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Conservation agriculture and its impact on soil health and yield: A Review

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Abstract

Conservation Agriculture (CA) has emerged as a sustainable and resource-efficient cropping system based on three key principles: minimum soil disturbance, permanent soil cover and diversified crop rotations. These fundamental principles synergize to enhance the quality of the soil and the long-term sustainability of agricultural production. This review highlights the research results on the effect of CA on the soil health, and crop yield within various agro-ecosystems. It has been shown that CA strongly improves physical properties of the soil through enhanced aggregation, porosity and water infiltration and decreased bulk density and compaction. Soil chemical properties are also enhanced, with increased soil organic carbon (SOC) and improved nutrient availability and cation exchange capacity (CEC). Furthermore, CA enhances soil biological activity by increasing microbial biomass, enzyme activity and biodiversity, hence contributing to nutrient cycling and soil fertility. One of the major advantages of CA is its contribution to carbon sequestration, as reduced tillage and residue retention enhance soil organic matter content and mitigate greenhouse gas emission. CA enhances water use efficiency through conservation of soil moisture and reduction in evaporation losses and this attribute is considered to be the best particularly under drought and rainfed conditions. The effect of CA on crop yield might fluctuate at start with but long-term adoption generally leads to an increase in yield stability and resilience to climatic stress. However, a number of challenges such as residue management, weed control, high initial cost and limited awareness among farmers hinder its widespread adoption. Taken as a whole, CA provides a realistic means to enhance soil health, maintain crop productivity and foster climate-resilient agriculture.

Keywords: Conservation agriculture, soil health, soil organic carbon, crop yield, carbon sequestration, water-use efficiency, soil microbial activity

Introduction

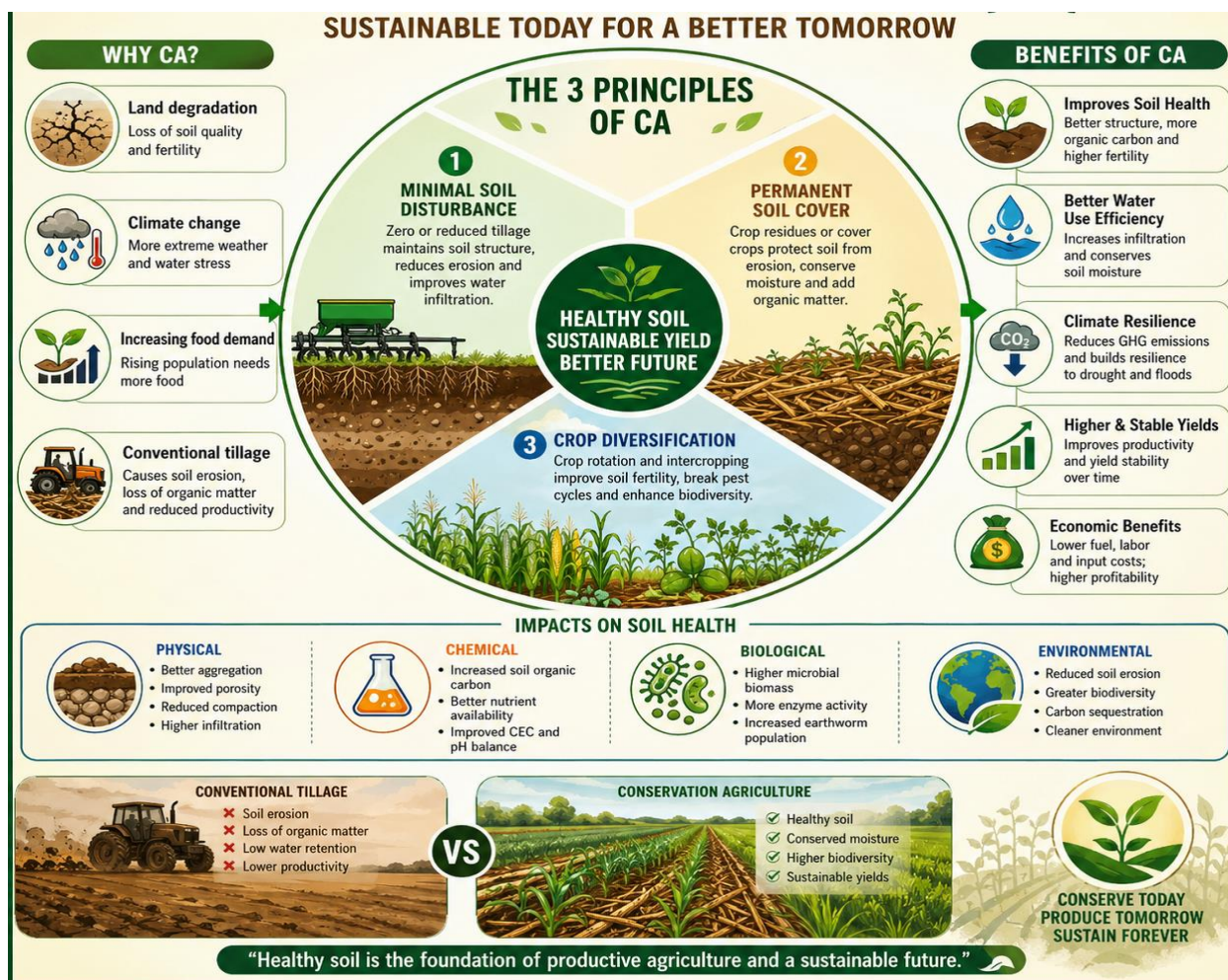
The agriculture sector is facing its own set of complex and interrelated problems, including land degradation, diminishing soil fertility, climate change and growing demand for food due to the increasing global population. Decades of adoption of unsustainable agricultural practices, including intensive tillage, overuse of chemicals and monoculture farming, have substantially degraded the quality of soil. These methods have "accelerated erosion, lowered soil organic matter, compromised soil structure and led to a reduction in productivity and environment quality". Also, climate change has increased the occurrence of extreme weather events, such as droughts, floods and temperature variations, posing even greater risks to agricultural sustainability and food security (Matisic *et al.*, 2024; Verma *et al.*, 2024; Basheer *et al.*, 2024)^[4, 36, 55].

Hence, Conservation Agriculture (CA) has been recognized as a suitable and sustainable approach to mitigate these formidable challenges. CA relies on three basic tenets: minimum disruption of the soil, continuous soil cover and crop diversification. Limit soil disturbance, which is commonly accomplished by no-till or reduced tillage, to preserve soil structure, prevent erosion and retain soil moisture. Continuous soil coverage, by means of crop residues or cover crops, shields the soil surface from erosive forces, has weed-suppressing properties and can increase soil organic matter. Crop diversification through rotations and or intercropping contributes to nutrient cycling, disrupt pest and disease cycles and makes the system more

resilient (Kassam *et al.*, 2019; Jat *et al.*, 2020) [26, 29].

These mechanisms are synergistic and lead to improved physical, chemical, and biological soil conditions. With time, CA practices contribute to the enhancement of soil health, water use efficiency and biodiversity. Consequently, they

promote sustainable crop production with little or no damage to the environment. Hence, the Conservation Agriculture is being considered as an effective approach for ensuring long-term sustainability of agriculture and its resilience to the global challenges (Teng *et al.*, 2024; Thapa *et al.*, 2024) [49, 50].



2. Concept and Principles of Conservation Agriculture

Conservation agriculture (CA) is an innovative, sustainable and productive system for crop production that contributes in enhancing soil health, crop productivity and environmental sustainability. It is based on three basic tenets: minimum mechanical soil disturbance, maintenance of a permanent soil cover and diversification of crops. These act synergistically to establish a robust and resilient agriculture that can be functionally sustainable over time (Kumar *et al.*, 2023; Francaviglia *et al.*, 2023) [21, 32]. Minimal disturbance of the soil (usually by practicing zero or reduced tillage) conserves the soil structure and avoids the disruption of soil aggregates. This reduces runoff and increases water infiltration into the soil, conserving soil moisture.

The limited disturbance also protects beneficial soil organisms, including the microbes and earthworms that are essential for nutrient cycling and soil fertility (Pittelkow *et al.*, 2015) [39]. Permanent soil cover (via retention of crop residues and/or use of cover crops) serves as a blanket over the soil. This blanket reduces losses through evaporation, buffers soil temperature, limits weed infestations and plays a role in the enhancement of soil organic matter. With increasing organic matter, soil fertility and water-holding capacity are greatly improved (Mulumba *et al.*, 2023). Crop diversification (i.e. through crop rotations, intercropping) promotes biodiversity within the farming system.

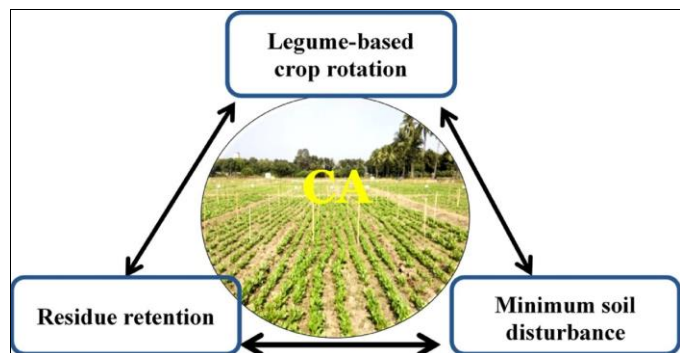
It enhances efficiency of nutrient use, interrupts cycles of pests and diseases and decreases dependency on synthetic fertilizers and pesticides (Tamburini *et al.*, 2020) [38, 48].

3. Global and Indian Scenario of Conservation Agriculture

Conservation Agriculture (CA) has witnessed an increasing trend globally for the past few decades and is now practiced on millions of hectares in the world across different agro-ecological zones. CA adoption has been the highest in countries such as the United States, Brazil and Australia, mainly as a result of strong policy support, high level of mechanization and awareness among farmers. In these areas, CA has been successfully adapted to commercial farming systems, resulting in better soil protection, water-use efficiency and high quality non-crisis food production. Zero tillage and the literature knowledge on residue retention have a significant influence on the reduction of soil degradation and on production inputs and cost and crop yields may be preserved or improved through time of adoption (Derpsch *et al.*, 2010; Kassam *et al.*, 2022) [16, 29].

In India too, Conservation Agriculture (CA) is gaining ground, especially in the Indo-Gangetic Plains rice-wheat system where already the bulk of the world population feeds itself. Availability of technologies like zero-till seed drills and Happy Seeder machines, the seed drill with an integrated straw distribution system is helping farmers to more readily adopt CA practices.

Studies in Indian conditions reveal that CA enhances soil fertility by improving soil organic carbon, nutrient availability and biological activity. This also helps reduce input expenses and increases farm profitability by conserving fuel, labor and irrigation water (Korav *et al.*, 2022)^[31].



4. Soil Health: Concept and Indicators

Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plant and animal productivity, supports environmental quality, and maintains ecosystem stability and resilience (Karlen *et al.*, 1997). It plays equal importance in sustainable agriculture as well, because healthy soils enable effective nutrient cycling, water regulation and biological activity. Soil health is most often assessed by a suite of physical, chemical and biological parameters that reflect different functions of the soil system (Doran and Zeiss 2000; Bongiorno *et al.*, 2026)^[18, 19, 27].

- Bulk density, porosity, aggregation and water infiltration rate are included in the physical indicators. These features govern the soil structure and aeration, as well as the soil's capacity to hold and move water. Soils that aggregate well with sufficient porosity support adequate root growth and minimize erosion and compaction (Karlen *et al.*, 1997)^[27].
- Chemical factors include soil pH, availability of nutrients (e.g. nitrogen, phosphorous and potassium) and cation exchange capacity (CEC). They affect the retention of

nutrients and availability to plants. Balanced soil pH and an adequate supply of nutrients are crucial for good crop growth and yield (Havlin *et al.*, 2020)^[23].

- Biological indicators are microbial biomass, enzyme activity and earthworm abundance. These living elements are important to organic matter digestion, nutrient cycling and the shaping of soil structure. Biological activity is typically considered an indicator of a fairly healthy and productive soil ecosystem (Smith *et al.* 2015)^[47].

5. Impact of Conservation Agriculture on Soil Physical Properties:

Conservation Agriculture (CA) is also known to contribute to improvement of soil physical properties, which are essential to maintain crop growth and productivity in the long term. Among the major CA practices reduced or zero tillage is the practice that least disturbs the soil and ensures maximum protection of the soil fabric. Contrary to traditional tillage which destroys soil aggregates and can cause compaction over time minimal tillage preserves soil porosity and limits hard pan development. This promotes root growth and the movement of air and water in the soil profile (Hobbs *et al.*, 2008;)^[24].

Residue retention, in which the crop residues are retained on the soil surface rather than removal and or burnt, is another vital factor in CA. It is a natural way to obtain well-aggregated soil because aggregation of soil particles is enhanced by organic matter. Good aggregation also increases soil stability, which reduces the potential for erosion by wind and rain. The uniform cover of residues also attenuates the impact of raindrops on the soil surface, thereby decreasing the extent of surface sealing and crusting (Six *et al.*, 2008)^[46].

Due to these changes, CA soil brought about better water infiltration and less surface runoff. With increased infiltration, more water is made available to the soil for use by plants. In addition, better soil structure and greater organic matter results in higher waterholding capacity of special relevance in arid and semiarid regions. In general, these almost physical changes, lead to stability of soils and less degradation and higher agricultural production in long term (Rockstrom *et al.* 2010)^[44].



6. Impact on Soil Chemical Properties

The enhancement of soil chemical properties under Conservation Agriculture (CA), a set of soil and crop management practices, is of high importance in the context of soil fertility and crop growth. Among the various advantages, increasing SOC is one of the most relevant benefits attributed to CA. Practices such as minimum tillage and maintenance of plant residues on the soil surface contribute to reducing oxidation of organic matter and favour its recovery inside the land. Increased SOC results in improved soil fertility, enhanced nutrient availability and better soil structure (West and Post, 2002) [56].

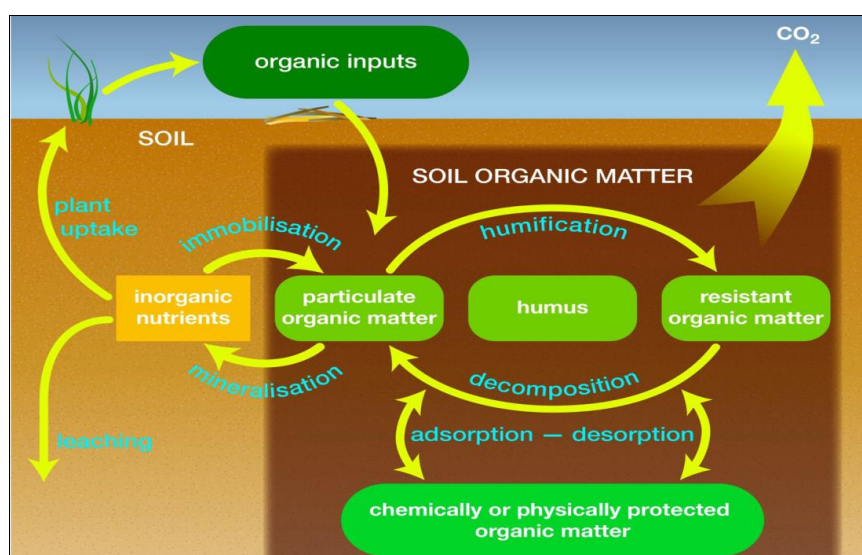
Leftover residues of organic material on soil surface also contribute significantly to nutrient cycling. Nutrients like nitrogen, phosphorus and potassium are released as these residues break down on or in the soil and they are taken up by plants. This natural recycling of nutrients tends to minimize losses of nutrients and balance the nutrients within the soil system. From this, it follows that the nutrient supply becomes more sustainable compared to conventional systems over the time (Brady and Weil, 1996; Dinesh *et al.*, 2024; Bhardwaj *et al.*, 2023) [5, 9, 18].

What is more, CA enhances the cation exchange capacity (CEC), soil nutrient retention and supply to plants. Increased CEC allows an essential nutrients to be less susceptible to leaching, leading to an enhancement of nutrient-use efficiency. CA is also beneficial for retaining balanced soil pH for good nutrient availability and microbial activities.

7. Impact on Soil Biological Properties

Biological activity in the soil is strongly stimulated in Conservation Agriculture (CA), consequently it is considered as a major factor for enhanced soil quality and ecosystem services. The left over crop residues and minimal soil disruption also result in the formation of a stable and favourable micro-environment for the soil microflora. In contrast to traditional tillage practices, which are disruptive to microbial and soil fauna communities, CA allows for a sequence of inputs that are organic, continuous and enablers of biological diversity (Gupta *et al.*, 2022) [2].

The “digestible” substrates provided by organic residues on the soil surface are the main source of energy for soil microbes and result in increasing soil microbial biomass and activity. These organisms, namely bacteria and fungi, are crucial for breaking down organic matter and releasing nutrients in a form that plants can take up. Enzyme activity is also stimulated under CA, promoting the biochemistry of nutrient mineralization and the degradation of organic matter (Lori *et al.*, 2017; Gupta *et al.*, 2022) [22, 35]. Along with bacteria, organisms like earthworms and other soil fauna flourish in CA. Earthworms are essential for enhancing soil porosity, since they are agents of bioturbation that improve aeration and water infiltration. Their feeding also contributes to mixing organic material with mineral soil, which further supports nutrient cycling and soil aggregation (Briones *et al.*, 2017; Blanchart *et al.*, 1999) [6, 10].



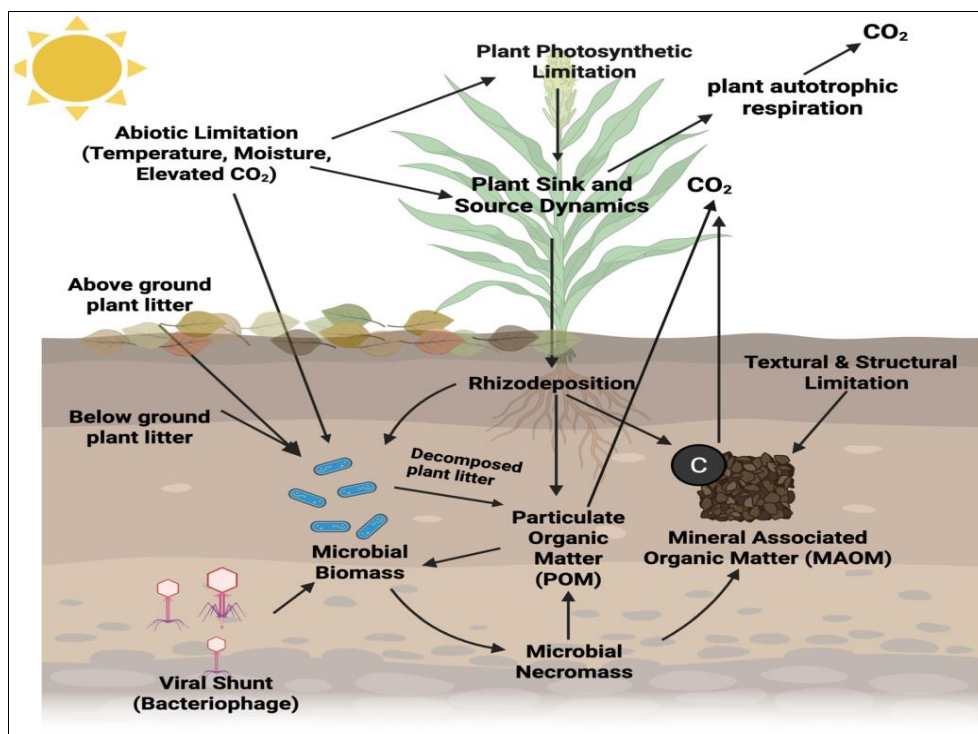
8. Soil Organic Carbon and Carbon Sequestration

Enhancement of soil organic carbon (SOC) storage, which is an essential attribute of soil health and a critical parameter for evaluating soil quality is one of the largest benefits of CA. Low-disturbance tillage practices decrease tillage-induced mineralization of organic matter by limiting soil disturbance and exposure of organic matter to oxidation. As a result, the combination of soil inversion burial with application of organic matter on the soil surface plus retention of crop residues on the soil surface can be credited with gradual soil C build-up (Minasny *et al.*, 2017) [37].

Several soil properties are enhanced by the increase of SOC, such as nutrient content, water holding capacity and soil structure. Increased organic carbon content results in higher

retention of vital elements in the soil as well as increased microbial activity, leading to more active circulation of nutrients. This system increases soil fertility, thus crop yields improve with passages of time (Purakayastha *et al.*, 2024; Chang *et al.*, 2024) [13, 42].

Accumulation of SOC under CA is also essential for climate change mitigation besides soil productivity. Conservation agriculture (CA) croplands reduce greenhouse gas (GHG) emissions by conserving and sequestering carbon in the soil instead of releasing it into the atmosphere. This is part of a process called carbon sequestration, and it helps counterbalance emissions from farming and supports efforts to mitigate climate change.

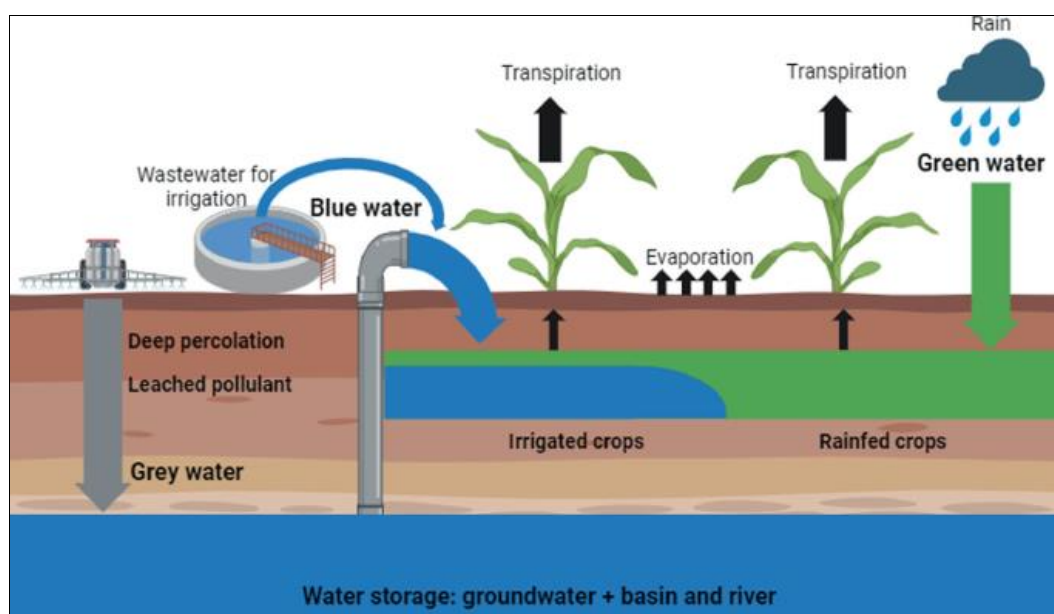


9. Water Use Efficiency and Soil Moisture Management

The Conservation Agriculture (CA) has an important role to play in raising water-use efficiency for sustainable crop production, particularly under condition of water scarcity. Improved infiltration and soil water conservation are two additional mechanisms by which CA systems increase water use efficiency. Reduced and no-tillage practices preserve the physical integrity of the soil, enabling better infiltration of water and greater water retention in the soil profile. This reduces water loss in runoff and more water can be taken up by plants (Kassam, 2013; Thierfelder *et al.*, 2015) [28, 29, 51]. The retention of crop residues on the soil surface serves as a protective mulch, which significantly decreases evaporation loss. This mulch cover further regulates soil temperature, protecting the soil from overheating and reducing moisture lost in hot weather. In

addition, residue cover on the soil surface also shields the soil from the impact of raindrops, which helps in maintaining soil structure and reduce surface sealing, enhancing infiltration rates (Verhulst *et al.*, 2010; Jat *et al.*, 2022) [25, 54].

These advantages are critical in rainfed and drought-susceptible regions wherein water is commonly the most limiting aspect of crop production. CA allows crops to better resist water stress and erratic rainfall by preserving soil moisture and increasing water availability. Increased water-use efficiency leads to stable crop yields and increased climate variability resilience in the long term. Therefore, CA in general is a promising approach for enhancing water use and maintaining the productivity of rainfed systems in arid and semi-arid areas (Thierfelder *et al.*, 2015; Jat *et al.*, 2020) [26, 51].



10. Impact on Crop Yield

Climate, soil type, cropping system and management practice all influenced the effect of conservation agriculture (CA) on crop yield. Crop yields with CA during the dryland adoption years can be sustained or occasionally be slightly reduced. This effect is transitory and it is primarily associated with the fact that the soil ecosystem goes through a transition phase where it adjusts to the reduced tillage, residue retention and alteration of nutrient dynamics. Differences in residue decomposition rates, transient immobilization of nitrogen, or weed pressure have also been mentioned as causes of these short-term variations (Ahmed *et al.*, 2024; Purakayastha *et al.*, 2024) ^[2, 42]. Yet, with the continuation of CA activities over time, the system starts to stabilize and provide substantial positive yield returns. Enhanced soil structure, SOC content, and biological activities allow for improved nutrient availability and uptake. Simultaneously, enhanced soil moisture conditions and water use efficiency favor crop growth, particularly in drought or erratic precipitation environments. The long-term application of CA usually results in higher yield stability even when the environmental condition is unfavourable. Crops grown under CA systems are generally more resilient to climatic stresses such as drought, heat, and excessive rainfall. This resistance decreases the year-to-year variability in yields and leads to more jective production (Lal, 2020; Thierfelder *et al.*, 2015) ^[33, 51].

11. Yield Stability and Climate Resilience

Conservation Agriculture (CA) is an important factor for climate resilience of agriculture systems, particularly under acute climate perturbations. CA naturally promotes better soil structure as a result of less soil disturbance and more organic matter input, resulting in a more stable and well aggregated soil profile. This new texture increases the porosity and allows better infiltration and retention of water which is important in an environment characterized by intermittent rain or long dry seasons (Blanco-Canqui *et al.*, 2020) ^[7].

The retention of crop residue on the soil surface also contributes to increasing this resilience as a form of a mulch layer. It moderates soil temperature and reduces evaporation and contributes to a more uniform soil moisture supply. Therefore, under CA practice, soil moisture is available to the plants for an extended period of time even in dry spells. This increased water availability leads to improved growth and crop yield stability (Demo and Bogale, 2024; Ramos *et al.*, 2024; Adak *et al.*, 2023) ^[1, 15, 43].

12. Environmental Benefits of Conservation Agriculture

Conservation agriculture (CA) has a broad range of attendant positive environmental effects that make a substantial contribution to sustainable land management and the stability of ecosystems. One of the major benefits is the prevention of soil erosion. Conserving agriculture products system integrity due to reduction of soil disruption as well as soil working under high moisture together with any sort of soil cover (i.e. crop residues or even cover crops) defends soil surface through wind and rain impacts. As a result, topsoil, full of nutrients and vital to growing plants is preserved. CA is also positively impacted in relation to above ground and below017019ground diversity. The combination of organic residues and reduced disturbance affords an excellent environment for soil organisms such as bacteria, insects and earthworms. Positive effects on ecosystems, such as increased biodiversity, lead to improved nutrient cycling and natural pest control, enabling farmers to rely less on chemicals (Tian *et al.*, 2024; Chand *et al.*, 2023) ^[52].

Yet another environmental advantage of CA is that it contributes substantially to diminishing greenhouse gases. Tillage can also reduce fuel use, as soil organic carbon (SOC) increases through residue retention which promotes carbon sequestration. This contributes to climate change mitigation by sequestering carbon from the atmosphere and storing it in the land (Fagodiya *et al.*, 2024; Cariappa *et al.*, 2024) ^[11, 20].

13. Economic Benefits

The economic benefits of Conservation Agriculture (CA) are significant, making it an appealing choice for farmers aiming for sustainable and cost-effective production systems. Reduction of production costs is one of the major benefits of CA. Through reduction or elimination of tillage, CA drastically reduces need for fuel, labor, and use of machinery. This not only reduces the operational costs but also the maintenance costs of agriculture machinery, which are high and can be decreased with less use of farm machines (Lorenzetti and Fiorini, 2024) ^[34]. Moreover, CA contributes to the decrease of intensive and repeated field operation like ploughing, harrowing and levelling, all time - and money - demanding activities. Leaving crop residues on the surface and improving soil quality may also facilitate moisture conservation, which may reduce irrigation needs and related costs. Moreover, enhanced nutrient cycling under CA systems may help reduce reliance on synthetic fertilizers over time (Pramanick *et al.*, 2024) ^[41]. While early adoption of CA may necessitate purchase of specialized equipment such as zero-till seed drills or residue management machinery, the initial cost is typically recouped through savings and increased efficiency. Gradually, soil fertility, water-use efficiency, and crop productivity are improved, leading to higher and more stable yields and farm profitability in general (Dey *et al.*, 2024) ^[17].

14. Challenges in Adoption of Conservation Agriculture

However, CA also has some practical and socio-economic challenges that hinder its widespread adoption, especially by smallholder farmers. In many traditional farming systems, crop residues are fed to livestock or used as fuel, so that it is difficult to maintain enough residues on the field for ground cover. Improper residue management can also affect the planting process if suitable equipment is not available. Weed management is also a significant issue with CA systems. Reduced tillage can lead to increased weed pressure initially as the seeds of weeds stay close to soil surface. This usually requires a more dependence on herbicides, particularly during the transition phase, which can bring about more cost and thus a lot of management to prevent environmental damage (Barberi *et al.*, 2025) ^[3].

The need for specialized equipment, such as zero-till seed drills and residue management gear like Happy Seeders is yet another obstacle. These equipment may be costly or unavailable for all farmers, mainly in developing countries. Custom hiring centers and subsidies can assist with this, but access is inconsistent (Porwal *et al.*, 2023) ^[40]. Awareness and technical knowledge are a critical barrier as well. Conservation Agriculture is a new concept for most of the farmers, who also sometimes are not properly trained in its application. Adoption rates are low due to insufficient extension services and demonstrations. 5) Initial yield variability in the transition period may discourage farmers from continuing CA. Overcoming these challenges through appropriate policy support, farmer awareness, technological development, and financial incentives will be key in facilitating further adoption of Conservation Agriculture.

15. Research Gaps and Future Needs

Additional investigations are required to improve the efficiency and serve as the basis for scaling up of CA in different agro-ecosystems. A high priority is the establishment of long-term field trials. As several advantages of CA (e.g., increased soil organic carbon, soil structure and soil biological activity) only become more apparent with the passage of time, long-term experiments are required to properly evaluate the sustainability, productivity and environmental implications of CA under various climatic and soil conditions.

- The formulation of CA practices for specific regions also remains a key topic of research. Agricultural systems differ dramatically in soil type, rainfall patterns, cropping systems, and socio-economic context. Hence, site-specific advice is necessary for the adaptation of CA techniques to local conditions to make them suitable and viable for local farmers (Deibler, 2025)^[14].
- The homogenization of soil health indicators also matters'. Although many physical, chemical, and biological indicators have been proposed for evaluating soil health, there is not yet a commonly accepted, practical framework that allows for the integrative evaluation and comparison of studies across different regions. This will facilitate more effective monitoring of CA effects and for policy guidance.
- Integration of CA with precision agriculture and digital technologies is another area rich in potential. Technology like remote sensing, GIS, sensors and data-driven decision making can contribute to better resource use efficiency, input application and crop management under the CA programmes (Bongiorno *et al.*, 2026)^[8].
- These research activities will synergistically advance the scientific basis of CA, increase its flexibility and expedite its adoption on a large scale for sustainable agriculture.

16. Future Prospects

The prospects of Conservation Agriculture (CA) are associated with that of futuristic, evolving agricultural tools enabling greater productivity, precision and sustainability. With the advent of precision farming, remote sensing, and artificial intelligence (AI), these techniques are expected to significantly improve real-time monitoring of soil condition, crop status, and moisture content, revolutionizing CA. Application of precision-farming solutions, including global positioning system (GPS)-based machinery and variable rate technology (VRT), results in more efficient use of resources such as water, fertilizers, and pesticides with reduced environmental impact and increased production (Zhang and Kovacs, 2012)^[57].

Remote sensing, such as satellite and drone technology, can also reveal insights regarding crop performance, soil moisture availability, and nutrient deficiencies. These tools enable CA farmers to make decisions and manage their fields more successfully. In the same way, model and decision-support system based on AI can process huge amount of data to best fit planting date, irrigation and nutrient management, etc., to enhance the system as a whole (Shamshiri *et al.*, 2024)^[45].

Strong policy support is also crucial to encourage CA adoption alongside technological progress. Policy interventions such as subsidies on CA machinery, support on sustainable practices and funding on research and services may promote transition to such methods. Farmer education and capacity-building initiatives are of equal significance to facilitate effective comprehension and application of CA principles (van Asseldonk *et al.*, 2023)^[53]. With the combined support of technology, policy, and education, Conservation Agriculture has the

potential to become a cornerstone of sustainable agriculture. It offers a promising pathway for enhancing productivity, conserving natural resources and building resilience against climate change.

17. Conclusion

Conservation agriculture (CA) has become a widely accepted and sustainable mean to enhance soil quality and support relatively stable crop productivity over time. CA improves key soil properties, including soil structure, fertility and biological activity, by shifting the focus on minimal soil disturbance, continuous soil cover and crop diversification. Enhanced soil structure stimulates root development, water infiltration and aeration, while high soil organic matter leads to increased nutrient availability and water holding capacity. Simultaneously, high biological activity also promotes efficient nutrient cycling, which is important for the functioning of the soil ecosystem. These changes are responsible for increased productivity and more resilient cropping systems, particularly in the face of climatic variability and resource limitations. CA practices have greater potential to mitigate prevailing environmental stresses more effectively in the long term such as drought, intermittent rainfall and extreme temperatures, thus leading to more stable and dependable yields. While challenges exist, such as yield variability in the short-term, residue management issues and knowledge and equipment requirements, the long-term benefits of CA far exceed these constraints. On a business level they can benefit from reduced input costs as there are less fertilizer requirements and the process helps improve and maintain the soil fertility. In summary, Conservation Agriculture is a potential approach for sustainable agricultural development. It strengthens both the production of food and the conservation of environment, climate change mitigation and the ultimate goal of food security for world.

References

1. Adak S, Bandyopadhyay K, Purakayastha TJ, Sen S, Sahoo RN, Shrivastava M, *et al.* Impact of contrasting tillage, residue mulch and nitrogen management on soil quality and system productivity under maize-wheat rotation in the north-western Indo-Gangetic Plains. *Front Sustain Food Syst.* 2023;7:1230207.
2. Ahmed MS, Nasrin S, Halder M. Does the presence of mineral nutrient enhance the carbon sequestration, soil aggregation, and microbial biomass in the subtropical clay soil? *Discover Soil.* 2024;1(1):10.
3. Barberi P, Carlesi S, Leoni F. Weed management in organic conservation agriculture systems. In: *Weed management in conservation agriculture systems*. Cambridge, UK: Burleigh Dodds Science Publishing; 2025. p. 237-267.
4. Basheer S, Wang X, Farooque AA, Nawaz RA, Pang T, Neokye EO. A review of greenhouse gas emissions from agricultural soil. *Sustainability.* 2024;16(11):4789.
5. Bhardwaj AK, Malik K, Rani M, Mandal UK, Basak N, Singh A, *et al.* Residue recycling options and their implications for sustainable nitrogen management in rice-wheat agroecosystems. *Ecol Process.* 2023;12(1):53.
6. Blanchart E, Albrecht A, Alegre J, Dubois A, Gilot C, Pashanasi B, *et al.* Effects of earthworms on soil structure and physical properties. In: *Earthworm management in tropical agroecosystems.* 1999;5:149-171.
7. Blanco-Canqui H, *et al.* Soil structure and organic matter interactions in conservation systems. *Soil Tillage Res.* 2020;199:104585.

8. Bongiorno G, Wesselink M, Van Den Berg W, Bai Z, De Goede R, Ferreira CSS, *et al.* Selecting promising soil quality indicators for monitoring soil management effects based on 10 European long-term field experiments. *J Plant Nutr Soil Sci.* 2026.
9. Brady NC, Weil RR. The nature and properties of soils. 1996.
10. Briones MJJ, Schmidt O. Conventional tillage decreases the abundance and biomass of earthworms and alters their community structure in a global meta-analysis. *Glob Change Biol.* 2017;23(10):4396-4419.
11. Cariappa AA, Konath NC, Sapkota TB, Krishna VV. Evaluating the potential and eligibility of conservation agriculture practices for carbon credits. *Sci Rep.* 2024;14(1):9193.
12. Chandra P, Khippal AK, Prajapat K, Barman A, Singh G, Rai AK, *et al.* Influence of tillage and residue management practices on productivity, sustainability, and soil biological properties of rice-barley cropping systems in Indo-Gangetic Plain of India. *Front Microbiol.* 2023;14:1130397.
13. Chang F, Yang W, Wang S, Yin L, Deng X. Long-term optimization of agronomic practices increases water storage capacity and available water in soil. *Agronomy.* 2024;14(10):2286.
14. Deibler LK. From aspiration to action: a multi-country analysis of agroforestry adoption and household welfare among smallholder farmers in Sub-Sahara Africa. 2025.
15. Demo AH, Asefa Bogale G. Enhancing crop yield and conserving soil moisture through mulching practices in dryland agriculture. *Front Agron.* 2024;6:1361697.
16. Derpsch R, Friedrich T, Kassam A, Li H. Current status of adoption of no-till farming in the world and some of its main benefits. *Int J Agric Biol Eng.* 2010;3(1):1-25.
17. Dey S, Abhishek K, Saraswathibatta S, Singh PK, Kuntamalla S, Bommaraboyina PR, *et al.* Impact of zero tillage maize. 2024.
18. Dinesh GK, Sharma DK, Jat SL, Venkatramanan V, Boomiraj K, Kadam P, *et al.* Residue retention and precision nitrogen management effects on soil physicochemical properties and productivity of maize-wheat-mungbean system in Indo-Gangetic Plains. *Front Sustain Food Syst.* 2024;8:1259607.
19. Doran JW, Zeiss MR. Soil health and sustainability: managing the biotic component of soil quality. *Appl Soil Ecol.* 2000;15:3-11.
20. Fagodiya RK, Singh A, Prajapat K, Chandra P, Malyan SK, Verma K, *et al.* Conservation agriculture practices for carbon sequestration and greenhouse gas mitigation. In: *Waste management for sustainable and restored agricultural soil.* Academic Press; 2024. p. 323-343.
21. Francaviglia R, Almagro M, Vicente-Vicente JL. Conservation agriculture and soil organic carbon: principles, processes, practices and policy options. *Soil Syst.* 2023;7(1):17.
22. Gupta A, Singh UB, Sahu PK, Paul S, Kumar A, Malviya D, *et al.* Linking soil microbial diversity to modern agriculture practices: a review. *Int J Environ Res Public Health.* 2022;19(5):3141.
23. Havlin J, Heiniger R. Soil fertility management for better crop production. *Agronomy.* 2020;10(9):1349.
24. Hobbs PR, Sayre K, Gupta R. The role of conservation agriculture in sustainable agriculture. *Philos Trans R Soc B Biol Sci.* 2008;363(1491):543-555.
25. Jat HS, Choudhary M, Kakraliya SK, Gora MK, Kakraliya M, Kumar V, *et al.* A decade of climate-smart agriculture in major agri-food systems: earthworm abundance and soil physico-biochemical properties. *Agronomy.* 2022;12(3):658.
26. Jat ML, Chakraborty D, Ladha JK, Rana DS, Gathala MK, McDonald A, *et al.* Conservation agriculture for sustainable intensification in South Asia. *Nat Sustain.* 2020;3(4):336-343.
27. Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. Soil quality: a concept, definition, and framework for evaluation. *Soil Sci Soc Am J.* 1997;61(1):4-10.
28. Kassam AH. Conservation agriculture: global prospects and challenges. 2013.
29. Kassam A, Friedrich T, Derpsch R. Global spread of conservation agriculture. *Int J Environ Stud.* 2019;76(1):29-51.
30. Kassam A, Friedrich T, Derpsch R, Kienzle J. Global spread of conservation agriculture. *Int J Environ Stud.* 2022;79(1):1-20.
31. Korav S, Rajanna GA, Yadav DB, Paramesha V, Mehta CM, Jha PK, *et al.* Impacts of mechanized crop residue management on rice-wheat cropping system-a review. *Sustainability.* 2022;14(23):15641.
32. Kumar N, Hashim M, Nath CP, Hazra KK, Singh AK. Pulses in conservation agriculture: an approach for sustainable crop production and soil health. *J Food Legumes.* 2023;36(1):1-9.
33. Lal R. Soil organic matter and water retention. *Agron J.* 2020;112(5):3265-3277.
34. Lorenzetti LA, Fiorini A. Conservation agriculture impacts on economic profitability and environmental performance of agroecosystems. *Environ Manage.* 2024;73(3):532-545.
35. Lori M, Symnackzik S, Mader P, De Deyn G, Gattinger A. Organic farming enhances soil microbial abundance and activity-a meta-analysis and meta-regression. *PLoS One.* 2017;12(7):e0180442.
36. Matisic M, Dugan I, Bogunovic I. Challenges in sustainable agriculture-the role of organic amendments. *Agriculture.* 2024;14(4):643.
37. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, *et al.* Soil carbon 4 per mille. *Geoderma.* 2017;292:59-86.
38. Mulumba LN, Lal R. Mulching effects on soil physical properties and crop productivity. *Soil Tillage Res.* 2023.
39. Pittelkow CM, Liang X, Linquist BA, Van Groenigen KJ, Lee J, Lundy ME, *et al.* Productivity limits and potentials of the principles of conservation agriculture. *Nature.* 2015;517(7534):365-368.
40. Porwal M, Verma B, Jha AK. New and innovative technologies and machinery in conservation agriculture. In: *Climate smart agriculture: principles and practices.* 2023. p. 113-127.
41. Pramanick B, Kumar M, Naik BM, Singh SK, Kumar M, Singh SV. Soil carbon-nutrient cycling, energetics, and carbon footprint in calcareous soils with adoption of long-term conservation tillage practices and cropping systems diversification. *Sci Total Environ.* 2024;912:169421.
42. Purakayastha TJ, Bera T, Dey S, Pande P, Kumari S, Bhowmik A. Biochar aided priming of carbon and nutrient availability in three soil orders of India. *Sci Rep.* 2024;14(1):8420.
43. Ramos TB, Darouich H, Pereira LS. Mulching effects on soil evaporation, crop evapotranspiration and crop

- coefficients: a review aimed at improved irrigation management. *Irrig Sci.* 2024;42(3):525-539.
44. Rockstrom J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, *et al.* Managing water in rainfed agriculture-the need for a paradigm shift. *Agric Water Manag.* 2010;97(4):543-550.
 45. Shamshiri RR, Sturm B, Weltzien C, Fulton J, Khosla R, Schirrmann M, *et al.* Digitalization of agriculture for sustainable crop production: a use-case review. *Front Environ Sci.* 2024;12:1375193.
 46. Six J, Conant RT, Paul EA, Paustian K. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil.* 2002;241(2):155-176.
 47. Smith P, Cotrufo MF, Rumpel C, Paustian K, Kuikman PJ, Elliott JA, *et al.* Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *Soil.* 2015;1(2):665-685.
 48. Tamburini G, Bommarco R, Wanger TC, Kremen C, Van Der Heijden MG, Liebman M, *et al.* Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv.* 2020;6(45):eaba1715.
 49. Teng J, Hou R, Dungait JA, Zhou G, Kuzyakov Y, Zhang J, *et al.* Conservation agriculture improves soil health and sustains crop yields after long-term warming. *Nat Commun.* 2024;15(1):8785.
 50. Thapa S, Shah GA, Xue Q. Soil health and crop management in conservation agriculture. *Agronomy.* 2024;14(10):2291.
 51. Thierfelder C, Rusinamhodzi L, Ngwira AR, Mupangwa W, Nyagumbo I, Kassie GT, *et al.* Conservation agriculture in Southern Africa: advances in knowledge. *Renew Agric Food Syst.* 2015;30(4):328-348.
 52. Tian J, Dungait JA, Hou R, Deng Y, Hartley IP, Yang Y, *et al.* Microbially mediated mechanisms underlie soil carbon accrual by conservation agriculture under decade-long warming. *Nat Commun.* 2024;15(1):377.
 53. van Asseldonk M, Girvetz E, Pamuk H, Wattel C, Ruben R. Policy incentives for smallholder adoption of climate-smart agricultural practices. *Front Polit Sci.* 2023;5:1112311.
 54. Verhulst N, Govaerts B, Verachttert E, Castellanos-Navarrete A, Mezzalama M, Wall P, *et al.* Conservation agriculture, improving soil quality for sustainable production systems. *Adv Soil Sci Food Secur Soil Qual.* 2010:137-208.
 55. Verma S, Singh A, Pradhan SS, Kushuwaha M. Impact of climate change on agriculture: a review. *Int J Environ Clim Change.* 2024;4(3):615-620.
 56. West TO, Post WM. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Sci Soc Am J.* 2002;66(6):1930-1946.
 57. Zhang C, Kovacs JM. The application of small unmanned aerial systems for precision agriculture: a review. *Precis Agric.* 2012;13(6):693-712.