

Conservation Agriculture-Based Cropping Systems for A Pathway of Soil Health Improvement

**Shailendra Pratap Singh^{1*},
C. L. Maurya²,
Kaushal Kumar³,
Sarvesh Kumar⁴**

¹Teaching Associate,
Department of Soil Conservation
and Water Management,
Chandra Shekhar Azad
University of Agriculture and
Technology (CSAUA&T),
Kanpur

²Department of Seed Science
and Technology

^{3,4}Professor, Department of Soil
Conservation and Water
Management, Chandra Shekhar
Azad University of Agriculture
and Technology (CSAU),
Kanpur



*Corresponding Author

Shailendra Pratap Singh*

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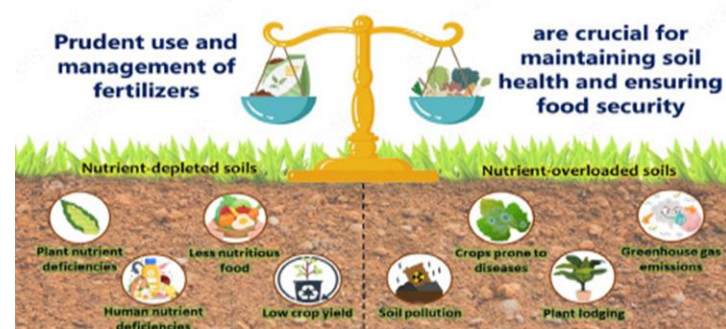
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INTRODUCTION

Agriculture in the 21st century faces complex challenges such as soil erosion, nutrient depletion, declining soil organic matter, and erratic climate patterns. Traditional plough-based agriculture has intensified soil degradation across many regions. Conservation agriculture (CA), recommended by FAO, is increasingly recognized as a promising solution for conserving soil and water resources while maintaining or enhancing crop productivity.

Conservation agriculture-based cropping systems (CACs) integrate CA principles with crop rotations, cover crops, and residue retention. These systems enhance soil biological activity, improve soil structure, and promote eco-friendly farming. CACs not only improve soil health but also enhance water-use efficiency, carbon sequestration, and climate resilience.

Conservation Agriculture (CA) is a paradigm shift in farming, moving away from extractive, intensive conventional methods toward an integrated, resource-efficient approach.¹ It is not merely a set of practices but an agro-ecological management system founded on three core, inseparable principles.² Its primary goal is to achieve sustainable intensification—increasing productivity while simultaneously conserving the soil and natural resources, thereby significantly improving soil health.



3. Defining the Pillars of Conservation Agriculture (CA)

The fundamental strength of CA lies in the synergistic application of its three main principles, which mimic natural ecosystem processes to restore the soil's function as a living system.

3.1. Continuous Minimum Mechanical Soil Disturbance (No-Till/Reduced Tillage)

This principle is the most distinct departure from conventional farming. It advocates for eliminating or significantly reducing the mechanical inversion and mixing of the soil layers (e.g., plowing, harrowing).⁶ The ideal manifestation is Zero Tillage (ZT) or No-Till, where crops are sown directly into the previous crop's residues using specialized seed drills.

Impact on Soil Physical Properties: Tillage disrupts soil aggregates (clusters of soil particles bound together by organic matter).⁷ By minimizing disturbance, CA protects these aggregates, leading to a stable soil structure with continuous, interconnected pores (macropores) created by earthworms and old roots. This structure dramatically improves water infiltration, reduces surface runoff, and lowers the risk of soil compaction and erosion.

Impact on Soil Chemical Properties: Tillage introduces oxygen deep into the soil profile, accelerating the decomposition and oxidation of Soil Organic Carbon (SOC). Reduced tillage slows this process, allowing organic matter to accumulate, particularly in the top layer (0–10 cm). This carbon sequestration is a key benefit, both for soil fertility and for climate change mitigation.⁹

Impact on Soil Biological Properties: Tillage is a physical disturbance that destroys the habitat and network of soil biota (fungi, bacteria, earthworms). No-Till provides a stable environment for these organisms, especially the mycorrhizal fungi critical for plant nutrient uptake, enabling them to perform "biological tillage" that continuously aerates and structures the soil.

4. The Mechanisms of Soil Health Improvement

Soil health, defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans, is actively restored by CA practices. This restoration is observable across the physical, chemical, and biological dimensions of the soil.

4.1. Physical Restoration: Structure and Water Dynamics

The combination of no-till and permanent residue cover is a powerful defense against soil degradation.

Erosion Control: Residues act as a physical buffer, intercepting the impact of raindrops and reducing wind velocity at the soil surface. This

significantly minimizes the detachment of soil particles, controlling both water and wind erosion.

Water Use Efficiency (WUE): The mulch layer reduces evaporation from the soil surface, conserving moisture. Simultaneously, the undisturbed, well-structured soil with increased macropores ensures rapid water infiltration, reducing runoff. The result is a soil that holds more plant-available water, making CA systems inherently more resilient to drought.

4.2. Chemical Enhancement: Carbon and Nutrient Cycling

The increase in Soil Organic Matter (SOM) is the single most important outcome of successful CA adoption.

Carbon Sequestration: Reduced oxidation and continuous carbon inputs from residues and cover crops lead to an increase in SOC stock. This SOC accumulation is central to soil health, as it is the primary source of food for soil microorganisms and a major determinant of soil fertility.

Nutrient Availability: SOM increases the soil's Cation Exchange Capacity (CEC), enhancing its ability to hold and supply essential nutrients to crops. The slower, biological decomposition of residues in CA provides a more sustained and balanced release of nutrients, often leading to improved nutrient use efficiency. Furthermore, crop rotation, particularly with legumes, fixes atmospheric nitrogen into the soil, reducing the need for synthetic nitrogen fertilizers.

4.3. Biological Revival: Diversity and Function CA transforms the soil from an inert growing medium into a vibrant, biologically active ecosystem.

Microbial Biomass and Diversity: The stable temperature, conserved moisture, and continuous food source (residues) favor the proliferation of beneficial microorganisms (bacteria, archaea, fungi) and macrofauna (earthworms, arthropods). These organisms drive the key processes of nutrient mineralization and the formation of stable soil aggregates (biologically induced soil structure).

Pest and Disease Management: Diverse crop rotations, along with the presence of beneficial microorganisms that out-compete pathogens, help to break the life cycles of specific pests and diseases. This natural control mechanism reduces reliance on chemical inputs.

5. Implementation and Challenges

While the benefits are profound, the transition to CA-based systems involves initial challenges that require technical support and adaptation.²⁴

5.1. Management Requirements

Weed Management: Since mechanical weed control (tillage) is removed, farmers must rely more on a combination of herbicide use (especially during the transition phase), cover crops (for physical and allelopathic suppression), and crop rotation to manage weeds.

Residue Management: Successfully managing large amounts of surface residue requires specialized no-till planters/seeder capable of cutting through the residue and placing the seed at the correct depth. Livestock grazing access to crop residues can also be a social and technical constraint.²⁵

Nutrient Stratification: In the initial years of no-till, nutrients tend to accumulate near the surface. While the biological activity of the topsoil usually mitigates this, careful surface application and monitoring are crucial.

5.2. Socio-Economic and Policy Context

The adoption of CA is heavily influenced by the socio-economic context:

Initial Investment: Specialized no-till machinery can represent a significant upfront investment, particularly for smallholder farmers.

Knowledge Gap: CA is a knowledge-intensive system. Farmers need training to understand the system's principles, recognize the signs of a healthy soil ecosystem, and adapt the system to local soil and climatic conditions.

Policy Support: Supportive policies, such as input subsidies for no-till equipment, financial incentives for carbon sequestration, and strong extension services, are essential to encourage widespread and sustained adoption.

6. CONCLUSION AND FUTURE OUTLOOK

Conservation Agriculture-Based Cropping Systems represent the most comprehensive and

evidence-based pathway to improving soil health in modern agriculture. By adhering to the trifecta of minimal soil disturbance, permanent soil cover, and crop diversification, CA transforms degraded soils into highly productive, resilient, and functioning ecosystems. The resultant improvements in soil structure, water holding capacity, nutrient cycling, and carbon sequestration not only ensure higher and more stable crop yields but also deliver vital ecosystem services that address global challenges like climate change mitigation and water quality. CA is, therefore, not just a farming technique; it is an essential component of the global strategy for sustainable food security and environmental stewardship.

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