__Review Article__

Conservation agriculture: A long-term approach towards sustainability

Abstract: With the application of intensive agricultural techniques, conventional agriculture has been successful in meeting production goals but has also led to the depletion of natural resources. Sustainability in the management of the natural resource base is necessary for ongoing and expanded agricultural output to provide food security for future generations. Over a long period, the traditional tillage practice has led to the destruction of the natural resource base of the land. As a result of its inherent connection to the physical, chemical, and biological aspects of soil, it has led to a significant loss of soil and SOM, which is a crucial component of soil quality. Therefore, a suitable cropping system and land use must be implemented and adopted to ensure food security on a sustainable basis. These measures should be based on principles to prevent land degradation, protect the natural resource base, and improve food and nutritional security through crop diversification and optimal rotation. The one sustainable cropping method that may reverse soil erosion, increase crop output, and improve the socioeconomic status of small landholder farmers is conservation agriculture (CA). Conservation agriculture (CA) is the integrated management of the available natural resources such as soil, water, flora, and fauna, with certain outside inputs to maximize the effectiveness of natural resource utilization. To fulfill the objective of sustainable crop production, an alternative approach known as conservation agriculture has emerged. It represents a significant advance in the direction of sustainable agriculture. This article reviews the emerging concerns due to the continuous adoption of conventional agriculture systems, contrasting features between conventional and conservation agriculture systems, and various principles and practices in conservation agriculture. It also highlights the benefits and limitations of CA and various challenges in the adoption of CA.

Keywords: Conservation Agriculture, Crop diversification, Production, Natural resources, and Sustainability.

Introduction:

By 2050, the population of the globe is expected to reach 9.1 billion people (FAO, 2009). Based on the limited land resources, it is clear that urgent measures must be taken to assure enhanced food supply and food security. Agriculture, which is the sole source of human food, is the world's largest industry and major land use, accounting for 40% of all available land (Sah and Devakumar 2018). Since the global supply, economic growth, and access are not keeping up with the rising population in developing nations, food security has become more crucial on both the international and domestic fronts. Through industrialization and the expansion of agricultural production into marginal lands, rapid population increase and economic development gravely damaged the ecosystem. Growing issues with resource degradation, such as groundwater depletion, water logging, salinization, soil erosion, biodiversity loss, and invasive species, further compound the problem of food security (Oliver and Gregory, 2015). The task of supplying food demand is made even more difficult by the declining per capita availability of arable land and the delayed pace of climate change adaptation. While climate change may have an impact on the entire planet, its effects are particularly severe in Asian regions due to the region's high reliance rate (Kumar, 2003). Therefore, the main challenges faced by most Asian countries are ensuring food security for a growing population and reducing poverty while maintaining agricultural systems in the face of depleting natural resources, adverse effects of climate variability, spiraling input costs, and unstable food prices. Along with these challenges, soil erosion, a reduction in soil organic matter, and salinization are the main warning signs that agricultural systems are not sustainable. These are mostly brought about by (i) heavy tillage-induced soil organic matter reduction, soil structural degradation, water, and wind erosion, decreased rates of water infiltration, surface sealing and crusting, soil compaction, (ii) insufficient return of organic material, and (iii) monoculture. Low-input subsistence farming typically results in lower crop yields and deteriorating soil quality (Lobo et al. 2023; Montenegro et al. 2021). Excessive and improper tillage decreases soil productivity and soil organic carbon (Lal, 2004) and speeds up soil erosion and degradation (Cerda *et al.,* 2009; Olivares et al. 2011; Olivares et al. 2015). Thus, intensification of agriculture is required without further depleting the natural resource base. Therefore, a paradigm change in farming practices is essential for future productivity advances while preserving natural resources (eliminating unsustainable components of conventional agriculture, such as plowing/tilling the soil, removing all organic material, and monoculture) (Bhan and Behera, 2014). The numerous crop management techniques referred to as "conservation agriculture" (CA) are widely used to increase crop output (Hernandez et al. 2018a; 2018b), conserve soil, and build robust systems to weather-induced pressures (Hernandez et al.

2018c), especially those brought on by irregular weather patterns (Hernandez et al. 2017) and climatic change (Viloria et al. 2023). CA is a significant agronomic practice that has steadily expanded globally to cover about 11% of the world's arable land (157.8 Mha) (FAO, 2016). FAO (2010b), has defined CA as a concept for resource-saving agricultural productivity that aims to provide high and sustained levels of output while also preserving the environment. Dumanski *et al.* (2006) stated that conservation agriculture (CA) is not "business as usual", as it does not aim to maximize yields while utilizing the resources of the soil and agro-ecosystem. Instead, CA focuses on increasing profitability and yields to strike a balance between agricultural, economic, and environmental benefits. It argues that the social and economic gains from both production and environmental protection, including lower material and labor costs, outweigh those from production alone. By using fewer fossil fuels, pesticides, and other pollutants while preserving environmental services and integrity, farming communities can provide more hygienic living conditions for the larger population. The three main tenets of CA are systematic crop rotation, crop residues that permanently coat the soil, and minimal or no tillage (Rusinamhodzi,2015). The FAO guidelines state that "CA is an approach to managing agricultural ecosystems for enhanced and sustained productivity, improved returns, and food security while maintaining and improving the resource base and the environment."It is an agronomic practice that includes rotational planting of pulses and legumes together with reduced tillage (RT), no-tillage (NT), or minimum tillage with stable organic matter cover, and crop residue retention. It is stated that the aforementioned concepts apply to all CA systems (Sayre, 2000). However, elements that are specific in nature, such as the choice of farm implements, establishing techniques, rotation of crops with pulses or legumes, management of soil fertility, management of mulch and crop residue, etc., vary depending on the environment. The prospect of CA is that it may be used in many agricultural ecological zones and beneficial in improving food security for a significant number of smallholder residents of underdeveloped nations (Derpsch and Friedrich, 2009). Comparing Conservation Agriculture (CA) to conventional tillage (CT) systems, researchers found that CA can alter soil's physical, chemical, and biological soil quality metrics. In response, the increased sink for carbon storage within the soil helps to counterbalance the climate variability, which has an impact on ecosystem services and the sustainability of crop production systems (Yadav *et al.*, 2017). He stated that conservation agriculture is a successful strategy for promoting an agricultural production system that includes a greater diversity of soil microorganisms, which are crucial for enhanced soil quality, crop yield, and numerous ecosystem services. For sustaining prospects, CA is the best management of natural resources like soil, water, vegetation, and biodiversity. CA have the ability to mitigate the consequences of climate change by increasing crop output and benefits while coordinating agricultural, financial, and ecological benefits ((FAO, 2011a).

Conventional and Conservation Agriculture: To implement conservation agriculture systems, traditional agriculture must completely change the management of crops, land, water, nutrients, weeds, and farm machinery.

Table 1. Contrasting features between Conventional and Conservation agriculture

Conventional agriculture	**Conservation agriculture**
Cultivation using science and technology to dominate nature	Least interference with natural processes
Excessive mechanical tillage and soil erosion	No-till or significantly reduced tillage (biological tillage)
Monocultures or crop rotation in tillage framework	Crop rotation or intercropping is a permanent feature
Residue burning or removal (bare surface)	Surface retention of residues (permanently covered)
The oxidation of organic matter caused by traditional tillage's exposure to air and sunlight results in low soil carbon content, which has an impact on soil structure.	Accumulation of the organic matter in soil provides better soil aggregation.
Low infiltration rate of water	High infiltration rate of water
High wind and soil erosion	Low wind and soil erosion
Kills established weeds but also encourages more weed seeds to germinate	Weeds are a problem in the beginning but decrease over time
Use of ex-situ FYM/composts	Use of in-situ organics/composts; Brown manuring/cover crops (surface retention)
Free-wheeling of farm equipment and	Controlled traffic, tramline compaction, and

increased soil compaction.	reduced soil compaction in crop areas.

(Choudhary *et al.*, 2016)

Principles of Conservation Agriculture:

1. **Permanent or semi-permanent soil cover with organic materials:** A permanent soil cover is essential for three reasons: it protects the soil from the harmful consequences of exposure to rain and sunlight, it continuously supplies "food" to the micro- and micro-organisms in the soil, and it modifies the microclimate in the soil to promote the growth and development of soil organisms, including plant roots. Therefore, it enhances soil biological activity, biodiversity, soil aggregation, and carbon sequestration (Ghosh *et al.*, 2010). Kumar and Goh (2000) studied the impact of crop residues and management techniques on soil quality, soil nitrogen dynamics and recovery, and crop output and reported that agricultural residues from cultivated crops have a major impact on crop productivity due to their effects on the physical, chemical, and biological activities of the soil as well as the quality of the water and soil. When a previous crop is left anchored or loose after harvest or when a cover crop (legume or non-legume) is established and killed or clipped to provide mulch, crop residue is produced. Composts and manures can also be used as external mulch, but their use may be limited to higher-value crops like vegetables due to the cost of transporting such large materials to the field. The force of raindrops striking bare soil causes runoff and soil erosion by destroying soil aggregates, blocking soil pores, and drastically reducing water penetration. Mulch deflects this energy, preventing soil aggregate breakdown on the surface while also improving water infiltration and reducing soil erosion (Dormaar &Carefoot 1996). In comparison to tilled soils, no-tillage with mulch improves water infiltration, decreases runoff, and boosts yield (Thierfelder*et al.*, 2005). Roldan *et al.* (2003) demonstrated that after 5 years of NT maize in Mexico, soil wet aggregate stability had increased over conventional tillage, as had soil enzymes, soil organic carbon (SOC), and microbial biomass (MBM). Madari *et al.* (2005) demonstrated that NT with residue cover had higher aggregate stability, higher aggregate size values, and total organic carbon in soil aggregates than TT in Brazil. Through competition and depriving weed seeds of the light they frequently need for germination, a cover crop and the subsequent mulch or leftover crop residue assist in

reducing weed infestation. Additionally, there is proof that cereal residues have allelopathic characteristics that prevent the germination of surface-level weed seeds. (Jung *et al.,* 2004). Vagen *et al.* (2005), reported that the creation of natural or modified fallow systems (agroforestry) with attainable C accumulation rates of 0.1 to 5.3 Mg C ha^{-1} yr^{-1} has the greatest potential for raising SOC. According to them, adding crop wastes or manure to cropland in addition to NT can produce C accumulation rates that are attainable, up to 0.36 Mg C ha^{-1} yr^{-1}. Lal (2005) predicted that increasing SOC by 1 Mg ha^{-1} yr^{-1} can enhance food grain production by 32 Mg yr^{-1} in impoverished nations as SOC is a crucial measure of soil quality. Through their roots, cover crops aid in promoting biological soil tillage; the top mulch supplies food, nutrients, and energy to underground worms, arthropods, and microorganisms that also biologically till soils. Compaction under zero-tillage systems can also be reduced by using biological agents (earthworms, etc.) and deep-rooted cover crops. According to recent studies, more soil fauna is found in no-tillage, residue-retained management regimes compared to tillage plots. The networks of soil pores, particularly those of mycorrhizal hyphae, which are crucial for the availability of phosphorus in some soils, are damaged and disrupted by tillage (McGonigle & Miller, 1996). Thus, zero-tillage produces healthier soil with a greater mix of bacteria and other species. Ground cover encourages an increase in biodiversity both below and above ground; ground cover and mulch have been shown to enhance the number of beneficial insects, which in turn helps control insect pests (Jaipal *et al.*,2002). Crop health, yield, and soil quality are all impacted by interactions between rhizobacteria and root systems. Exudates released by plants stimulate and maintain certain rhizobacterial populations that improve nitrogen fixation, bio-control of plant pathogens, disease resistance, and nutrient cycling.

2. **Minimum Mechanical Soil Disturbance or No-Tillage (NT) or Reduced Tillage or Minimum Tillage:** The biological activity of the soil creates very solid soil aggregates and holes of different sizes that enable the infiltration of air and water. The term "biological tillage" might be used to describe this process, which is incompatible with mechanical tillage. The biological soil structuring mechanisms will cease to exist with mechanical soil disturbance. Minimal soil disturbance promotes/maintains ideal proportions of respiration gases in the rooting zone, moderate organic matter oxidation,

porosity for water transport, retention, and release, and restricts the exposure of weed seeds to new light and their germination (Kassam and Friedrich, 2009). Minimal tillage refers to either direct sowing or dissemination of seed with the least amount of soil disturbance by opening the slot with the use of a khurpi or other equipment. Regardless of what is lower, the disturbed area shall be no wider than 15 cm or no larger than 25% of the harvested area. (FAO 2014b). Numerous advantages of minimal soil disturbance were stated in the section on permanent soil cover above, and it is crucial to combine these two techniques for the greatest outcomes. When used for plowing, tractors generate greenhouse gases (mostly CO_2) that increase expenses while also consuming a significant amount of fossil fuels (Grace *et al.,* 2003). Animal-based tillage systems are particularly costly because farmers must care for and feed a pair of animals for a whole year. Animals also release methane, a greenhouse gas that is 21 times more powerful than carbon dioxide in causing global warming (Grace *et al.,* 2003). These expenses and emissions are decreased with zero-tillage. According to farmer surveys conducted in Pakistan and India, zero-tilling wheat after rice lowers production costs by US$60 per hectare by using less fuel (60-80 l ha^{-1}) and manpower (Hobbs & Gupta 2004). Since farmers utilize 2 to 12 passes of a plow to create a good seedbed, the turnaround time in this rice-wheat system from rice to wheat ranges from 2 to 45 days (Hobbs & Gupta 2003). With zero-till wheat, this period is only 1 day long. Due to increased oxidation brought on by tillage and modern agricultural practices, soil organic matter decreases with time, resulting in soil degradation and a loss of soil biological fertility and resilience (Lal,1994). On the other hand, zero-tillage has been demonstrated to cause an accumulation of organic carbon in the surface layers when paired with permanent soil cover (Lal, 2005). No-tillage is a potential method for maintaining or even increasing soil C and N stocks since it reduces SOM losses (Bayer *et al.,* 2000). Leake (2003) discusses the impact of tillage on different types of soil diseases using numerous instances. In his conclusion, he acknowledged that healthy soil with a high microbial diversity does play a role by being hostile to soil pathogens and stated that the impact of tillage on diseases is uncertain. To help shift the advantage from the disease to the crop, he also recommended that NT farmers alter management to control infections by sowing date, rotation, and resistant cultivars. Tillage increases the amount of wear and tear on equipment and increases tractor maintenance costs relative to zero-tillage systems, which is another economic factor to take into account.

3. **Crop Rotation with Pulses or Legumes:** Crop rotation is essential not just to provide a varied "diet" for soil microorganisms, but also to explore through various soil levels for nutrients that have leached to deeper layers and can be "recycled" by crops in rotation. A diversified crop rotation also results in diverse soil flora and fauna. Legumes are used in crop sequences and rotations because they disrupt the life cycles of pest species, fix nitrogen biologically, reduce off-site pollution, and increase biodiversity (Kassam and Friedrich, 2009). Rotation should comprise a minimum of three different crops. Crop rotation is a method of agricultural management that has a long history. In zero-till systems, a larger network of root channels and macro-pores is encouraged by the rotation of several crops with various rooting patterns and low soil disturbance. This aids in the penetration of water into deeper levels. The risk of pests and disease outbreaks caused by pathogenic organisms is decreased as a result of rotations because the biological diversity helps keep pathogenic organisms in check (Leake, 2003). The life cycle of many weeds is disrupted by rotating crops, which also results in a decline in the overall weed population. Due to these advantages, crops cultivated in rotation often produce 10% more than crops grown in monoculture (Vanlauwe *et al.*, 2014). Additionally, a variety of crops grown in rotation produce a diversity of soil flora and fauna because the roots excrete various organic substances that draw various bacteria and fungi, which are crucial for the conversion of these substances into nutrients for plants (FAO, 2015). It is crucial for soil health because it lessens the allelopathic effect of crops and improves soil fertility and quality while also increasing crop output. Mono-cropping or growing the same crop in the same location for an extended period hurts the health of the soil, making it sick. Diversified crops are cultivated, which improve soil porosity, moisture retention, root penetration, and nutrient recycling. Sharma *et al*., 2022). It results in better N/P/K balance from both organic and mineral sources, as well as better biological N_2 fixation through specific plant-soil biota symbionts.

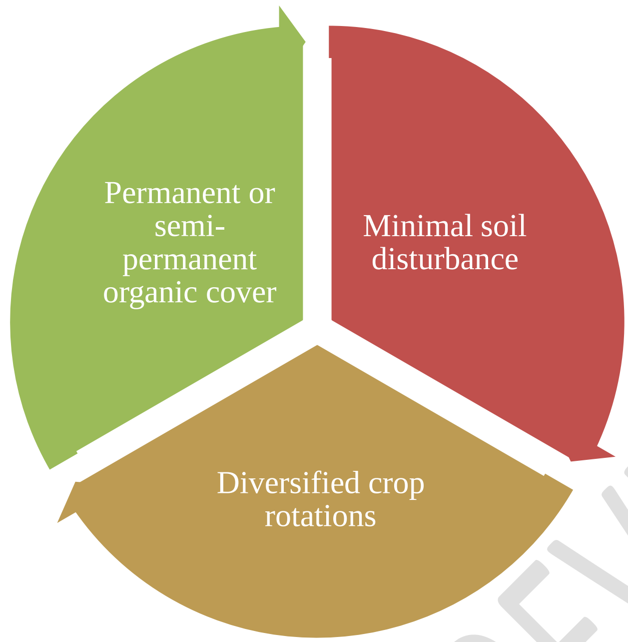

Fig. 1. Principles of Conservation Agriculture

Benefits of conservation agriculture:

1. **Soil Aggregation, Aggregate Stability, and Structure:** The sensitivity of soil to alter under natural or manmade activity is the subject of soil aggregate stability. Because soil erodibility is closely correlated with aggregate stability, it is crucial for soil conservation owing to water erosion. Between aggregate stability in water, aggregate size, and total organic carbon content, there is a medium-to-high aggregate connection (Olivares et al. 2022a). Conventional tillage encourages soil organic matter loss, which causes soil aggregate disintegration and erosion (Olivares et al. 2022b). CA methods that leave more agricultural residue on the soil's surface typically allow for improvements in aggregate stability and soil aggregation. Additionally, it shields surface aggregates from splash or raindrop degradation. According to studies conducted in California, no-tillage with stubbles that retained treatment exhibited greater water-stable aggregation. No-tillage CA that retains crop residue is beneficial for soil aggregation and aggregate stability (Li *et al.*, 2011). According to studies on soil structure, persistent no-tillage management in semi-arid Morocco promoted the growth and persistence of a soil surface horizon rich in stable aggregates (Mrabet and El Brahli2005). Under no-tillage as opposed to traditional

tillage, Mrabet (2002) found greater mean weight diameter (MWD) and aggregation index (AI) at the surface (0–7 cm) of a self-mulching expanding clay soil. To improve infiltration, plant-available water, and aggregate stability, CA needs a suitable amount of soil cover (Palm *et al.*, 2013). Additionally, it raises the fraction of soil micropores, boosts water-holding capacity, and lowers evaporation.

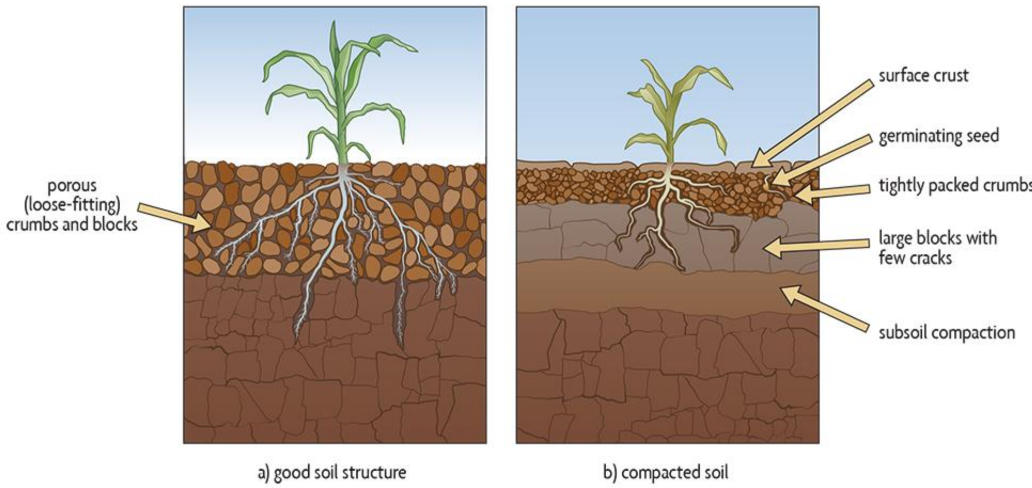

Fig. 2 a) Plants growing in good soil structure b) Plants growing in compacted soil shows three types of compaction: surface crusting, plow layer/surface compaction, and subsoil compaction

2. **Soil and moisture conservation:** From the perspective of sustainability and off-site environmental harm, runoff, and soil loss are key concerns of sloping agriculture land in Himalayan regions, particularly those with unstable aggregates in the surface horizon. As such, this has been and continues to be an extremely important research field. CA with agricultural residue mulch can offer soil cover to lessen the impact of rain and provide barriers against runoff; this will aid in increasing moisture uptake and reducing soil separation (Franzluebbers 2002). According to research on the western Loess Plateau of China, a wheat-pea rotation system decreased soil loss from erosion by about 62% while reducing runoff and runoff intensity with no-tillage and stubble retention (Zhao *et al.* 2007). In summary, CA could lessen soil detachment and improve water infiltration, which implies a reduction in water flow; as a result, soil erosion would be decreased(Table 2). The fact that conventional tillage (CT) results in more physical

disruption and less production of aggregate stabilizing elements in conventional farming systems leads to higher soil deterioration (Bradford and Peterson 200). Additionally, adding crop residue through plowing, removing them from the field for use as cow feed, or burning them exposes the soil to the effects of rain, wind, and solar heating, speeding up the pace of soil degradation. Lower soil erosion potential in CA practices than in traditionally tilled areas is caused by higher aggregate stability in CA (Govaerts*et al.*, 2007). In contrast to CT, CA leaves more plant debris on the surface, protecting the soil from the damaging impacts of rain, strong winds, and solar heating. Due to less runoff in fields under CA circumstances, soil erosion is further declined (Araya *et al.*, 2012).

Table 2. Different tillage systems, runoff, and infiltration

Tillage system	**Five years means as % of rainfall**	
	Seasonal runoff	Seasonal infiltration
Conventional tillage	20	80
Conservation tillage	1	99

(Marongwe *et al.*, 2012)

3. **Enhance Soil Quality:** The ability of a particular type of soil to function, within naturally controlled ecosystem boundaries, in a way that supports plant and animal productivity, maintains or improves water and air quality, and supports human health and habitation is known as soil quality (Karlen *et al.*, 1997). Verhulst *et al.* (2010) stated that In terms of agricultural output, excellent soil quality, "equates to the ability of the soil to maintain a high productivity without significant soil or environmental degradation." The physical, chemical, and biological aspects of the soil are used to evaluate its quality. Good-grade soil can be referred to as "healthy soil" in terms of biological soil quality (2). A stable system with high levels of biological diversity and activity, internal nutrient cycling, and resistance to disturbance is referred to as healthy soil (Shaxson *et al.*, 2008). When CA is used for a sufficient amount of time, the quality of the soil is significantly improved, especially in the surface layers (Verhulst *et al.*, 2010). When evaluating the sustainability of agricultural production systems, soil structure is an important component to consider (Verhulst *et al.*, 2010). It is frequently described as the degree of stability of aggregates (Bronick and Lal, 2005). In comparison to CT, ZT with residue retention increases both the dry and the wet aggregate size distribution (Govaerts *et al.*, 2007).

While CA reduces soil compaction due to reduced tillage operation and growth of the deep-rooted cover crops or legumes in rotation, which break the compact layers in the sub-surface, CT, for example, can cause compactness in soil subsurface layers leading to restricted root growth, water logging, and poor aeration (Lal *et al.,* 1994). Recent studies showed that CA improves aeration and water retention by reducing bulk density, especially in surface layers (Nurbekov, 2008). In soils under CA, residue retention leads to increased microbial biomass and an abundance of earthworms and macro-arthropods, such as termites and ants, which benefits soil fertility. Due to extensive nitrification, NO3-leaching, and H3O+ excretion by legume roots, the addition of legumes to crop rotations in CA may lower the pH of alkaline soils (Qadir *et al.*, 2007). Thus, it can be said that soils under CA are generally layered physically, chemically, and biologically, with the surface layers having better soil quality.

4. **Enhance Nutrient Use Efficiency:** The distribution, recycling, and transformation of nutrients in soils are significantly influenced by conservation tillage, crop residue management, and crop rotation with pulses or legumes (Verhulst *et al.* 2010). CA can affect the availability of soil nitrogen because of its effects on soil organic carbon and nitrogen mineralization (Bradford and Peterson 2000; Araya et al. 2020). Under CA, soil fertility often increases over time and requires fewer fertilizer amendments to produce ideal yields over time. Additionally, NT has been shown to increase the availability of potassium and phosphorus. Mrabet *et al.* (2001) found that No-tillage soil has more phosphate and potassium near the soil surface than tilled soil. According to Rahman *et al.* (2008), the surface soil under NT had much greater exchangeable Ca, Mg, and K levels than the soil that had been plowed. The biochemical decomposition of organic crop residue at the soil surface, which is significant for feeding the soil microbes, improves soil nutrient supply and cycling. Reduced runoff and the use of suitable deep-rooting cover crops help CA fields retain more nutrients (FAO, 2001). Crop residues release nutrients gradually, preventing leaching and/or denitrification-related nutrient losses. Additionally, immobilizing mineral N through residue retention may help stop possible losses brought on by NO_3-N leaching (Thomas *et al.,* 2007). The short-term immobilization of mineral nutrients by microorganisms may result in reduced fertilizer

use efficiency. Long-term nutrient availability, however, rises as a result of microbial activity and nutrient recycling (Carpenter-Boggs *et al.*, 2003).

5. **Enhance crop yields:** The initial soil fertility state (Olivares, 2022), climate (Parra et al. 2012), the amount of rainfall experienced during the season (Paredes et al. 2021), the management practices, and the type and quantity of crop residues kept, among other factors, all have an impact on the short-term effects of CA on crop production in comparison to CT (López-Beltrán et al. 2019; López and Olivares, 2019). As a result, the short-term impacts of CA on agricultural yield could be favorable, neutral, or adverse. However, over time, CA has reportedly been shown to increase crop yields because of its additional advantages, such as the reduction of soil erosion, higher soil quality, better moisture regimes, timely field activities (mostly sowing), and the advantages of crop rotation (Sharma *et al*., 2021; Hernandez et al. 2020). Mulching and rotational planting of legumes result in better soil physical, chemical, and biological qualities that, over time, minimize soil degradation and produce higher and more consistent yields in CA fields (Sisti *et al.,* 2004). Due to enhanced RWUE from greater infiltration, less evaporation loss, higher soil water holding capacity, and timely crop planting in rainfed circumstances in dry areas where soil moisture is the main limiting factor, CA aids to boost agricultural yields. With the right fertilizer management, conservation agriculture may help boost crop output, enhance soil health, and generate revenue. Bell *et al.* (2019) discovered that the longer-term practice of conservation agriculture enhanced rice grain output (by up to 12%). Khorami *et al.* (2018) found that conservation agriculture, which includes reduced tillage, enhanced agronomy, and improved varieties, has produced beneficial results, including an increase in wheat yield and maize biomass. According to Baumhardt *et al.* (2013), straw mulching increased the water flow of both rainfed and irrigated crops. Similarly, Bashour *et al.* (2016) found that using conservation agriculture increased wheat crop yield by 27%. In southern Africa, conservation agriculture produced higher yields of maize (*Zea mays* L.) than conventional tillage, as reported by Thierfelder*et al.*, (2015). Karki *et al.* (2014a) documented that conservation tillage with residue has a lower benefit-cost ratio (1.7) than conventional tillage without residue (2.5). Afzalinia *et al.* (2012) also observed increased wheat and maize (*Zea mays* L.) yield and biomass as a result of conservation agriculture. Mosquera *et al.* (2019), reported that the adoption of a

conservation agriculture system as opposed to conventional methods boosted crop yield and net (of the cost of production) benefits of the system by up to 25 and 24%, respectively. In potato-based systems, enhanced CA practices over 7 years revealed that soil carbon concentration in the entire profile was 29% higher under conservation tillage than under conventional tillage sites, and the carbon content was greater by 33% (Quintero and Comerford, 2013).

Table 3. Percent increase in grain yield in conservation agriculture

Crop	**Increase in grain yield**	**References**
Rice	12%	Bell *et al.* (2019)
Wheat	27%	Gathala*et al.* (2011)
Potato	24%	Mosquera *et al.* (2019)
Lentil	27.7%	Bashour*et al.* (2016)
Soyabean	20%	Thiagalingam*et al.* (1991)
Bean	7%	Liben*et al.* (2017)

6. **Enhance soil biodiversity:** When it comes to the activities of soil fauna and flora and the improvement of biological characteristics, conservation tillage is preferred above conventional tillage (Busari *et al.* 2015). Cookson *et al.* (2008) found that as tillage disturbance increased, bacterial biomass increased and fungal biomass decreased. Additionally, they discovered that the microbial community's composition and mode of substrate utilization had changed, with unique substrate usage in no-tillage soil. It offers a genuinely sustainable production system, preserving natural resources while also enhancing them (Hernández and Olivares, 2020). It also increases the variety of soil biota, fauna, and flora (including wildlife), as well as the microbial count in agricultural production systems, all without compromising yields at high production levels. The conservation agriculture systems raise microbial biomass by 83%, lower the metabolic quotient by 32%, and enhance the MBC: total carbon ratio by 23%. CA increases agricultural output by disrupting insect and disease cycles, reducing weed growth, and enhancing nutrient cycling, soil fertility, and biodiversity of soil biota (Palm *et al.*, 2013).

By providing habitats and food for birds, animals, reptiles, and insects among others, CA has been shown to promote above-ground biodiversity also (FAO, 2011).

7. **Mitigate the effects of climate change:** Conventional agriculture often emits more greenhouse gases (GHGs), which has a higher impact on climate change. Because of soil tilling, crop residue mixing, and biomass burning, conventional agriculture emits GHGs (Hobbs *et al.*, 2010). CA may reduce climate change by carbon sequestration, decreased CO_2 and N_2O emissions, and possibly reduced methane (CH_4) emissions. Due to SOM's slower breakdown and oxidation, less soil disturbance may increase carbon storage in CA crops (Jat *et al.,* 2012 b). By keeping crop residues on the soil's surface rather than burning them, like in CA, CO_2 emissions are decreased. Direct planting and avoiding tillage processes allow CA to save a significant amount of fuel, which lowers CO_2 emissions (Hobbs *et al.*, 2004). Long-term N_2O emission reduction in CA fields may be possible as a result of a decreased requirement for nitrogenous fertilizers brought on by better soil fertility. Conservation agriculture will boost the resilience of crops to adapt to local climate change through improved soil quality and nutrient cycling (Hobbs and Govaerts, 2010). The main ways that CA aids in adaptation to climate change are through improved soil moisture status, reducing extreme soil temperatures (Zingaretti et al. 2016; Cortez et al. 2018; Casana and Olivares, 2020), timely agricultural activities, and improved crop health in CA fields, thus minimizing the impacts of climate change (Olivares, 2018; Zingaretti and Olivares, 2018).

Limitations of conservation agriculture:

- The initial high cost of specialized sowing and/or planting equipment and the need for technical know-how for improved management are two short-term drawbacks of conservation agriculture (Baudron *et al.*, 2012)
- Initial years of adoption result in lower yields, higher input costs, more labor-intensive weeding, competition between mulching and animal feed for crop residue, and promotion of the practice as a universal method without taking socioeconomic or agroecological factors into account (Corbeels *et al.*, 2014).
- The absence of understanding about locally adapted cover crops that yield quality biomass under the existing conditions is a particularly significant knowledge gap.

- The adaptability and ingenuity of the farmer, extension agents, and researchers in a particular area are crucial factors that determine whether CA is successful or unsuccessful.

Challenges in conservation agriculture

To address the many, adaptable, and context-specific needs of technologies and their management, conservation agriculture, an emerging paradigm for growing crops, will need an innovative system viewpoint. Research and development (R&D) in conservation agriculture will therefore require several novel characteristics to address the issue. These include:

(a) **Being aware of the system**: Conservation agricultural systems are far more complicated than traditional systems. Site-specific information is the greatest obstacle to the CA system's widespread adoption (Derpsch, 2001; Olivares, 2014; Camacho et al. 2018). Understanding fundamental processes and how components interact to build a functioning system will be crucial to manage these systems effectively. For instance, crop residues that are kept on the surface operate as mulch, which lowers soil water losses owing to evaporation and upholds a stable soil temperature regime (Gupta and Jat, 2010). Crop residue can be a readily decomposable source of organic matter, but it can also host unwanted pest populations or otherwise change the ecology of the system. No-tillage techniques will affect the root system's spread and depth of encroachment. Therefore, it is necessary to acknowledge conservation agriculture as a system and create management plans.

(b) **Burning crop residues:** Farmers prefer to seed the crop in time by burning the residue to sow the following crop promptly and without the need for machinery for sowing under CA systems. This is now a usual aspect of the rice-wheat system in north India. This causes environmental and health issues (Tripathi *et al.*, 2013).

(c) **Developing a system and a farming system perspective:** A system perspective is developed by collaborating with farmers. Therefore, creating and promoting new technologies will require a core group of scientists, farmers, extension agents, and other stakeholders operating in partnership mode. The system is to determine research goals and allocate resources within a framework in this case, which is rather different from typical agricultural R&D. Relationship-building and looking for connections with partners that operate in complementary disciplines are given less consideration (Abrol and Sangar, 2006).

(d) **Site specificity**: Adapting techniques for conservation agricultural systems will be very site-specific, but learning from different locations will be a valuable approach to comprehending why particular technology or practices are useful in some conditions but not in others. Building a foundation of knowledge for sustainable resource management will be accelerated by this learning approach.

(e) **Skilled and scientific staff:** Expert and scientific manpower is required for managing CA systems, and researchers' capacity to approach issues from a systems viewpoint and collaborate closely with farmers and other stakeholders must be improved. We urgently need to improve the mechanisms for exchanging knowledge and information.

Conclusion: Different from the usual framework for agricultural research and development, which was primarily focused on meeting specific food grain production targets in India, conservation agriculture offers a fresh approach. Given the pervasive issues of resource degradation that came along with previous tactics to boost production with little regard for resource integrity, a paradigm shift has become necessary. To achieve continuous productivity growth, it is now essential to integrate issues related to productivity, resource conservation, soil quality, and the environment. The knowledge base required for creating and promoting CA systems will be extremely difficult to meet. For this, scientists' ability to approach issues from a systems viewpoint, collaborate closely with farmers and other stakeholders, and promote knowledge and information-sharing must all be significantly increased. By lowering cultivation costs, and increasing resource use efficiency, competitiveness, and sustainability in agriculture, conservation agriculture provides a chance to halt and reverse the downward spiral of resource degradation. However, there is a need to support research in India to determine the best crop combinations, management techniques, weed management, insect pest, and disease control tactics, as well as to create CA machinery that is appropriate for different agro-climatic areas. The new mission must be "Conserving resources - enhancing productivity."

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