CA is hindered by investment costs in new machinery, training and inputs among smallholder farmers.

The zero-till drill, residue management tools and precision planter involve substantial upfront investments, which marginal farmers cannot afford. Many farmers lack awareness of the CA principles, its benefits and best practices. Inadequate extension services, demonstration programs, and farmer training slow down the adoption rate.Subsidies and supports under government initiatives in CA are not uniformly accessible for resource-poor farmers, increasing the hurdles towards transition.

Weed and Pest Management difficulties

Weed population increases significantly during reduced tillage because it occurs without disturbance in the soil mass, requiring integrated weed control plans.

CA farmers have been known to primarily rely on chemical herbicides, such as glyphosate, for weed management. This increases the input cost and the chances of developing resistance. Continuous mulching cover and crop residues alter pest and pathogen life cycles. At times, this increases the infestation of stem borers, termites and soil-borne pathogens. The CA system is threatened by the resultant weed pressure and pest attacks. Biological controls, cover cropping, crop rotation, and eco-friendly herbicides have to be promoted.

Limited Suitability in certain Agro-Climatic Zones

CA principles do not apply uniformly across all regions due to variation in soil type, rainfall pattern and cropping systems.

In regions with low biomass production, maintaining adequate residue cover is difficult.In high-rainfall or coastal regions prone to waterlogging, zero tillage can impede drainage and affect crop growth.Many Indian farmers have small and fragmented landholdings, which are not amenable to mechanized CA practices.

Policy and Institutional barriers

Although, CA is aligned with India's sustainability goals, there are gaps in policy support, research focus and institutional coordination.

Conventional agriculture enjoys heavy subsidies on fertilizers and irrigation, whereas CA lacks proper policy support for its large-scale adoption. CA knowledge dissemination through KVKs, agricultural universities, and farmer cooperatives needs to be strengthened.Despite the fact that some states (Punjab and Haryana) have advocated for zero-tillage wheat, there is no integrated national-level strategy for the promotion of CA.

Future Prospects and Recommendations

Eventhough, there are challenges, the potential of CA to enhance Indian agriculture's sustainability, productivity, and climate resilience is tremendous. To speed up its adoption, the following policies and support systems should be further strengthened:

Government Policies and Support Systems

Financial incentives for CA equipment: Subsidies, low-interest loans and rental services for the necessary CA machinery, such as Happy Seeder, Zero-Till Drills and Mulchers, can be provided to smallholder farmers to shift towards CA.

CA should be included in schemes like PM-KISAN, National Mission for Sustainable Agriculture (NMSA), and Rashtriya Krishi Vikas Yojana (RKVY) to promote its wider adoption.CA and the linking of farmers to carbon trading programs can also generate additional incomes.

Farmer Awareness and Capacity Building

Workshops, field demonstrations and farmer schools through KVKs, ICAR institutes and NGOs can be planned to enhance the awareness.Selection and training progressive farmers as CA ambassadors will encourage peer-to-peer learning and facilitate faster adoption. Universities and colleges must develop curricula on CA to prepare the next generation of agronomists and extension workers

Facilitating IWM Developing environment-Friendly alternatives for Herbicides

Crop diversification and cover cropping to control weeds through natural meansUtilizing precision agriculture tools to target pests, thus minimizing excessive pesticide use.

Adoption of CA Models Specific to different Agro-Climatic Regions

Research should focus on designing customized CA strategies for different soil types, rainfall patterns and cropping systems. Engaging farmers in on-field experiments will help refine CA techniques for diverse conditions.

Strengthening research and Technology development

Advancing no-till seed drills and precision planting equipment to improve efficiency.Exploring biochar and organic soil amendments to enhance carbon sequestration. Developing digital tools and mobile apps for real-time CA recommendations for farmers.

Conclusion

CA, thus, offers a paradigm shift into increasing agricultural productivity without loss of ecological balance. Its three basic principles—minimum soil disturbance, permanent soil cover and crop diversification—can be used as sustainable means for increasing crop yield, soil health, and carbon sequestration in Indian agricultural systems. Since the risk of soil degradation is increasing and the looming threats of climate change and dearth of natural resources are taking the maximum toll, CA can easily transform traditional farming, making Indian agriculture more resilient, productive, and environmentally efficient.

Conserving Agriculture is the only option available for India for long-term sustainability and resilience under the changing climate scenario. Collaborative efforts from policymakers, researchers, extension agencies, agribusinesses and farmers would help India succeed in the more productive, sustainable and climate-resilient agricultural future that it strives to achieve.

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