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Conservation agriculture in tropical cropping systems: Implications for soil health and productivity

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Abstract

Conservation agriculture (CA) has emerged as an effective strategy to improve soil health, enhance crop productivity, and promote sustainability in tropical cropping systems (Lal, 2015). Tropical agroecosystems frequently experience challenges such as soil erosion, nutrient depletion, land degradation, erratic rainfall, and climate change vulnerability that threaten long-term agricultural productivity (FAO, 2017). Conservation agriculture is based on three core principles: minimum soil disturbance, permanent soil cover, and diversified crop rotations that support ecological balance and soil functioning (Hobbs *et al.*, 2008). These practices improve soil structure, enhance microbial diversity, increase soil organic carbon, and promote efficient nutrient cycling processes (Six *et al.*, 2004). Research indicates that CA systems enhance soil physical, chemical, and biological properties, resulting in improved soil fertility and resilience (Palm *et al.*, 2014). Residue retention and cover cropping significantly increase biomass inputs and contribute to soil organic carbon accumulation in tropical soils (Blanco-Canqui & Lal, 2008). Improved soil aggregation and organic matter stabilization under CA enhance water retention capacity and nutrient availability (Bronick & Lal, 2005). Several studies demonstrate that conservation agriculture increases soil carbon sequestration potential and strengthens climate resilience in agricultural systems (Paustian *et al.*, 2016). Long-term experimental evidence suggests that CA improves soil organic carbon stocks and contributes to sustainable soil management (Powlson *et al.*, 2014). CA practices also reduce soil erosion losses and improve water use efficiency, which is critical for tropical rainfed agriculture (Thierfelder & Wall, 2010). Yield stability under CA systems has been reported in many tropical cropping systems due to improved soil moisture retention and nutrient availability (Kassam *et al.*, 2012). Thus, conservation agriculture is widely recognized as a climate-resilient approach that enhances resource use efficiency and environmental sustainability (Montgomery, 2007). This review synthesizes recent findings on conservation agriculture in tropical systems, focusing on soil health indicators, productivity benefits, challenges, and future research needs (Pretty & Bharucha, 2014).

Keywords: Conservation agriculture, tropical cropping systems, soil health, productivity, sustainability, soil organic carbon, climate resilience

Introduction

Agriculture in tropical regions faces multiple constraints including soil erosion, declining soil fertility, water scarcity, and climate variability that significantly affect long-term productivity (Lal, 2016) ^[14]. Intensive conventional tillage practices accelerate soil degradation, reduce soil organic matter content, and increase greenhouse gas emissions, thereby threatening sustainability of agroecosystems (Zheng *et al.*, 2018) ^[15]. Conservation agriculture has been widely promoted as a sustainable alternative capable of improving soil health and maintaining crop productivity while conserving natural resources (Hobbs *et al.*, 2008) ^[3]. Conservation agriculture is based on three interlinked principles that include minimum soil disturbance, permanent soil cover, and crop diversification which together enhance agroecosystem stability (Kassam *et al.*, 2012) ^[11]. Minimum soil disturbance through zero or reduced tillage helps preserve soil structure and microbial habitats essential for soil biological functioning (Six *et al.*, 2004) ^[4]. Permanent soil cover using crop residues or cover crops protects the soil surface from erosion and improves soil moisture conservation (Blanco-Canqui & Lal, 2009) ^[17].

Crop diversification through rotations or intercropping improves nutrient cycling and enhances biodiversity within agricultural systems (Lin, 2011) ^[18]. Agriculture in tropical regions faces multiple constraints including soil erosion, declining soil fertility, water scarcity, and climate variability that significantly affect long-term productivity (Lal, 2016) ^[14]. Intensive conventional tillage practices accelerate soil degradation, reduce soil organic matter content, and increase greenhouse gas emissions, thereby threatening sustainability of agroecosystems (Zheng *et al.*, 2018) ^[15]. Conservation agriculture has been widely promoted as a sustainable alternative capable of improving soil health and maintaining crop productivity while conserving natural resources (Hobbs *et al.*, 2008) ^[3]. Conservation agriculture is based on three interlinked principles that include minimum soil disturbance, permanent soil cover, and crop diversification which together enhance agroecosystem stability (Kassam *et al.*, 2012) ^[11]. Minimum soil disturbance through zero or reduced tillage helps preserve soil structure and microbial habitats essential for soil biological functioning (Six *et al.*, 2004) ^[4]. Permanent soil cover using crop residues or cover crops protects the soil surface from erosion and improves soil moisture conservation (Blanco-Canqui & Lal, 2009) ^[17]. Crop diversification through rotations or intercropping improves nutrient cycling and enhances biodiversity within agricultural systems (Lin, 2011) ^[18]. These practices enhance soil biological activity, improve soil aggregation, and significantly reduce soil erosion losses especially in fragile tropical ecosystems (Bronick & Lal, 2005) ^[7]. Tropical cropping systems such as rice–wheat systems have demonstrated improved soil fertility and yield stability under conservation agriculture practices (Jat *et al.*, 2014) ^[19]. Maize–legume based conservation agriculture systems improve soil organic carbon accumulation and nutrient availability (Thierfelder *et al.*, 2012) ^[20]. Rice–maize cropping systems under conservation agriculture improve soil structure, water retention, and productivity compared with conventional tillage systems (Parihar *et al.*, 2016) ^[21]. Sugarcane-based conservation agriculture systems enhance soil microbial activity and nutrient use efficiency leading to improved productivity (Govaerts *et al.*, 2009) ^[22].

Principles of Conservation Agriculture

Minimum Soil Disturbance

Reduced or zero tillage minimizes soil disturbance and preserves soil structural stability, which is essential for maintaining soil quality (Hobbs *et al.*, 2008) ^[3]. Minimum soil disturbance improves soil aggregation and enhances pore continuity, allowing better root penetration and aeration (Six *et al.*, 2000) ^[23]. Conservation tillage practices enhance water infiltration and reduce runoff losses, thereby improving water availability in crop root zones (Lal, 2015) ^[11]. Reduced tillage also minimizes oxidation of soil organic matter and helps maintain soil carbon stocks essential for long-term soil fertility (Paustian *et al.*, 1997) ^[24]. Zero tillage systems create favorable conditions for soil microbial growth and activity, enhancing soil biological processes (Nannipieri *et al.*, 2003) ^[25]. Earthworm populations and soil macrofauna are generally higher under reduced tillage systems, contributing to improved soil porosity and nutrient cycling (Edwards & Bohlen, 1996) ^[26]. Enhanced biological activity under minimum soil disturbance improves nutrient mineralization and overall soil fertility in tropical agroecosystems (Franzluebbers, 2002) ^[27].

Permanent Soil Cover

Retention of crop residues or cover crops on the soil surface protects soil from erosion caused by rainfall impact and wind forces (Montgomery, 2007) ^[12]. Surface residue cover reduces evaporation losses and improves soil moisture conservation, particularly in tropical climates (Unger & McCalla, 1980) ^[28]. Permanent soil cover moderates soil temperature fluctuations and creates favorable soil microclimatic conditions for crop growth (Mulumba & Lal, 2008) ^[29]. Residue mulching enhances soil organic matter accumulation and improves soil nutrient availability through gradual decomposition (Blanco-Canqui & Lal, 2007) ^[30]. Surface mulch promotes nutrient cycling by adding organic inputs that enhance microbial decomposition processes (Palm *et al.*, 2001) ^[31]. Crop residues on the soil surface also suppress weed growth by limiting light availability and modifying soil environmental conditions (Teasdale & Mohler, 2000) ^[32].

Crop Diversification

Crop rotation improves soil nutrient balance by alternating crops with different nutrient requirements and rooting characteristics (Karlen *et al.*, 1994) ^[33]. Intercropping systems enhance nutrient use efficiency and improve resource utilization by reducing competition among crops (Lithourgidis *et al.*, 2011) ^[34]. Crop diversification helps break pest and disease cycles and reduces reliance on chemical pesticides in cropping systems (Altieri, 1999) ^[35]. Diverse cropping systems enhance soil biological diversity including beneficial microorganisms that support soil health (Drinkwater *et al.*, 1995) ^[36]. Crop rotation contributes to improved soil organic carbon dynamics and enhances long-term soil fertility (West & Post, 2002) ^[37, 80]. Diversified cropping systems improve resilience of agricultural production systems against climate variability and environmental stresses (Lin, 2011) ^[18].

Conservation Agriculture in Tropical Cropping Systems Rice–Wheat Cropping System

Rice–wheat is one of the most dominant cropping systems in tropical and subtropical regions, contributing significantly to global food security (Ladha *et al.*, 2003) ^[38]. Continuous intensive tillage in rice–wheat systems has resulted in soil degradation, declining factor productivity, and increasing cost of cultivation (Gupta & Seth, 2007) ^[39]. Conventional puddling and repeated ploughing adversely affect soil structure and reduce long-term sustainability of the production system (Hobbs & Gupta, 2003) ^[40]. Conservation agriculture practices such as zero tillage help reduce soil disturbance and improve soil physical properties (Erenstein & Laxmi, 2008) ^[41]. Residue retention under CA enhances soil organic carbon accumulation and improves nutrient cycling in rice–wheat systems (Jat *et al.*, 2014) ^[19]. Zero tillage combined with residue management improves water productivity and reduces irrigation requirements (Gathala *et al.*, 2011) ^[43]. Adoption of conservation agriculture improves crop yield stability and enhances sustainability of rice–wheat production systems (Kassam *et al.*, 2012) ^[11].

Maize-Based Cropping Systems

Maize-based cropping systems are widely adopted in tropical agriculture due to their high productivity potential and adaptability (Shiferaw *et al.*, 2011) ^[44]. Maize–legume rotations improve soil nitrogen availability through

biological nitrogen fixation processes (Giller, 2001) ^[45]. Legume integration enhances soil fertility by increasing nitrogen contribution to subsequent crops (Peoples *et al.*, 2009) ^[46]. Conservation agriculture practices improve soil organic matter accumulation in maize-based systems (Thierfelder & Wall, 2010) ^[10]. Improved soil structure enhances root proliferation and nutrient uptake efficiency in maize cropping systems (Blanco-Canqui *et al.*, 2012) ^[48]. Increased soil organic matter improves water retention and enhances crop productivity under conservation management (Verhulst *et al.*, 2010) ^[49]. Conservation agriculture practices improve long-term sustainability and resilience of maize-based production systems (Thierfelder *et al.*, 2012) ^[20].

Rice–Maize Cropping System

Rice–maize cropping systems are increasingly popular in tropical regions due to their productivity advantages (Timsina *et al.*, 2010) ^[50]. Continuous intensive tillage in rice–maize systems can reduce soil aggregation and nutrient availability (Choudhary *et al.*, 2018) ^[51]. Conservation agriculture practices improve soil aggregation and stability through improved soil organic matter content (Six *et al.*, 2002) ^[52]. Microbial biomass carbon increases significantly under conservation agriculture practices due to improved organic residue inputs (Zuber & Villamil, 2016) ^[53]. Improved nutrient availability enhances crop growth and productivity in conservation agriculture-based systems (Palm *et al.*, 2014) ^[5]. Conservation agriculture improves system productivity and enhances long-term sustainability of rice–maize cropping systems (Jat *et al.*, 2018) ^[54]. Improved soil health under CA contributes to stable crop yields under varying climatic conditions (Lal, 2015) ^[1].

Agroforestry and Mixed Cropping Systems

Agroforestry systems integrate trees with crops and livestock to improve resource use efficiency and sustainability (Nair, 2011) ^[56]. Integration of trees in cropping systems improves carbon sequestration potential and reduces atmospheric carbon dioxide levels (Albrecht & Kandji, 2003) ^[57]. Tree-based systems improve soil structure through root biomass addition and organic matter inputs (Young, 1997) ^[58]. Agroforestry practices enhance biodiversity and promote ecological balance in agricultural landscapes (Jose, 2009) ^[59]. Mixed cropping systems improve soil fertility through improved nutrient cycling and organic matter addition (Drinkwater *et al.*, 1998) ^[60]. Agroforestry-based conservation agriculture systems improve resilience against climate variability and extreme weather conditions (Garrity, 2004) ^[61]. Integration of trees with crops improves long-term productivity and sustainability in tropical agroecosystems (Nair *et al.*, 2010) ^[62].

Impact of Conservation Agriculture on Soil Health Physical Properties

Conservation agriculture improves soil structure by promoting the formation of stable aggregates that enhance soil resilience against erosion (Six *et al.*, 2002) ^[52]. Improved aggregate stability under conservation agriculture enhances soil porosity and aeration (Bronick & Lal, 2005) ^[7]. CA practices increase water infiltration rate by improving soil pore continuity and reducing surface crust formation (Franzluebbers, 2002) ^[27]. Residue retention and

reduced tillage improve soil water holding capacity by increasing soil organic matter content (Blanco-Canqui *et al.*, 2015) ^[64]. Reduced tillage decreases soil compaction and bulk density, thereby improving soil physical condition (Hamza & Anderson, 2005) ^[65]. Improved soil structure under conservation agriculture enhances root penetration and root proliferation (Batey, 2009) ^[66]. Improved soil physical properties contribute to better crop establishment and productivity under conservation systems (Lal, 2015) ^[1].

Chemical Properties

Soil organic carbon is considered a key indicator of soil health and sustainability in agricultural systems (Lal, 2004) ^[68]. Conservation agriculture increases soil organic carbon accumulation through residue retention and reduced oxidation of soil organic matter (Paustian *et al.*, 2016) ^[8]. Reduced tillage practices help protect soil organic matter from rapid decomposition and enhance carbon stabilization (West & Post, 2002) ^[37, 80]. Increased soil organic carbon improves cation exchange capacity and nutrient retention ability of soils (Brady & Weil, 2016) ^[69]. Studies report increased availability of essential nutrients such as nitrogen, phosphorus, and potassium under conservation agriculture systems compared with conventional tillage (Govaerts *et al.*, 2009) ^[22]. Residue decomposition contributes to gradual nutrient release and improves soil fertility (Palm *et al.*, 2001) ^[31]. Improved nutrient availability under conservation agriculture enhances crop growth and productivity (Drinkwater & Snapp, 2007) ^[70].

Biological Properties

Conservation agriculture enhances microbial biomass carbon due to increased organic matter inputs and reduced soil disturbance (Zuber & Villamil, 2016) ^[53]. Soil enzyme activity increases under conservation agriculture due to improved microbial functioning and substrate availability (Dick, 1994) ^[71]. Conservation agriculture promotes soil biodiversity including bacteria, fungi, and actinomycetes essential for soil health (Nannipieri *et al.*, 2003) ^[25]. Increased microbial activity improves nutrient cycling and enhances soil fertility (Smith & Paul, 1990) ^[73]. Residue retention provides energy sources for soil microorganisms and improves microbial population diversity (Wardle, 1995) ^[74]. Earthworm populations increase under reduced tillage systems due to favorable soil habitat conditions (Edwards & Bohlen, 1996) ^[26]. Increased abundance of beneficial microorganisms improves soil aggregation and nutrient mineralization (Six *et al.*, 2006) ^[75]. Improved soil biological activity enhances long-term sustainability of agricultural systems (Lori *et al.*, 2017) ^[76].

Impact of Conservation Agriculture on Crop Productivity

Crop productivity under conservation agriculture systems is influenced by improved soil moisture conservation, enhanced nutrient availability, and reduced soil erosion losses (Lal, 2015) ^[1]. Improved soil structure and residue retention under CA practices increase water infiltration and reduce evaporation losses, thereby improving crop growth conditions (Verhulst *et al.*, 2010) ^[49]. Long-term experiments indicate that conservation agriculture can maintain or increase crop yields compared to conventional tillage systems due to improved soil quality (Pittelkow *et al.*, 2015) ^[78]. Increased soil organic carbon under CA enhances nutrient supply capacity and improves crop

productivity (Paustian *et al.*, 2016) ^[8]. Conservation agriculture practices improve water use efficiency by optimizing soil moisture availability throughout crop growth stages (Rockström *et al.*, 2009) ^[79]. Research findings indicate that CA reduces yield variability and improves crop performance under climatic stress conditions such as drought (Thierfelder & Wall, 2010) ^[10]. Residue retention and reduced tillage improve soil moisture storage which supports crop growth during dry spells (Blanco-Canqui *et al.*, 2015) ^[64]. Yield advantages under conservation agriculture are often more pronounced in rainfed tropical systems where soil moisture conservation is critical for crop productivity (Kassam *et al.*, 2012) ^[11]. Improved root growth and nutrient uptake under CA contribute to stable yields under water-limited conditions (Jat *et al.*, 2014) ^[19]. Conservation agriculture enhances resilience of cropping systems and improves long-term productivity sustainability (Pretty & Bharucha, 2014) ^[13].

Environmental Benefits of Conservation Agriculture Climate Change Mitigation

Conservation agriculture enhances carbon sequestration by increasing soil organic carbon through residue retention and reduced soil disturbance (Lal, 2004) ^[68]. Reduced tillage minimizes oxidation of soil organic matter and helps store carbon in stable soil aggregates (Six *et al.*, 2002) ^[52]. Conservation agriculture reduces greenhouse gas emissions by lowering fuel consumption and minimizing soil disturbance intensity (West & Marland, 2002) ^[37, 80]. Increased biomass input under CA improves long-term carbon storage potential in agricultural soils (Paustian *et al.*, 2016) ^[8]. Improved soil carbon sequestration contributes to climate change mitigation and enhances environmental sustainability (Powlson *et al.*, 2014) ^[9].

Soil Erosion Control

Crop residue cover protects soil surface from rainfall impact and reduces detachment of soil particles (Montgomery, 2007) ^[12]. Surface mulch reduces runoff velocity and minimizes soil erosion losses in sloping lands (Lal, 1998) ^[81]. Conservation agriculture improves soil aggregation which increases resistance to erosion processes (Bronick & Lal, 2005) ^[7]. Reduced tillage practices help maintain soil structure and decrease susceptibility to wind and water erosion (Holland, 2004) ^[82]. Improved soil cover reduces sediment loss and enhances long-term soil sustainability (Blanco-Canqui & Lal, 2008) ^[6].

Water Conservation

Conservation agriculture improves soil infiltration rate by maintaining soil structure and pore continuity (Franzluebbers, 2002) ^[27]. Residue retention reduces evaporation losses and improves soil moisture conservation (Unger & Parker, 1976) ^[83]. Improved soil organic matter enhances soil water holding capacity and moisture availability to crops (Hudson, 1994) ^[84]. Reduced runoff losses under CA improve water use efficiency in rainfed cropping systems (Rockström *et al.*, 2009) ^[79]. Conservation agriculture is particularly beneficial in drought-prone tropical regions due to improved soil moisture storage (Kassam *et al.*, 2012) ^[11].

Biodiversity Enhancement

Conservation agriculture promotes soil biodiversity by creating favorable habitat for microorganisms and soil fauna (Nannipieri *et al.*, 2003) ^[25]. Residue retention provides organic substrates that support microbial growth and activity

(Wardle, 1995) ^[74]. Reduced tillage enhances population of beneficial insects and earthworms which improve soil aeration and nutrient cycling (Edwards & Bohlen, 1996) ^[26]. Increased microbial diversity improves soil ecological stability and resilience (Brussaard *et al.*, 2007) ^[85]. Conservation agriculture enhances ecosystem functioning through improved biological interactions in soil systems (Giller *et al.*, 1997) ^[86].

Constraints in Adoption of Conservation Agriculture in Tropical Regions

Despite multiple agronomic and environmental benefits, the adoption of conservation agriculture (CA) in tropical regions faces several technical, socio-economic, and institutional constraints (Knowler & Bradshaw, 2007). Lack of suitable machinery such as zero-till seed drills and residue management equipment limits adoption among smallholder farmers (Erenstein *et al.*, 2012). Small farm size and fragmented landholdings reduce the economic feasibility of investing in CA machinery in many developing tropical countries (Giller *et al.*, 2009). Limited awareness and inadequate technical knowledge regarding CA practices also restrict adoption among farmers (Kassam *et al.*, 2014). Initial yield fluctuations are often observed during the transition period from conventional tillage to conservation agriculture due to changes in soil biological and physical processes (Pittelkow *et al.*, 2015) ^[78]. Crop residue management poses challenges in tropical regions where residues are often used as livestock feed or fuel, limiting their availability for soil cover (Valbuena *et al.*, 2012). Weed management is another major constraint under zero tillage systems due to reduced soil disturbance, which may initially increase weed pressure (Chauhan *et al.*, 2012). Limited policy support, lack of financial incentives, and inadequate extension services further restrict large-scale adoption of conservation agriculture (Corbeels *et al.*, 2014). Socio-economic constraints such as limited access to credit, labour availability, and market uncertainties influence farmers' decision to adopt CA practices (Feder *et al.*, 1985). Institutional barriers and absence of location-specific recommendations also hinder adoption in diverse tropical agro-ecosystems (Govaerts *et al.*, 2009) ^[22]. Addressing these constraints through research support, policy interventions, and capacity building is essential for wider adoption of conservation agriculture in tropical regions (Lahmar, 2010).

Future Research Needs

Future research should focus on the development of location-specific conservation agriculture (CA) practices that consider variability in soil type, climate, and cropping systems across tropical agro-ecosystems (Kassam *et al.*, 2019). Site-specific recommendations can improve adoption efficiency and enhance productivity under diverse environmental conditions (Corbeels *et al.*, 2014). Integration of precision agriculture tools such as remote sensing, GIS, and decision support systems can optimize input use efficiency and improve soil management practices (Gebbers & Adamchuk, 2010). Advanced spatial technologies can assist in monitoring soil moisture, nutrient variability, and crop performance in CA systems (Zhang *et al.*, 2002). Long-term experiments in tropical soils are required to evaluate the sustainability and resilience of conservation agriculture practices under variable climatic conditions (Lal,

2015)^[1]. Long-duration studies help in understanding soil carbon dynamics, nutrient cycling, and productivity stability in CA-based cropping systems (Paustian *et al.*, 2016)^[8]. Research on the role of soil microbiome in improving nutrient availability, soil aggregation, and plant growth can provide insights into biological mechanisms underlying CA benefits (Bender *et al.*, 2016). Improved understanding of soil microbial interactions can enhance soil fertility management strategies in tropical regions (Trivedi *et al.*, 2017).

Climate-smart conservation agriculture technologies need further development to address climate variability, water scarcity, and extreme weather events (Lipper *et al.*, 2014). Integration of organic amendments such as compost, farmyard manure, green manure, and biofertilizers can improve soil organic matter content and enhance microbial activity in CA systems (Chivenge *et al.*, 2011). Combined use of organic inputs and conservation agriculture practices can enhance nutrient use efficiency and soil sustainability (Vanlauwe *et al.*, 2010).

Emerging technologies such as artificial intelligence (AI)-based soil monitoring, sensor-based nutrient management, and predictive modelling can support sustainable soil management and improve decision-making processes (Liakos *et al.*, 2018). AI-driven decision support systems can improve resource use efficiency and enable climate-resilient crop production strategies in tropical agriculture (Shamshiri *et al.*, 2018). Future interdisciplinary research integrating digital agriculture and conservation agriculture can significantly enhance productivity and environmental sustainability (Rose *et al.*, 2021).

Conclusion

Conservation agriculture plays a significant role in improving soil health and sustaining crop productivity in tropical cropping systems through the combined effects of minimum soil disturbance, permanent soil cover, and crop diversification (Lal, 2015)^[1]. These core principles enhance soil structure, improve aggregation, and increase soil organic carbon, thereby strengthening the physical foundation of productive soils (Six *et al.*, 2002)^[52]. Reduced tillage and residue retention practices stimulate microbial activity and improve nutrient cycling, contributing to enhanced soil fertility and biological functioning (Nannipieri *et al.*, 2003)^[25]. Crop diversification through rotations and intercropping improves nutrient balance and supports long-term soil productivity (Kassam *et al.*, 2012)^[11]. Conservation agriculture provides multiple environmental benefits including increased carbon sequestration, reduced soil erosion, improved water use efficiency, and enhanced resilience to climate variability (Paustian *et al.*, 2016)^[8]. Residue retention protects soil surface from erosion and reduces runoff losses, thereby maintaining soil depth and productivity (Montgomery, 2007)^[12]. Improved soil organic matter enhances soil moisture retention and supports crop growth under drought-prone tropical conditions (Rockström *et al.*, 2009)^[79]. Adoption of conservation agriculture contributes to climate change mitigation by reducing greenhouse gas emissions and improving carbon storage in soils (Powlson *et al.*, 2014)^[9].

Although several challenges such as limited machinery availability, residue management constraints, and socio-economic barriers affect adoption, appropriate policy

support, capacity building, and technological innovations can significantly improve adoption rates (Knowler & Bradshaw, 2007). Research advancements in precision agriculture, climate-smart technologies, and soil biological management can further strengthen conservation agriculture systems in tropical regions (Gebbers & Adamchuk, 2010). Increased farmer awareness and extension support are essential for large-scale adoption of conservation agriculture practices (Corbeels *et al.*, 2014). Overall, conservation agriculture represents a sustainable and climate-resilient approach for improving soil health, enhancing resource use efficiency, and ensuring long-term productivity in tropical agroecosystems (Pretty & Bharucha, 2014)^[13]. Integration of scientific innovations with traditional knowledge can further promote sustainable intensification and environmental conservation in tropical agriculture (Giller *et al.*, 2009).

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