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REVIEW ARTICLE

Weed management and conservation agriculture in cotton-based systems: Implications on soil quality and climate change mitigation

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ABSTRACT

Conservation agriculture (CA), characterized by reduced tillage, continuous soil cover through mulching or cover cropping, and crop rotation, is established as a sustainable approach for enhancing soil health and agricultural resilience, particularly in cotton-based systems. Several studies indicated that CA in cotton systems played a crucial role in climate mitigation by enhancing soil carbon sequestration and mitigating greenhouse gas (GHG) emissions. CA practices reportedly increased soil organic carbon (SOC) levels, which helped stabilize atmospheric CO_2 Additionally, CA minimized energy-intensive inputs by reducing reliance on machinery, thereby further lowering CO_2 emissions. With reduced tillage, weed management became more challenging but remained essential for productivity, soil health, and sustainability. Research showed that weed management practices in CA systems influenced soil physical, chemical, and biological properties. CA was found to improve physical attributes such as bulk density, soil structure, aggregation, and hydraulic conductivity, which enhanced porosity, root growth, and water infiltration. CA-based weed control helped in stabilizing the soil pH, reducing electrical conductivity, increasing cation exchange capacity, and enhancing SOC, thereby improving nutrient retention. Reliance on herbicides in CA-based cotton systems was shown to impact soil microbial diversity and enzyme activity, varying with herbicide type and frequency of application. Some herbicides temporarily inhibit soil microorganisms and enzyme functions (*e.g.,* dehydrogenase, urease, phosphatases). However, mulching and organic residue retention in CA systems demonstrated positive effects on soil microbial biomass carbon (SMBC) and microbial activity. CA practices gradually stored carbon by sequestering CO_2 in SOC, thereby stabilizing carbon and supporting biodiversity.

Keywords: Climate change, Conservation agriculture, Cotton, Soil quality, Weed management

INTRODUCTION

Conservation agriculture (CA) is based on three key principles: (1) minimal soil disturbance or no tillage/direct seeding, (2) continuous soil cover with crops, cover crops, or mulch, and (3) crop rotation and cover crop use (FAO 2015). Over time, agricultural innovations have contributed to intensifying food production in CA-based systems (Muoni *et al.* 2013). Conservation agriculture, which recommends zero tillage ZT coupled with crop residue mulching and diversified crop rotation, has come forward as a sustainable management system that could revert physical soil degradation in resource poor farms across very different agro-ecological conditions (FAO 2012).

Reducing tillage intensity and frequency in CA often leads to increased weed infestations. Compared to conventional tillage (CT), zero tillage (ZT) results in more weed seeds accumulating on the soil surface, encouraging higher weed germination. Weed infestations change with the adoption of practices such as sowing techniques, tillage methods, weed control strategies, residue management, and input application.

Cotton is India's most important commercial crop, with the country being the world's leading cotton producer. India cultivates cotton in 13.06 million hectares, accounting for about 40% of the global cotton-growing area. About 67% of India's cotton is grown in rain-fed areas, while the remaining 33% is cultivated on irrigated lands (Ministry of Textiles 2023). The adoption of conservation agriculture (CA) in cotton (*Gossypium hirsutum*) systems offers both agronomic and environmental benefits (Ferdush *et al.* 2024).

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Rising temperatures, especially warmer nights, impact the cotton, where higher night temperatures lower yields by increasing respiration rates more than photosynthesis, despite cotton's drought tolerance (Nouri *et al.* 2021). Climate change has already reduced agricultural productivity growth by 21% over the past 50 years (Ortiz-Bobea *et al.* 2021). Without long-term solutions, issues such as GHG emissions, soil degradation, and dwindling groundwater will worsen. Thus, systemic solutions integrating climate-smart, regenerative practices are needed to protect soil health and sustain production (Jat *et al.* 2022). South Asia's future food security will depend on efficient, climate-smart practices like Conservation Agriculture (CA), which aligns with the United Nations' Sustainable Development Goals (SDGs) (Roy *et al.* 2022). Over the last two decades, CA has been recognized in South Asia as a strategy for increasing productivity, profitability, soil health, and climate resilience, contributing to "sustainable intensification" (Bell *et al.* 2018).

With the reduction in tillage, reliance on herbicides for weed management in CA cotton increases. Herbicide use is a vital component of cotton grown under reduced-till systems. More than one million kg of herbicide-active ingredients are applied annually to achieve weed-free cotton fields in Australia (Charles 1991). Herbicide use is an essential management practice in cotton growing and multiple applications of a wide array of herbicides in a single season are a common practice.

Soil health is an inherent component of conservation agriculture maintaining the capacity of soil to function as the dynamic living system within the ecosystem and land management practices, sustaining crop productivity, regulating water and air quality, controlling soil nutrient cycling, and improving plant and animal health (Daryanto *et al.* 2018, Wade *et al.* 2022). This review provides a brief summary of current knowledge regarding the impact of weed management practices on soil properties within conservation agriculture (CA)-based cotton cropping systems, as derived from globally published peer-reviewed studies.

Effect of weed management in conservation agriculture (CA) on soil attributes in cotton-based system

Weed management practices play a crucial role in determining soil physical properties in cotton-based cropping systems, especially under conservation agriculture (CA).

Soil physical properties

Bulk density: Bulk density of soils, an essential indicator of soil compaction and porosity, significantly influences root penetration and water movement. Studies in the semi-arid regions of Telangana found that conservation tillage combined with mulching reduced bulk density compared to conventional tillage, enhancing root growth and water infiltration (Srinivasarao *et al.* 2014a). In rainfed cotton systems mulching with crop residues decreased bulk density, particularly in areas with hard-setting soils, such as parts of Maharashtra and Karnataka (Patil *et al.* 2017a).

Rao *et al.* (2016) observed that reduced tillage systems under CA lowered bulk density by improving soil structure and reducing compaction. Retaining crop residues also contributed to reduced bulk density, as increased organic matter promoted soil biota, which enhanced porosity (López-Garrido *et al.* 2011). Although bulk density assessments prior to annual tillage did not differ significantly between no-till and conventional tillage systems, Nouri *et al.* (2019) observed that cone penetration resistance was greater under tilled systems.

Soil structure and aggregation: Soil structure, defined by the arrangement of soil particles into aggregates, plays a crucial role in water retention and nutrient availability. Lal (1991) emphasized that no-tillage and cover crops improve soil resilience by modifying structural characteristics such as aggregate stability, pore size distribution, and soil ped arrangement.

In cotton-growing regions with loamy soils, Bhattacharyya *et al.* (2015a) observed that mulching with organic residues helped stabilize fine soil particles, promoting better aggregate formation and reducing soil erosion risks. Similarly, Sharma *et al.* (2018a) reported that conservation agriculture (CA) practices involving mulching and minimal disturbance improved soil aggregation in Haryana, which enhanced organic carbon sequestration and reduced erosion. Minimal tillage and herbicide applications significantly improved the geometric mean diameter (GMD) of soil aggregates, highlighting the role of minimal disturbance in maintaining soil stability (Rao *et al.* 2009).

In Gujarat, Patra *et al.* (2016) found that retaining cotton stalk residues increased organic carbon content and microbial activity, which promoted soil aggregation. Studies by Rathore *et al.* (2020) in India and Ferreira *et al.* (2019) in Brazil also showed that crop residue retention improved aggregate stability, leading to better water infiltration and reduced erosion in cotton systems. Better soil aggregation supports both root penetration and soil resilience, essential for the long-term sustainability of cotton cropping systems under CA.

Mitigating climate change involves lowering atmospheric GHG concentrations by addressing emission sources. Soil plays a key role in climate change mitigation and carbon-climate interactions. Intensive tillage practices break down soil macroaggregates, speeding up carbon loss from the soil and increasing GHG emissions. Whereas, CA systems by minimizing or eliminating tillage, enhance carbon sequestration in the soil, decrease gaseous emissions, and support environmental sustainability.

Soil penetration resistance: Weed management practices like mechanical weeding and frequent tillage often increase soil compaction, leading to higher penetration resistance. However, under CA, practices such as herbicide use or mulching help reduce soil compaction. Mitchell *et al*. (2012) found that minimizing soil disturbance in cotton fields in the USA led to more friable soils, lowering penetration resistance and improving root growth and yields.

CA combined with crop residue retention reduced soil compaction in semi-arid regions and mulching helped retain soil moisture and reduced surface sealing, significantly lowering penetration resistance (Ghosh *et al*. 2010). Similarly, minimal tillage with mulching in rainfed cotton fields reduced compaction (Rajanna *et al*. 2015). In the Indo-Gangetic Plains, Kaur *et al.* (2016) noted that residue retention with reduced tillage lowered penetration resistance in cotton-wheat systems by maintaining soil porosity. Similar results in central India were reported by Chaudhary *et al.* (2014), where residue retention improved soil structure and reduced compaction. Long-term CA practices, including residue retention, have consistently lowered penetration resistance (Sarkar *et al.* 2007, Mondal *et al.* 2019).

Rao *et al.* (2013) found that no-tillage combined with mulching reduced penetration resistance, improving water-use efficiency. Similarly, Dahiya *et al.* (2018) and Srinivasarao *et al.* (2014a) observed deeper root growth and improved nutrient uptake due to lower penetration resistance. Penetration resistance increased with depth, it stayed below harmful levels under controlled traffic systems in irrigated cotton, promoting healthy root growth (Bennett *et al.* 2017).

Hydraulic conductivity and infiltration rate: Studies in Africa (Kassam *et al*. 2017) and India (Kumar *et al*. 2020) highlighted that mulching enhanced soil organic matter and reduced surface sealing, leading to better water infiltration. No-tillage systems under CA, paired with effective weed control, improve soil structure and porosity, promoting higher hydraulic conductivity (Blevins *et al*. 2013). These improvements are critical for enhancing cotton yields, particularly in arid and semi-arid regions where water management is essential.

Using cotton stalk residues as organic mulches in CA cotton fields reduced the weed density as well as significantly improved hydraulic conductivity. The increased organic matter from mulches enhanced soil porosity, facilitating better water infiltration and reducing surface runoff Singh *et al*. (2018). In Zambia, Thierfelder and Wall (2010) found that CA plots had significantly higher infiltration rates compared to conventionally ploughed plots in the cotton-maize rotation system.

Soil physico-chemical properties

CA practices like reduced tillage, mulching, and residue retention under CA play a critical role to stabilize pH, reduce salt accumulation, and enhance the soil CEC by increasing organic matter.

Soil pH: Soil pH is critical for nutrient availability, directly affecting cotton growth. Organic residues maintained soil pH close to neutral, optimal for cotton. Crop residues buffer pH fluctuations and enhance microbial activity, which promotes overall soil health (Kumar *et al*. 2017a). In Karnataka, Rajanna *et al.* (2015) observed that reduced tillage and mulching kept soil pH in the 6.5-7.0 range, enhancing nutrient availability in semi-arid rainfed cotton fields. Similarly, Doran *et al.* (2014) reported that organic mulches in Australian cotton fields stabilized soil pH.

Electrical conductivity (EC): Holland *et al.* (2015) found that CA practices kept EC within sustainable limits, improving crop performance, particularly in arid conditions in US cotton-based systems. Crop residue mulching in cotton reduced surface evaporation, maintaining moisture levels and preventing salt accumulation in surface layers (Patil *et al.* 2017b). Singh *et al.* (2019) also noted that no-tillage combined with organic mulching in cotton significantly lowered EC.

Cation exchange capacity (CEC): CEC is a key indicator of soil fertility, reflecting the soil's ability to retain and exchange essential nutrients. In semi-arid ecosystems, Rao *et al*. (2018) observed that conservation tillage combined with residue retention significantly increased soil organic carbon, thereby enhancing soil CEC in cotton systems. Crop residue mulching improved soil CEC in rainfed cotton fields in central India by increasing soil organic matter (Bhattacharyya *et al.* 2015a). Li *et al.* (2013) also demonstrated that CA practices adopted in cotton in China increased CEC, indicating improved nutrient retention due to crop residue accumulation.

Soil organic carbon (SOC) and carbon pools: Weed management practices under CA minimize the soil disturbance and incorporate organic matter and enhance SOC levels. Lal (1997) highlighted the role of SOC in improving soil resilience through enhanced nutrient cycling and aggregation. Govaerts *et al.* (2009) in Mexico and Singh *et al.* (2020) in Gujarat demonstrated that reduced tillage with residue retention improved stable carbon pools, enhancing SOC retention. Similarly in US cotton fields, Franzluebbers *et al.* (2004) noted increases in SOC and stable carbon due to reduced tillage. Lal *et al.* (2015) and Blanco-Canqui *et al.* (2017) found similar results in the United States and Brazil, where reduced tillage and mulching in cotton systems increased SOC, improving soil fertility and long-term carbon sequestration. Conversion of all agricultural land to conservation tillage globally could sequester 25 Gt C over the next 5 decades which is equivalent to 1,833 Mt CO_2-eq/yr, making CA one of the significant opportunities from all sectors for mitigating global GHG concentrations (Baker *et al.* 2007).

Weed management practices also influence carbon pool dynamics. In Punjab, no-till and residue retention enhanced both pools, promoting microbial activity in the labile pool and carbon sequestration in the stable pool (Sharma *et al.* 2017). Similarly, CA practices in Mediterranean and sub-Saharan African cotton systems increased stable carbon pools, highlighting the benefits of minimal soil disturbance on long-term carbon sequestration (Álvaro-Fuentes *et al.* 2009, Six *et al.* 2002).

Herbicide use combined with reduced tillage helped to maintain higher SOC by reducing mechanical weeding and carbon oxidation (Rao *et al.* 2019a). Patil *et al.* (2017b) reported that mulching in rainfed cotton fields increased SOC and labile carbon, promoting soil fertility. Crop residues in cotton fields improved labile carbon, which supports microbial activity, and stable carbon, which contributed to long-term carbon storage (Bhattacharyya *et al.* 2018).

In addition to reducing wind erosion, conservation practices—such as no-till, reduced tillage, and cover cropping—have been shown to decrease net greenhouse gas emissions (Paustian *et al.* 1997). Keeping plant residue on the soil surface helps protect sequestered carbon by minimizing tillage (Schomberg and Jones 1999). Roberts and Chan (1990) observed lower CO_2 emissions in less-intensive tillage simulations compared to more intensive ones. Long-term no-till combined with cover crops can lead to lower soil CO_2 losses, increasing soil organic carbon levels and contributing to the sustainability of cotton production, especially in regions like the Texas High Plains (McDonald *et al.* 2019).

Impact on nutrient availability

Weed management practices in conservation agriculture (CA) have a significant impact on the availability of macro and micronutrients in cotton-based systems by improving nutrient cycling, organic matter retention, and microbial activity.

Macronutrients: Mupangwa *et al.* (2017) showed that crop residue mulching in Southern African cotton systems increased nitrogen availability. Residue retention and no-till practices in India reduced nitrogen losses, improving nitrogen availability (Parihar *et al.* 2018, Nthebere *et al.* 2023). In systems rich in labile substrates, bacteria efficiently decompose organic matter, accelerating nitrogen mineralization (Moore *et al.* 2003, Doles *et al.* 2001). Chivenge *et al.* (2015) reported that mulching boosted phosphorus availability in sub-Saharan African cotton systems through increased microbial activity. Improved phosphorus retention in Indian cotton fields using residue management, especially in phosphorus-deficient soils was noticed by Dwivedi *et al.* (2017). Mwila *et al.* (2018) noted improved potassium availability in Zambia due to steady nutrient release from organic residues. Similarly, Pathak *et al.* (2020) reported that mulching in rainfed cotton systems in India helped retain potassium and reduce leaching. In addition, additional advantages of CA in rainfed systems are reduced nutrient losses along eroded soil with intense rainfall events (Pathak *et al.* 2021). Nitrogen leaching and runoff losses can also be cutdown under CA systems and thereby reducing the need for fertilizer N by 30–50 % (Crabtree, 2010) and has potential to reduce nitrous oxide emissions and mitigate climate change as well.

Micronutrients: Mulching and reduced tillage increased zinc availability in Indian and Ethiopian cotton systems by enhancing microbial activity (Behera *et al.* 2016, Teferri *et al.* 2019). Similarly, Nyamangara *et al.* (2014) found that reduced tillage improved iron availability in Zimbabwean cotton fields. Jha *et al.* (2019) demonstrated that residue mulching enhanced iron availability in India by maintaining soil moisture. Acharya *et al.* (2018), Mbatha *et al.* (2020) both found that CA practices improved copper availability by promoting organic matter retention. Saha *et al.* (2016), Gupta *et al.* (2021) also reported improved manganese availability in cotton systems through mulching and no-till practices, enhancing soil moisture and microbial activity.

Impact of CA in cotton: Reduced GHG emissions, mitigating climate change

In India, conservation agriculture (CA) in cotton based cropping systems could be a vital strategy for climate mitigation, primarily by enhancing the soil's carbon sink, reducing greenhouse gas (GHG) emissions, and minimizing high energy inputs. CA achieves these goals through increased SOC levels and lower CO_2 output due to reduced machinery use. CA practices improve soil nutrient availability, reduce fertilizer needs and thus lowering N_2O emissions. Enhanced soil moisture retention also lowers irrigation demand, saving electricity and reducing associated GHG emissions. CO_2 emissions primarily result from soil tillage and fuel use, crop residue burning, and production of fertilizers and pesticides.

Conservation tillage is particularly effective, as intensive tillage accelerates organic matter decomposition, increasing CO_2 emissions, while reduced tillage slows this process and retains soil carbon (Reicosky *et al.* 1997). Reducing tillage intensity can cut CO_2 emissions and improve carbon sequestration (Reicosky *et al.* 1997). Conservation tillage techniques, such as leaving crop stubble on the soil, help prevent erosion, add organic matter, and conserve moisture (Farooq *et al.* 2011).

Beyond agricultural benefits, CA plays a role in reducing GHGs, enhancing carbon storage, and supporting biodiversity. By enabling gradual sequestration of atmospheric CO_2 into SOC, CA practices stabilize carbon (Pathak *et al.* 2021). In rainfed regions, which cover about 55% of India's arable land and provide around 40% of food production, degraded soils with low SOC and nutrient deficiencies are common. Cotton, widely grown in these dryland areas, benefits substantially from CA practices that improve soil health and sustain productivity.

Impact on soil microbial population, activity and diversity

Soil microorganisms contribute immensely to soil health and quality, and secrete soil enzymes which play a pivotal role in nutrient cycling and transformation in the soil (Wu *et al.* 2016). Application of herbicides manifested adverse effects on non-target organisms including microorganisms such as bacterial, fungal, actinomycetes and free-living nitrogen-fixing organisms *i.e.*, *Azotobacter* and *Azospirillum* (Latha and Gopal 2010). Herbicides may not influence the overall size of the microorganism pool but selectively affect specific groups of biota resulting in modifying the balance of soil microbial populations and consequently nutrient availability, pest & disease incidence and crop growth (Gupta and Roberts 2003). However, Wardle and Parkinson (1990) reported that herbicides may increase or stimulate the population growth of microorganisms and activities given the ability of the microorganisms to utilize herbicides as a source of carbon and other required nutrients.

A study by Chaudhari *et al.* (2020) in a cotton-greengram system showed that inter-cultivation combined with hand weeding (IC + HW) at various intervals significantly increased soil microbial population and activity, particularly when followed by pendimethalin application. The same observations were also reported by Sivakumar *et al.* (2021). Nthebere *et al.* (2024) observed a decline in microbial activity in cotton-maize-Sesbania CA systems due to herbicide application, with recovery noted after 60 days as toxicity decreased. This aligned with the study by Bowels *et al.* (2014) and Jarvan *et al.* (2014). Such patterns suggest that herbicides at recommended rates do not permanently inhibit microbial activity (Lupwayi *et al.* 2004, 2009; Nalayini *et al.* 2013, Tejashree *et al.* 2018). The influence of pre-emergence herbicide diuron was higher in black soils than in red soils on soil bacterial counts (Faizullah *et al.* 2020a).

Conservation agriculture (CA) practices are associated with increased microbial diversity due to reduced tillage, promoting fungal dominance in systems with surface crop residue (Frey *et al.* 2003, Moore *et al.* 2003, Paustian *et al.* 2000, Holland 2004). Blanchart *et al.* (2004) and Six *et al.* (2006) emphasized the role of these organisms in creating stable soil aggregates and organo-mineral complexes. Earthworm activity, in particular, is stimulated by the absence of tillage, leading to reduced physical damage and habitat disturbance (Castellanos-Navarrete *et al.* 2012).

Research has shown that climate change markedly influences microbial community composition and biomass (Ochoa-Hueso *et al.* 2018), enzyme activity levels (Burns *et al.* 2013), and the functional traits of soil microbes (Bai *et al.* 2019). These shifts in microbial communities due to climate change have profound implications for nutrient cycling processes. Yet, most studies have primarily examined these effects in natural or semi-natural ecosystems, leaving significant gaps regarding the impact of climate change on soil microbial communities within agroecosystems (Poll *et al.* 2013). Notably, bacteria within microbial communities exhibit greater sensitivity to water stress, such as drought, compared to fungi (De Vries *et al.* 2012). However, substantial uncertainty remains about the specific effects of climate change on soil enzyme activity.

Soil enzyme activity

Soil enzymes play a pivotal role in energy transfer through the decomposition of soil organic matter, nutrient recycling and are vital indicators of soil health, soil pollution and ecological restoration (Wu *et al.* 2016). In the studies on *Bt* cotton fields treated with various herbicides, it was reported that pendimethalin-treated soils exhibited higher soil dehydrogenase activity (DHA), indicating lower toxicity compared to other herbicides (Atri *et al.* 2006, Veena *et al.* 2010, Tejashree *et al.* 2018). Srinivasarao *et al.* (2014b) observed increased DHA in cotton systems under no-till and mulching practices due to improved microbial conditions in the soil supported from the study by Wang *et al.* (2018) from China. Zhang *et al.* (2015) reported higher urease activity under reduced tillage in Australia. Rao *et al.* (2019b) observed increased urease activity, where crop residue mulch combined with minimal tillage provided a conducive environment for nitrogen retention and microbial activity. Application of diuron as pre-emergence herbicide to cotton significantly reduced the soil urease activity till 30 DAS (Faizullah *et al.* 2020b).

Sharma *et al.* (2018b) found significantly higher phosphatase activity in no-till systems with crop residue retention in Punjab, India, while García-Ruiz *et al.* (2012) observed in Mediterranean cotton fields. In conservation agriculture (CA), Sebiomo *et al.* (2011) reported increased acid phosphatase (AcP) activity in *Bt* cotton treated with pendimethalin, attributed to microbial adaptation to the herbicide. A 46% increase in AcP and a 61% increase in alkaline phosphatase activity under no-till systems, indicating that reduced tillage boosts phosphatase activity (Balota *et al.* 2004). Activity of soil acid phosphatase enzyme was inhibited by the application of diuron where the reduction of activity increased with the increase in dosage of the chemical to cotton crop. While the activity of the alkaline phosphatase remained unaffected (Varsha *et al.* 2019).

Fluorescein diacetate (FDA) hydrolysis, a measure of overall microbial activity, was significantly higher in cotton fields under CA with mulching in Maharashtra (Kumar *et al.* 2017b). This was linked to improved microbial habitat, a finding confirmed by Paz-Ferreiro *et al.* (2011) in Spanish cotton systems under CA, where mulching supported higher microbial activity. Beta-galactosidase activity, crucial for organic carbon turnover, was found to be enhanced by mulching in Indian cotton systems (Bhattacharyya *et al.* 2015b). Kandeler *et al.* (2017) reported similar results in German cotton fields, where reduced tillage and mulching promoted microbial activity and organic matter decomposition.

Climate warming could accelerate enzyme actions (Wallenstein and Weintraub 2008), but it may also reduce enzyme production by soil micro-organisms (Allison *et al.* 2010) and heighten enzyme denaturation (Nottingham *et al.* 2016). Additionally, drought conditions can influence enzyme activity, as microorganisms under drought stress tend to allocate nutrients and energy towards synthesizing osmolytes and maintaining internal stability rather than enzyme production (Schimel 2018).

Effects on SMBC and SMBN

Soil microbial biomass carbon (SMBC) and nitrogen (SMBN) are essential indicators of soil microbial activity and overall health, particularly in conservation agriculture (CA) systems. Yadav *et al.* (2015) from Madhya Pradesh (India) found that IWM significantly increased SMBC and SMBN in cotton systems by providing organic matter from cover crops, while reduced herbicide use minimized microbial suppression. Similarly, higher SMBC and SMBN in IWM-managed cotton systems compared to conventional systems, attributed to increased nitrogen mineralization and carbon cycling (Patel *et al.* 2018). Rusinamhodzi *et al.* (2018) further demonstrated that combining herbicide use with cover cropping enhanced microbial biomass in cotton systems, mitigating the negative impacts of herbicide-only systems. Conversely, continuous glyphosate use, without organic matter input, led to reduced SMBC and SMBN over time (Weaver *et al.* 2007).

Gupta and Roberts (2003) reported that SMBC decreased after herbicide application but increased as the cotton season progressed, suggesting cotton-induced stimulation of microbial activity. Nthebere *et al.* (2024) further supported these results, showing varying effects of herbicides on SMBC. Long-term adoption of CA practices, including residue retention, boosts microbial biomass. Lal (2015) observed significantly higher SMBC and SMBN in Indian cotton systems that had adopted CA for over a decade. Silva *et al*. (2019) reported long-term benefits in cotton systems, highlighting the role of reduced tillage and cover crops in enhancing microbial activity. In India, Srinivasarao *et al*. (2014b), Nthebere *et al*. (2024) demonstrated that no-till practices with residue retention significantly increased SMBC and SMBN in cotton systems, while Bhattacharyya *et al*. (2013) confirmed the positive effects of reduced tillage in rainfed cotton areas. Franzluebbers *et al*. (1999), Das *et al*. (2018) reported similar findings, with no-till and leguminous cover crops like cowpea and pigeonpea significantly increasing SMBC and SMBN in cotton systems.

Several studies have reported metabolic quotient values (qCO_2) *i.e*., soil organic carbon per unit microbial biomass were higher under herbicides treatments than in the control soils (without herbicide treatment) in cotton CA-based system (Gupta and Roberts, 2003). A reduction in SMBC contents and increase in qCO_2 values generally indicates a stress on the growth of microbial community. As the microbial community recovered from herbicide impacts by the final sampling the qCO_2 values lowered (Nthebere *et al.* 2024).

Weed dynamics and herbicide efficacy changes with climate change under CA

Climate change is marked by rising temperatures and unpredictable precipitation which influence the C_3 and C_4 species differently. In CA systems, where mechanical weed control is limited, dependence on herbicides grows. Herbicide effectiveness varies with factors such as light, CO_2 levels, temperature, moisture, and wind:

Light – High light intensity keeps stomata open, enhancing foliar herbicide uptake. More branching increases surface area for herbicide application, though thicker leaves under high light can impede herbicide diffusion (Riederer and Schoneer 1985).

CO_2 – Elevated CO_2 can reduce stomatal conductance by up to 50%, altering herbicide effectiveness due to leaf thickening and fewer open stomata, which limit penetration. Glyphosate efficacy, for instance, declines in C_4 weeds with increased root-to-shoot ratios under high CO_2 (Ziska 2008, Ziska *et al.* 2004).

Temperature – Higher temperatures can decrease cuticle viscosity, enhancing herbicide absorption, though they may also speed up herbicide metabolism, reducing efficacy (Price 1983, Kells *et al.* 1984).

Precipitation and soil moisture – Low soil moisture, common in cotton-based systems, reduces herbicide uptake due to greater adsorption to soil particles (Dao and Lavy 1978). Moisture stress further limits herbicide diffusion and absorption (Kogan and Bayer 1996).

Soil quality

Soil quality refers to the ability of soil to function within an ecosystem to sustain biological productivity, maintain quality of the environment, and enhance plant and animal health (Doran and Parkin 1994). Soil quality index (SQI) is widely used to assess these aspects, integrating physical, chemical, and biological properties of soil. Agricultural practices, particularly tillage, play a crucial role in influencing these properties, with no-till systems generally showing improved soil structure and overall quality compared to conventional tillage (Mulat *et al.* 2021). Assessing soil quality, especially under conservation agriculture (CA), helps in evaluating degraded soils and understanding changes brought by different management practices (Tesfahunegn 2014). While soil quality cannot be measured directly, SQI provides a comprehensive measure by quantifying soil's physical, chemical, and biological properties. This index relies on appropriate indicators of soil functions, and methods like Principal Component Analysis (PCA) are used to handle data dimensionality (Rezaei *et al*.2006). Numerous studies have demonstrated the positive impact of no-till practices on soil quality, although their effectiveness depends on adequate residue input, which can be limited in low-residue cropping systems (Blanco-Canqui *et al.* 2011, Wang and Shao 2013).

Cover crops offer significant benefits to agricultural ecosystems, improving soil organic carbon (SOC) sequestration, microbial activity, moisture retention, and reducing soil erosion and nutrient leaching. These improvements in soil health and quality are well-documented (Alhameid *et al.* 2019, Nouri *et al.* 2019, Singh *et al.* 2022). Parihar *et al*. (2020) found significantly higher SQI under permanent bed/zero tillage systems compared to conventional tillage, with strong correlations between SOC and other soil parameters.

In a comparative study, Edralin *et al*. (2017) reported better soil quality with adoption of CA compared to conventional tillage. This improvement was attributed to increased soil organic carbon, nitrogen, higher soil moisture retention, and lower soil temperature during dry periods, highlighting the benefits of CA for enhancing soil health. Nthebere *et al*. (2024) noted that, considering both crop productivity and soil quality, IWM was the better weed management option compared to sole chemical weed management resulting in the higher productivity for the cotton-maize system and sustained soil quality. Acosta Martinez *et al*, (2023) found the potential of no-tillage and crop residue mulching to improve soil health in cotton production in semiarid tracts, which are more prone to climate change impacts, and a platform for a soil health evaluation that links different soil health pointers with functions related to soil organic carbon, soil water, and nutrient cycling.

Conclusions

CA practices are essential for enhancing soil health and preventing degradation in cotton-based systems. Weed management practices under CA significantly affect soil enzyme activities, including dehydrogenase, urease, and phosphatase. Herbicides may temporarily suppress microbial activity and enzyme functions, though these effects are often short-lived. Balancing herbicide use with sustainable practices like mulching and crop rotation is crucial to maintain soil quality and productivity in cotton-based CA systems. Further research into the impacts of weed management on the soil microbiome and nutrient cycling is essential to improve the sustainability of these systems. Conservation agriculture (CA) in cotton is a sustainable farming approach that recycles crop residues, uses less water and energy, and reduces global warming. In addition to its benefits as an agricultural development strategy, conservation agriculture (CA) addresses climate change challenges and aids significantly in climate change mitigation. This includes reducing GHG emissions, promoting carbon sequestration, and supporting the conservation of soil biodiversity.

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