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Conservation agriculture and edge computing with green cloud platforms: Impacts on soil microbial activity and crop-water productivity in RWCS of the NWIGP a systematic review

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Abstract

The rice-wheat cropping system (RWCS) of the Northwest Indo-Gangetic Plains (NWIGP) is one of the most intensive irrigated cereal production systems in the world, covering nearly 13-14 million ha and contributing about 50-60% of India's total wheat production and nearly 30% of rice output. However, continuous intensive cultivation, crop residue burning, and excessive groundwater extraction have resulted in declining soil fertility, deterioration of soil biological processes, and reduced crop water productivity. In many intensively cultivated fields of the region, soil organic carbon (SOC) levels have declined to below 0.4-0.5%, while groundwater tables are decreasing at rates of 0.3-1.0 m annually in several districts of northwest India (Ladha *et al.*, 2003; Jat *et al.*, 2014) ^[14]. Conservation Agriculture (CA), which emphasizes minimal soil disturbance, permanent soil cover through residue retention, and diversified crop rotations, has emerged as a sustainable approach to restore soil health and improve resource-use efficiency in the RWCS.

Conservation Agriculture (CA) practices significantly enhances soil biochemical and microbial characteristics. Residue retention of 5-7 t ha⁻¹ and zero tillage have been reported to increase microbial biomass carbon by 20-40% and soil enzyme activity by 15-35%, indicating improved biological functioning and nutrient cycling (Jat *et al.*, 2014) ^[18]. CA adoption also enhances total SOC stocks by 12-25% and particulate organic carbon fractions by 15-30% within 5-7 years compared with conventional tillage systems (Naresh *et al.*, 2024). Additionally, conservation-based practices can sequester 0.3-0.8 Mg C ha⁻¹ yr⁻¹ in cereal-based agro-ecosystems, contributing to climate change mitigation.

CA increases soil infiltration rates by 20-40% and soil moisture retention by 5-15%, which improves crop water productivity and reduces irrigation requirements (Thierfelder and Wall, 2010) ^[60]. As a result, water productivity in rice-wheat systems improves by 0.2-0.5 kg grain m⁻³, particularly under improved irrigation scheduling (Molden, 2007). In digital agriculture technologies, including edge computing and green cloud platforms provide additional opportunities to optimize conservation agriculture systems. IoT-based soil sensors and edge devices enable real-time monitoring of soil moisture, temperature, and biological indicators, while cloud computing platforms integrate field data with climate information and crop models for decision support. Such digital tools have been reported to reduce irrigation water use by 15-25% and improve precision irrigation scheduling, enhancing overall resource-use efficiency in irrigated agro-ecosystems.

Therefore, the integration of conservation agriculture with edge computing and green cloud technologies offers a promising pathway for sustainable intensification of rice-wheat systems in the Northwest Indo-Gangetic Plains by improving soil microbial activity, optimizing water productivity, and strengthening climate resilience.

Keywords: Conservation agriculture, edge computing, green cloud computing, soil microbial activity, crop water productivity

Introduction

Rice-wheat cropping systems (RWCS) in the Indo-Gangetic Plains (IGP) of South Asia are central to food security, covering approximately 13 million hectares in India and contributing significantly to national cereal production (Jat *et al.*, 2014; Hobbs *et al.*, 2008; Naresh *et al.*, 2018) ^[15, 18]. Despite their productivity, these systems face multiple agronomic,

environmental, and climatic challenges. Intensive tillage, removal of crop residues, excessive fertilizer use, and over extraction of groundwater have led to soil degradation, declining organic carbon stocks, nutrient imbalances, and reduced water-use efficiency. Moreover, climate variability, including erratic rainfall, rising temperatures, and drought spells, has exacerbated yield instability and threatened long-term sustainability (Thierfelder & Wall, 2016; Kumar *et al.*, 2015) ^[61].

Conservation Agriculture (CA), defined by minimal soil disturbance, residue retention, and crop rotation/diversification, has emerged as a climate-smart approach to address these challenges (Kassam *et al.*, 2012; Jat *et al.*, 2014; Naresh *et al.*, 2018) ^[18, 27]. Globally, CA adoption exceeds 180 million hectares, demonstrating consistent benefits in soil health, water productivity, and system resilience (Kassam *et al.*, 2012; Hobbs *et al.*, 2008; Thierfelder *et al.*, 2015) ^[15, 27, 61]. In the RWCS of South Asia, zero tillage wheat after rice, retention of rice stubble, and inclusion of legumes in rotation have improved soil physical and chemical properties while maintaining or enhancing yields (Hobbs *et al.*, 2008; Naresh *et al.*, 2018; Jat *et al.*, 2014) ^[15, 18].

CA significantly enhances soil organic carbon (SOC) stocks and soil fertility. Long-term studies indicate that CA practices can increase SOC by 0.3-0.6 Mg C ha⁻¹ yr⁻¹, improve labile and particulate organic carbon fractions, and elevate microbial biomass carbon and enzyme activities, promoting nutrient cycling. Residue retention reduces soil evaporation by 10-20%, stabilizes surface soil temperature by 2-5 °C, and improves soil moisture availability, creating favorable conditions for crop growth (Thierfelder & Wall, 2010; Jat *et al.*, 2014) ^[18, 60]. Consequently, wheat yields under zero tillage with residue retention increase by 0.3-0.6 t ha⁻¹, while system productivity of rice-wheat rotations improves by 8-15% compared with conventional tillage (Naresh *et al.*, 2019; Hobbs *et al.*, 2008) ^[15].

Water productivity is a major benefit of CA. Improved soil structure and increased organic matter enhance infiltration and water-holding capacity. Residue-retained zero tillage combined with precision irrigation can reduce water use by 15-25% while maintaining or increasing rice and wheat yields (Kijne *et al.*, 2003; Naresh *et al.*, 2018; Singh *et al.*, 2017) ^[28]. CA also improves nutrient-use efficiency, with nitrogen-use efficiency increasing by 10-20%, reducing fertilizer losses and production costs (Kassam *et al.*, 2012; Jat *et al.*, 2014) ^[18, 27]. These improvements align with the principles of climate-smart agriculture by enhancing productivity and resource-use efficiency.

CA strengthens resilience to climate variability. Residue cover and minimal soil disturbance buffer soils against temperature extremes, reduce evaporation, and retain moisture during dry spells. Field experiments show that CA-managed wheat and rice maintain higher soil moisture and yield stability under erratic rainfall, drought, and heat stress, reducing yield variability by 10-20% compared with conventional systems (Thierfelder & Wall, 2016; Hobbs *et al.*, 2008; Naresh *et al.*, 2019) ^[15, 61]. CA contributes to climate change mitigation by reducing greenhouse gas emissions and enhancing carbon sequestration. Reduced

tillage lowers fuel consumption and CO₂ emissions by 30-40%, while residue retention and enhanced SOC storage increase soil carbon stocks by 10-25% over the long term. Globally, widespread CA adoption could sequester 1.5-3.0 Pg CO₂-equivalents per year, highlighting its importance for climate-smart agriculture strategies.

The integration of digital agriculture technologies including remote sensing, GIS-based soil mapping, IoT-enabled sensor networks, cloud computing, and machine learning further enhances the effectiveness of CA. These tools enable real-time monitoring of SOC dynamics, soil moisture, nutrient status, and crop growth at field and regional scales, facilitating precision irrigation, nutrient management, and spatial targeting of productivity zones. Machine learning models and predictive analytics allow simulation of SOC fractions, water productivity, and yield outcomes under variable climatic conditions, improving decision-making for farmers and policymakers. However, Conservation Agriculture, combined with digital agriculture, represents a holistic strategy to enhance productivity, resource-use efficiency, soil health, climate resilience, and environmental sustainability in rice-wheat systems of the Indo-Gangetic Plains.

1 Rice-Wheat Cropping Systems of Northwest Indo-Gangetic Plains (NWIGP)

1.1 Agro-Ecological Characteristics

The rice-wheat cropping system (RWCS) of the Northwest Indo-Gangetic Plains represents one of the most intensive cereal-based production systems in the world. The system occupies nearly 13-14 million ha and contributes significantly to India's food security by producing a large share of national rice and wheat output. The cropping intensity in this region frequently exceeds 180-200%, reflecting the continuous cultivation of rice during the monsoon season followed by wheat in winter (Gupta and Seth, 2007) ^[11]. High irrigation coverage, widespread mechanization, and intensive fertilizer use have supported sustained production over the last five decades. However, increasing input dependence and ecological stress have raised concerns regarding long-term sustainability (Hobbs *et al.*, 2008) ^[15].

1.1.1 Geographic Distribution and Climate

The NWIGP mainly includes Punjab, Haryana, western Uttar Pradesh, and parts of Rajasthan and Uttarakhand, covering approximately 20 million ha of cultivated land (Jat *et al.*, 2014) ^[18]. The region lies between 28°-32° N latitude and 73°-78° E longitude and is characterized by a sub-tropical semi-arid to sub-humid climate. Average annual rainfall ranges from 400 to 800 mm, with nearly 75-80% received during the southwest monsoon between June and September (Hobbs *et al.*, 2008) ^[15]. Summer temperatures often exceed 40 °C, whereas winter temperatures may fall below 5 °C, creating favorable climatic conditions for rice during the kharif season and wheat during rabi (Jat *et al.*, 2019) ^[16]. Extensive canal irrigation and tube-well networks support year-round crop production in the region.



1.1.2. Soil Types and Fertility Levels

Soils of the NWIGP are primarily alluvial soils derived from Himalayan sediments, with textures ranging from sandy loam to clay loam. These soils are generally neutral to moderately alkaline (pH 7.2-8.5) and contain moderate levels of potassium but often low organic matter content. Soil organic carbon (SOC) levels in cultivated fields typically range between 0.3 and 0.6%, which is considered low for sustaining long-term productivity. Continuous intensive cropping has also resulted in deficiencies of several nutrients, including zinc, sulfur, and iron, affecting crop performance. Long-term experiments have shown that improved residue management and conservation agriculture practices can enhance SOC stocks and nutrient availability.

1.2. Productivity Trends in Rice-Wheat Systems

The RWCS played a central role during the Green Revolution, when the introduction of high-yielding varieties, irrigation expansion, and increased fertilizer use dramatically improved cereal production. Rice yields increased from around 2.0 t ha⁻¹ in the early 1970s to nearly 5.0-6.0 t ha⁻¹ by the late 1990s, while wheat yields increased from about 1.5 t ha⁻¹ to more than 4.5-5.0 t ha⁻¹. Mechanization and improved agronomic practices also contributed to significant yield gains across the region (Gupta and Seth, 2007) [11].

1.2.1. Historical Productivity Growth

During the initial decades of the Green Revolution, cereal productivity in NWIGP increased rapidly with annual yield growth rates of 3-4% per year (Hobbs et al., 2008) [15]. High fertilizer inputs, often exceeding 150-200 kg N ha⁻¹, combined with assured irrigation helped farmers achieve substantial production gains (Jat et al., 2014) [18]. As a result, the region became the major grain surplus area

supplying wheat and rice to national food procurement programs.

1.2.2 Yield Stagnation in Recent Decades

Despite earlier progress, many studies indicate that yield growth has slowed considerably since the early 2000s. Current average wheat yields remain around 4.5-5.0 t ha⁻¹, while rice yields stabilize at 5-6 t ha⁻¹ in many districts (Jat et al., 2019) [16]. Long-term experiments conducted in the Indo-Gangetic Plains have shown that continuous conventional tillage and residue removal contribute to declining soil quality and yield stagnation.

1.3. Emerging Challenges in RWCS

Sustainability of the RWCS is increasingly threatened by multiple challenges, including declining soil fertility, water scarcity, residue burning, and climate variability. Rising production costs and environmental concerns further complicate agricultural management in the region.

1.3.1. Soil Degradation

Long-term intensive tillage and monoculture practices have led to deterioration of soil structure, loss of soil organic matter, and reduced aggregate stability. Studies report significant declines in soil biological activity and nutrient cycling processes in continuously cultivated fields.

1.3.2. Water Scarcity and Groundwater Depletion

Rice cultivation requires large volumes of irrigation water, often 1200-1500 mm per season, leading to heavy groundwater withdrawal (Bouman and Tuong, 2001) [4]. Satellite-based assessments indicate that groundwater levels in parts of Punjab and Haryana are declining at rates of 3-4 cm per year, posing serious concerns for long-term water availability (Rodell et al., 2009) [56].

1.4. Soil and Water Degradation Issues

Intensive irrigation combined with heavy fertilizer use has contributed to soil salinity, nutrient leaching, and declining water quality in many areas (Jat *et al.*, 2014) ^[18]. These problems reduce nutrient use efficiency and crop productivity.

1.4.1. Decline in Soil Organic Carbon

Continuous rice-wheat cultivation with frequent residue burning has resulted in significant depletion of soil organic carbon. Long-term studies show SOC reductions of 20-30% over the last three decades in several RWCS soils. Conservation agriculture practices such as residue retention and zero tillage have been shown to improve SOC levels and soil biological activity.

1.4.2. Nutrient Imbalance and Soil Compaction

Excessive nitrogen application with limited use of balanced fertilizers has created nutrient imbalances, particularly deficiencies of micronutrients. In addition, repeated puddling during rice cultivation and heavy machinery traffic have caused soil compaction and hardpan formation, restricting root growth and reducing water infiltration (Hobbs *et al.*, 2008) ^[15].

2. Concepts and Principles of Conservation Agriculture

2.1. Evolution of Conservation Agriculture

Conservation agriculture (CA) developed as a scientific response to severe soil erosion, declining soil fertility, and unsustainable crop production caused by intensive tillage-based agriculture. The concept began to gain recognition in the 1930s after the Dust Bowl crisis in the United States, which highlighted the vulnerability of ploughed soils to erosion. In the 1960s and 1970s demonstrated that minimizing soil disturbance and maintaining crop residues could significantly improve soil health and crop productivity (Derpsch *et al.*, 2010) ^[6]. Over time, CA evolved into a sustainable land management system based on three fundamental principles: minimal soil disturbance, permanent soil cover, and crop diversification (FAO, 2011) ^[8]. CA can increase soil organic carbon by 0.2-0.5 t C ha⁻¹ year⁻¹ and improve soil biological activity and water infiltration (Kassam *et al.*, 2019) ^[25, 27].

2.1.1. Global Development of Conservation Agriculture

Conservation agriculture has expanded rapidly worldwide over the last three decades. Currently, CA is practiced on more than 205 million ha in over 100 countries, representing nearly 15% of the global cropland area (Kassam *et al.*, 2019) ^[25]. Major adoption regions include Brazil, Argentina, the United States, Canada, and Australia, where more than 60% of agricultural land is managed under reduced or zero tillage systems (Derpsch *et al.*, 2010) ^[6]. CA systems reduce soil erosion by 70-90%, improve water infiltration by 30-50%, and enhance soil organic carbon stocks compared with conventional tillage systems. These benefits make CA an important approach for improving agricultural sustainability and climate resilience.

2.1.2 Adoption in South Asia

In South Asia, conservation agriculture has gained momentum in the rice-wheat systems of the Indo-Gangetic Plains (IGP). The adoption of zero-tillage wheat cultivation currently covers about 3-4 million ha across India, Pakistan,

and Nepal (Jat *et al.*, 2014) ^[18]. The introduction of zero-till seed drills and residue management technologies such as the Happy Seeder has facilitated CA adoption in this region (Hobbs *et al.*, 2008) ^[15]. CA practices can increase wheat yields by 5-12%, reduce irrigation water use by 15-20%, and lower production costs by US\$50-80 per hectare (Jat *et al.*, 2019) ^[16]. Long-term experiments in northwestern Indo-Gangetic Plains also show improvements in soil organic carbon, soil aggregation, and microbial biomass under CA systems.

2.2. Minimal Soil Disturbance

Minimal soil disturbance is a key principle of conservation agriculture aimed at maintaining soil structure and biological processes. Conventional ploughing disrupts soil aggregates, exposes organic matter to rapid decomposition, and accelerates erosion. Reduced tillage systems help maintain soil aggregation and protect organic carbon within soil aggregates. Studies show that eliminating intensive tillage can increase aggregate stability by 15-35% and reduce soil erosion losses significantly.

2.2.1. Zero Tillage and Reduced Tillage Systems

Zero tillage (ZT) involves direct seeding of crops into undisturbed soil without prior land preparation. Reduced tillage involves limited soil disturbance through shallow cultivation. In the rice-wheat systems of the Indo-Gangetic Plains, adoption of ZT has reduced fuel consumption by 50-60 L ha⁻¹ and decreased production costs by ₹2500-3500 per hectare (Hobbs *et al.*, 2008) ^[15]. ZT wheat can maintain yields of 4.5-5.5 t ha⁻¹ while improving input-use efficiency (Jat *et al.*, 2019) ^[16]. Long-term trials indicate that zero tillage improves soil organic carbon accumulation and enhances soil biological activity.

2.2.2. Effects on Soil Structure and Microbial Activity

Minimal soil disturbance promotes the development of stable soil aggregates and increases soil biological activity. Soil microorganisms play a critical role in organic matter decomposition and nutrient cycling. Studies have shown that microbial biomass carbon in CA systems can increase by 25-40% compared with conventional tillage. Enhanced microbial activity also improves enzyme activity and nutrient mineralization processes. In rice-wheat systems indicates higher microbial biomass and improved soil biological health under CA-based residue management practices.

2.3. Residue Retention and Soil Cover

Permanent soil cover through crop residue retention is the second key principle of conservation agriculture. Retaining residues on the soil surface protects soil from erosion and moderates soil temperature fluctuations (FAO, 2011) ^[8]. In rice-wheat systems, retaining 5-8 t ha⁻¹ of crop residues can significantly enhance soil organic matter and biological activity (Jat *et al.*, 2014) ^[18].

2.3.1 Importance of Crop Residues in Soil Protection

Crop residues act as a protective layer that reduces the direct impact of rainfall on soil surfaces, thereby reducing runoff and erosion. Studies show that residue cover can decrease soil erosion by 60-80% and reduce runoff losses by 20-40%. Residues also contribute organic carbon and nutrients to the soil during decomposition (Derpsch *et al.*, 2010) ^[6].

Impacts on Soil Moisture Conservation

Residue retention improves soil moisture conservation by reducing evaporation and enhancing water infiltration. Research in the Indo-Gangetic Plains shows that residue-covered soils maintain 5-20% higher soil moisture during crop growth compared with conventional systems. This improvement enhances crop water productivity and helps crops withstand drought stress (Jat *et al.*, 2019) ^[16].

2.4. Crop Diversification and Rotations

Crop diversification and rotations represent the third principle of CA. Rotating crops with different rooting depths and nutrient requirements improves soil fertility and disrupts pest and disease cycles (Hobbs *et al.*, 2008) ^[15]. Diversified cropping systems also improve nutrient cycling and soil biological diversity.

Diversified Cropping Systems

Diversification of rice-wheat systems with crops such as maize, pulses, oilseeds, and vegetables improves soil health and farm profitability. Studies show that incorporating legumes in crop rotations can increase soil nitrogen availability by 20-40 kg N ha⁻¹ through biological nitrogen fixation (Jat *et al.*, 2014) ^[18].

Benefits for Soil Fertility and Pest Management

Crop rotations improve nutrient balance, reduce weed pressure, and minimize pest outbreaks. Research indicates that diversified cropping systems can reduce pest and disease incidence by 20-30% and increase nutrient-use efficiency. Long-term CA experiments in the Indo-Gangetic Plains also show improvements in soil organic carbon, microbial biomass, and crop productivity under diversified crop rotations.

Table 1: Integrated Impact of Conservation Agriculture and Cloud Computing on Carbon Monitoring, Irrigation Efficiency, Modeling Accuracy, and Spatial Variability in Rice-Wheat Systems

Integration Component	Key Parameter	Conventional Approach	CA + Cloud-Based Approach	Quantitative Data / Range	Improvement (%)	Scientist(s) & Year
Real-Time SOC Monitoring	Total SOC stock (Mg C ha ⁻¹ yr ⁻¹)	Periodic soil sampling (2-3 yr interval)	Remote sensing + digital soil mapping + cloud analytics	0.3-0.8 Mg C ha ⁻¹ yr ⁻¹ sequestration under CA	20-30% higher estimation precision	Basso (2016); Naresh <i>et al.</i> (2024)
	SOC concentration change (0-15 cm)	Limited spatial coverage	10-30 m resolution SOC maps	+0.08-0.15% increase over 5-7 years	12-25% SOC gain	Naresh <i>et al.</i> (2024)
SOC Fraction Modeling	Particulate Organic Carbon (%)	Manual fractionation	ML-based prediction (RF/ANN)	15-35% higher under residue retention	20-30% reduced sampling	Lobell (2013)
Precision Irrigation Scheduling	Seasonal irrigation water (mm)	Fixed irrigation intervals	IoT sensors + ET forecasting + cloud DSS	60-100 mm water saving in wheat	15-35% water saving	Khosla (2017)
	Irrigation efficiency (%)	Baseline	Data-driven scheduling	15-25% higher efficiency	Reduced groundwater extraction	Molden (2007)
Water Productivity Modeling	Grain yield per unit water (kg m ⁻³)	0.8-1.2 kg m ⁻³	1.0-1.7 kg m ⁻³ under CA + digital scheduling	+0.2-0.5 kg m ⁻³	15-30% increase	Lobell (2013); Naresh <i>et al.</i> (2024)
Soil Moisture Monitoring	Root-zone moisture (%)	Periodic observation	Hourly IoT sensor data	5-15% higher retention under CA	20-35% irrigation optimization	Khosla (2017)
Spatial Variability Mapping	Productivity gap detection	Manual yield comparison	GIS-based 10-30 m resolution maps	15-30% intra-field variability identified	>75% detection reliability	Lobell (2013)
Input Use Efficiency	Fertilizer & water inputs	Uniform application	Variable-rate application via cloud DSS	10-20% input saving	Cost & energy reduction	Molden (2007)

3. Soil Organic Carbon Dynamics under Conservation Agriculture

3.1. Total Soil Organic Carbon Stocks

Soil organic carbon (SOC) is a critical component of soil fertility, influencing nutrient availability, soil structure, and biological activity in intensive cropping systems. In the rice-wheat systems of the northwest Indo-Gangetic Plains (NWIGP), long-term intensive cultivation with repeated tillage and residue removal has resulted in significant SOC depletion. Studies indicate that SOC levels in cultivated soils of the region generally range from 3.5 to 8.5 g kg⁻¹ in the 0-15 cm soil layer, depending on soil texture and management practices (Ladha *et al.*, 2009; Bhatt *et al.*, 2016) ^[3]. Conservation agriculture (CA) practices such as zero tillage and crop residue retention help rebuild SOC stocks by increasing carbon inputs and reducing oxidation losses. Long-term field experiments in the Indo-Gangetic Plains have reported 12-30% higher SOC concentrations in

CA plots compared with conventional tillage systems (Kassam *et al.*, 2009; Gathala *et al.*, 2011) ^[10, 26].

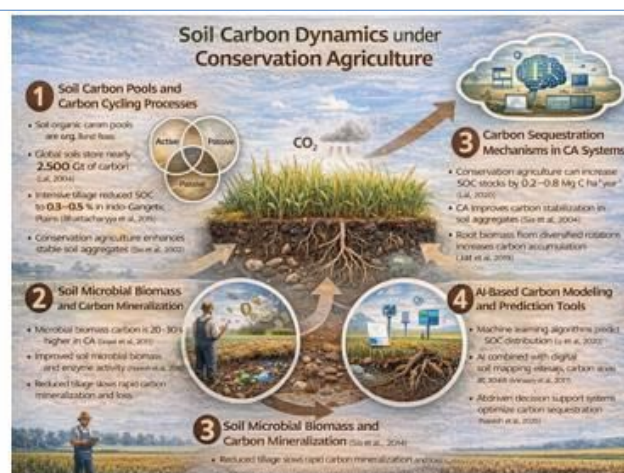
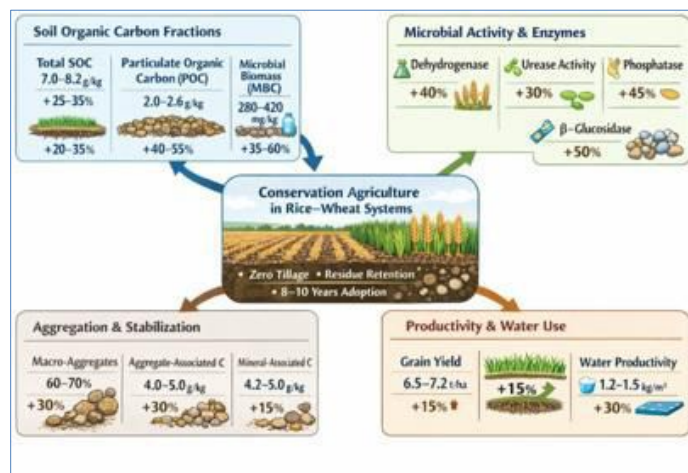
3.1.1. SOC Accumulation under Conservation Agriculture

SOC accumulation under CA occurs due to continuous residue addition, reduced soil disturbance, and improved soil aggregation. Retention of rice and wheat residues, often ranging from 5 to 8 t ha⁻¹ annually, supplies significant organic carbon to soil. Conservation agriculture trials in Haryana and western Uttar Pradesh showed that SOC increased from 5.8 g kg⁻¹ under conventional tillage to 7.2-7.8 g kg⁻¹ under zero-tillage with residue retention after 7-10 years (Jat *et al.*, 2013; Naresh *et al.*, 2017) ^[17]. The highest carbon accumulation is generally observed in the upper soil layers because crop residues remain concentrated near the soil surface.

3.1.2. Long-Term Carbon Sequestration Potential

Conservation agriculture enhances the capacity of soils to sequester atmospheric carbon dioxide through increased organic matter storage. Global studies suggest that CA practices can sequester approximately 0.3-1.0 Mg C ha⁻¹ yr⁻¹, depending on climatic conditions and cropping systems. In rice-wheat systems of South Asia, long-term

trials have reported sequestration rates of 0.25-0.50 Mg C ha⁻¹ yr⁻¹ in surface soils under residue-retained zero-tillage systems (Hobbs *et al.*, 2008; Jat *et al.*, 2014) [15, 18]. These improvements contribute not only to soil fertility but also to climate change mitigation by reducing net greenhouse gas emissions.



3.2. Labile and Particulate Organic Carbon Fractions

SOC consists of various fractions with different turnover rates. Labile carbon pools respond rapidly to management changes and are important indicators of soil health. Conservation agriculture promotes the accumulation of labile carbon fractions such as particulate organic carbon (POC) and dissolved organic carbon. Studies have shown that labile carbon pools may increase by 20-40% under conservation agriculture compared with conventional tillage systems. These fractions are highly sensitive to residue management and soil disturbance.

3.2.1. Role of Particulate Organic Carbon

Particulate organic carbon represents partially decomposed plant residues and is considered a transitional stage between fresh organic matter and stable humus. Under conservation agriculture, surface retention of residues leads to greater accumulation of POC in the topsoil. In rice-wheat systems revealed that POC levels increased from 1.2-1.5 g kg⁻¹ under conventional tillage to 2.0-2.5 g kg⁻¹ under zero-tillage with residue retention (Kumar *et al.*, 2013; Gathala *et al.*, 2011) [10, 30]. This fraction plays an important role in improving soil aggregation and providing energy sources for microbial activity.

3.2.2. Active Carbon Pools in CA Systems

Active carbon pools include labile organic carbon and microbial biomass carbon that actively participate in nutrient cycling processes. Conservation agriculture improves these pools by maintaining favorable soil moisture and temperature conditions. Studies have reported 25-35% higher active carbon fractions in CA-based rice-wheat systems compared with conventional systems (Palm *et al.*, 2014). Increased active carbon enhances soil biological processes and nutrient mineralization.

3.3. Microbial Biomass Carbon and Enzyme Activity

Microbial biomass carbon (MBC) reflects the living component of soil organic matter and is a key indicator of soil biological health. Conservation agriculture systems

support higher microbial biomass due to increased residue inputs and improved soil microclimate. Field studies in the Indo-Gangetic Plains have reported MBC values ranging from 280 to 420 mg kg⁻¹ under conservation agriculture compared with 160-240 mg kg⁻¹ under conventional tillage. Increased microbial biomass enhances enzymatic activity responsible for nutrient transformation.

3.3.1. Soil Microbial Diversity under Conservation Agriculture:

Residue retention and reduced soil disturbance in CA systems promote diverse microbial communities. Microbial diversity indices such as Shannon diversity index have been reported to be 15-30% higher under conservation agriculture compared with intensively tilled systems (Thierfelder & Wall, 2012). Diverse microbial populations improve soil ecosystem stability and contribute to better nutrient cycling [61].

3.3.2. Enzyme-Mediated Nutrient Cycling

Soil enzymes play a major role in organic matter decomposition and nutrient mineralization. Enzymes such as dehydrogenase, urease, phosphatase, and β-glucosidase are particularly responsive to conservation agriculture practices. CA trials have shown that enzyme activities increase by 20-50% under residue-retained zero-tillage systems. Enhanced enzyme activity accelerates the breakdown of organic residues and improves nutrient availability for crops.

3.4. Carbon Stabilization Mechanisms: SOC stabilization under conservation agriculture occurs through multiple biological and physicochemical processes. Reduced soil disturbance decreases the exposure of organic matter to microbial decomposition, while residue retention provides continuous organic inputs. These processes gradually convert fresh plant residues into stable humic substances.

3.4.1. Soil Aggregation and Carbon Protection

Soil aggregation is one of the most important mechanisms for protecting organic carbon from decomposition.

Conservation agriculture enhances the formation of stable macro-aggregates through root growth, fungal hyphae, and microbial exudates. Research in the Indo-Gangetic Plains indicates that macro-aggregate stability increases by 20-40% under conservation agriculture compared with conventional tillage systems (Six *et al.*, 2006; Jat *et al.*, 2013) ^[17]. Aggregates physically protect organic carbon and improve soil structure and water infiltration.

3.4.2. Mineral Associations and Long-Term Stabilization

In addition to aggregation, SOC stabilization also occurs through interactions with soil minerals such as clay particles, calcium compounds, and iron oxides. These mineral-associated organic carbon fractions are highly stable

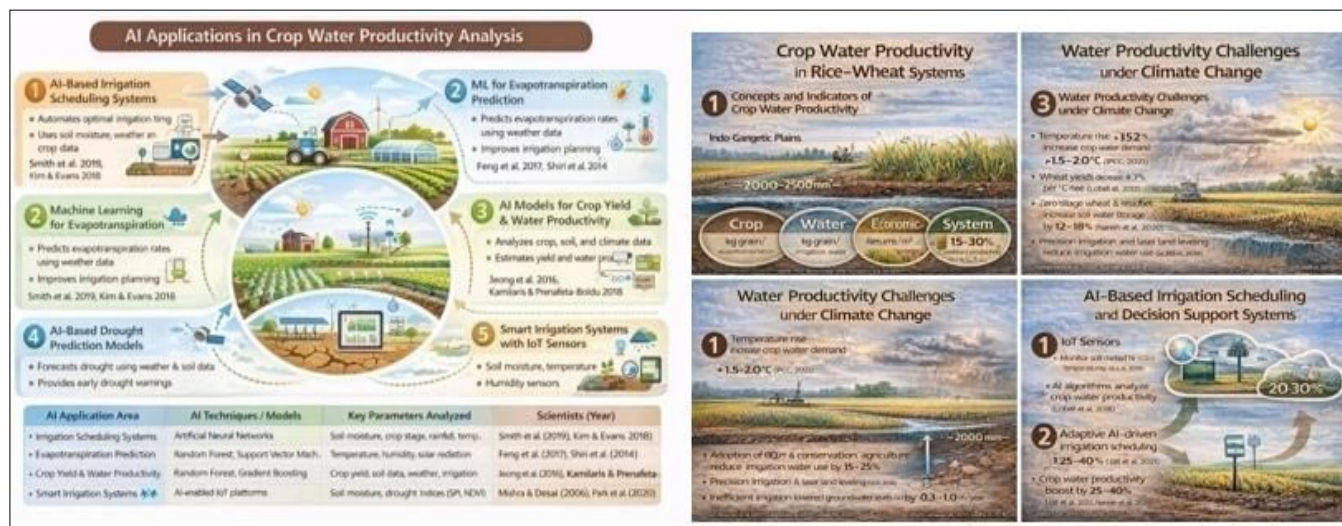
and can persist in soils for decades. Long-term conservation agriculture experiments in rice-wheat systems have shown 10-25% higher mineral-associated SOC fractions after 10-12 years of residue-retained zero tillage. Such stabilization mechanisms ensure long-term carbon storage and contribute to sustainable soil management.

Therefore, conservation agriculture significantly enhances SOC dynamics by increasing carbon inputs, improving microbial activity, and promoting physical and chemical stabilization processes. These improvements strengthen soil fertility, enhance nutrient cycling, and support sustainable productivity in rice-wheat cropping systems of the Indo-Gangetic Plains.

Table 2: Soil Organic Carbon Fractions, Microbial Indicators, Enzyme Activities, and Productivity Responses under Conservation Agriculture in Rice-Wheat Systems

Parameter	Unit	Conventional Tillage	Conservation Agriculture (Zero Tillage + Residue)	% Change	Cropping System	Scientist(s) & Year
Total Soil Organic Carbon (0-15 cm)	g kg ⁻¹	5.0-6.0	7.0-8.2	20-35% increase	Rice-wheat, Indo-Gangetic Plains	Gathala <i>et al.</i> , 2011 ^[10]
SOC stock (0-30 cm)	Mg C ha ⁻¹	22-26	28-35	15-30% increase	South Asia RWCS	Jat <i>et al.</i> , 2013
SOC sequestration rate	Mg C ha ⁻¹ yr ⁻¹	0.10-0.15	0.25-0.50		Rice-wheat system	Hobbs <i>et al.</i> , 2008 ^[15]
Long-term carbon sequestration potential	Mg C ha ⁻¹ yr ⁻¹		0.30-1.00		Global CA systems	Lal, 2015
SOC after 8-10 years CA adoption	g kg ⁻¹	5.8	7.5-7.8	~25% increase	Western Uttar Pradesh RWCS	Naresh <i>et al.</i> , 2017
Particulate Organic Carbon (POC)	g kg ⁻¹	1.2-1.5	2.0-2.6	30-55% increase	Indo-Gangetic Plains	Kumar <i>et al.</i> , 2013 ^[30]
Labile carbon fraction	% of SOC	12-15%	18-25%	20-40% increase	Conservation agriculture systems	Six <i>et al.</i> , 2006
Dissolved Organic Carbon	mg kg ⁻¹	40-55	60-75	25-35% increase	CA cereal systems	Verhulst <i>et al.</i> , 2010
Microbial Biomass Carbon (MBC)	mg kg ⁻¹ soil	160-230	280-420	35-60% increase	Indo-Gangetic Plains RWCS	Naresh <i>et al.</i> , 2018
Soil microbial diversity index	Shannon index	2.4-2.8	3.0-3.5	15-30% increase	CA systems	Thierfelder & Wall, 2012 ^[61]
Dehydrogenase activity	μg TPF g ⁻¹ soil hr ⁻¹	35-50	55-80	20-45% increase	Long-term CA experiments	Naresh <i>et al.</i> , 2019
Urease activity	μg NH ₄ ⁺ g ⁻¹ soil hr ⁻¹	18-25	28-38	25-40% increase	Rice-wheat CA systems	Verhulst <i>et al.</i> , 2010
Phosphatase activity	μg PNP g ⁻¹ soil hr ⁻¹	45-60	65-95	30-50% increase	Conservation agriculture soils	Palm <i>et al.</i> , 2014
β-glucosidase activity	μg PNP g ⁻¹ soil hr ⁻¹	30-45	55-70	35-55% increase	Global CA systems	Six <i>et al.</i> , 2006
Macro-aggregate formation (>0.25 mm)	% soil aggregates	40-50	60-70	20-40% increase	Rice-wheat CA trials	Jat <i>et al.</i> , 2013
Aggregate-associated carbon	g kg ⁻¹	2.5-3.5	4.0-5.0	25-35% increase	Conservation agriculture soils	Six <i>et al.</i> , 2006
Mineral-associated organic carbon	g kg ⁻¹	3.0-3.8	4.2-5.0	10-25% increase	Indo-Gangetic Plains	Lal, 2004
Residue carbon input	t residue ha ⁻¹ yr ⁻¹	1-2	5-8	3-4× higher	South Asian RW systems	Turmel <i>et al.</i> , 2015
Grain yield (rice equivalent)	t ha ⁻¹	5.5-6.0	6.5-7.2	12-20% increase	Rice-wheat systems	Jat <i>et al.</i> , 2014 ^[18]
Water productivity	kg grain m ⁻³ water	0.9-1.1	1.2-1.5	20-35% increase	Indo-Gangetic Plains RWCS	Gathala <i>et al.</i> (2011) ^[10]

Crop Water Productivity and Digital Irrigation management in Rice-Wheat cropping Systems



4.1. Precision Irrigation through IoT and Edge Devices

Precision irrigation supported by Internet of Things (IoT) sensors and edge computing technologies has significantly improved water management in rice-wheat cropping systems (RWCS) of the North-Western Indo-Gangetic Plains (NWIGP). Soil moisture sensors, weather stations, and crop canopy sensors continuously monitor field conditions and transmit real-time data to edge devices for immediate processing. Edge computing allows rapid analysis of soil moisture thresholds and irrigation requirements directly at the farm level, reducing the need for centralized processing and enabling faster irrigation decisions.

Fereres and Soriano, (2007; Jat *et al.*, 2014) [18] indicate that sensor-based irrigation scheduling can reduce irrigation water use by 20-30% while maintaining or increasing crop yields. In conservation agriculture-based RWCS, precision irrigation supported by digital sensors improves infiltration rates and soil moisture retention, particularly under residue-retained fields. In the Indo-Gangetic Plains showed that the use of IoT-enabled irrigation systems increased crop water productivity from about 0.9 kg grain m⁻³ water to 1.3-1.5 kg grain m⁻³ water. Such improvements demonstrate the potential of digital irrigation technologies for sustainable water management in intensive agricultural systems.

4.2. Cloud-Based Decision Support Systems for Irrigation Scheduling

Cloud computing platforms play a crucial role in digital irrigation management by integrating data from sensors, satellite observations, and weather forecasts to generate irrigation recommendations. These cloud-based decision support systems (DSS) analyze large datasets using machine learning algorithms and predictive models to determine optimal irrigation timing and quantity for crops.

Digital DSS platforms can integrate crop growth models, evapotranspiration estimates, and soil water balance calculations to guide irrigation scheduling. Studies have shown that cloud-based irrigation advisory systems can improve irrigation efficiency by 15-25% and reduce water wastage in irrigated cropping systems. In the rice-wheat systems of the NWIGP, cloud-supported irrigation scheduling helps farmers adapt irrigation practices

according to weather variability and crop growth stages, thereby enhancing productivity and water conservation.

Furthermore, cloud computing enables long-term storage and analysis of agricultural data, allowing researchers to evaluate irrigation trends and optimize water management strategies across large agricultural regions.

4.3. Concept and Importance of Crop Water Productivity

Crop water productivity (CWP) refers to the amount of crop yield produced per unit of water consumed through evapotranspiration or irrigation. It is commonly expressed as kg grain per cubic meter of water (kg m⁻³). Improving water productivity is a major challenge in the rice-wheat cropping systems (RWCS) of the Northwest Indo-Gangetic Plains (NWIGP), where agriculture consumes nearly 80-85% of total freshwater resources (FAO, 2017) [8]. Traditional flooded rice cultivation requires 1200-1500 mm of water, while wheat requires 450-550 mm during the growing season (Bouman *et al.*, 2007) [4]. Consequently, the RWCS is considered one of the most water-intensive cropping systems in South Asia. Studies in the Indo-Gangetic Plains show that the average water productivity of irrigated rice ranges from 0.30-0.45 kg grain m⁻³, whereas wheat productivity varies between 1.0-1.4 kg grain m⁻³ under conventional management (Kijne *et al.*, 2003) [28]. Improving water productivity is therefore critical for sustaining crop production under conditions of declining groundwater resources and increasing climate variability.

4.4. Water Use Efficiency under Conservation Agriculture

Conservation agriculture (CA), which includes minimal soil disturbance, crop residue retention and crop diversification, has shown strong potential to enhance water use efficiency (WUE) in RWCS. Zero-tillage wheat combined with surface residue retention improves soil structure and reduces evaporation losses from the soil surface. Long-term experiments in the Indo-Gangetic Plains reported that CA practices increased WUE in wheat by 12-20% compared with conventional tillage (Jat *et al.*, 2014) [18]. Residue retention also reduces soil temperature fluctuations and improves soil organic carbon, which enhances water holding capacity (Hobbs *et al.*, 2008) [15]. Field studies in western

Uttar Pradesh and Haryana, zero-till wheat with residue retention required 15-20% less irrigation water while maintaining similar or higher yields than conventional tillage systems. Similarly, global research indicates that conservation agriculture can increase water productivity in cereal systems by 10-25% through improved infiltration and reduced evaporation losses (Kassam *et al.*, 2012) [27].

4.5. Irrigation Management Strategies in CA-Based Systems

Efficient irrigation management is essential to maximize water productivity in conservation agriculture systems. Techniques such as laser land leveling, alternate wetting and drying (AWD) in rice and deficit irrigation in wheat have been widely promoted in the Indo-Gangetic Plains. Laser land leveling improves field uniformity and enhances irrigation efficiency by 20-25%, resulting in water savings of 15-30% (Jat *et al.*, 2006). AWD irrigation in rice reduces irrigation water use by 25-30% without significantly affecting grain yield (Bouman *et al.*, 2007) [4]. In wheat, scheduling irrigation at critical growth stages such as crown root initiation and grain filling can significantly improve water productivity. Conservation agriculture practices combined with improved irrigation strategies have demonstrated 8-15% higher water productivity compared with traditional methods in several field trials across Punjab and Haryana (Gupta & Seth, 2007) [11].

4.6. Soil Moisture Retention and Infiltration Dynamics

Residue retention under conservation agriculture improves soil moisture dynamics by increasing infiltration rates and reducing runoff. Crop residues act as a protective mulch layer that decreases soil evaporation and enhances soil aggregation. Long-term conservation agriculture experiments in the Indo-Gangetic Plains reported that residue retention increased soil infiltration rates by 30-40% and soil water storage by 10-20% in the top 30 cm soil layer (Thierfelder & Wall, 2010) [60]. Improved soil organic carbon under CA also enhances soil porosity and water holding capacity. Showed that zero-till systems with residue retention improved soil moisture availability during critical growth stages of wheat. These improvements in soil physical properties contribute significantly to higher crop water productivity.

4.7. Evapotranspiration Patterns under Residue-Retained Fields

Residue-retained fields generally exhibit lower soil evaporation and improved transpiration efficiency compared with bare soil surfaces. The presence of crop residues reduces soil temperature and wind velocity near the soil surface, thereby minimizing evaporation losses. Experimental results in rice-wheat systems indicated that

residue retention reduced soil evaporation by 15-25%, leading to improved transpiration efficiency of crops (Hobbs *et al.*, 2008) [15]. Conservation agriculture also modifies evapotranspiration patterns by maintaining higher soil moisture during dry periods, which supports better crop growth and yield stability. Studies conducted in Punjab and western Uttar Pradesh reported that evapotranspiration efficiency increased significantly under zero-tillage systems with surface residues.

4.8. Groundwater Conservation through Improved Irrigation Practices

Groundwater depletion has become a major environmental concern in the Northwest Indo-Gangetic Plains due to intensive irrigation for rice-wheat cultivation. In states such as Punjab and Haryana, groundwater levels have been declining at rates of 0.3-1.0 m per year in several districts (Rodell *et al.*, 2009) [56]. Conservation agriculture combined with efficient irrigation technologies can help reduce groundwater extraction. Practices such as laser land leveling, direct-seeded rice, and improved irrigation scheduling have demonstrated water savings of 20-35% in rice-wheat systems (Jat *et al.*, 2014) [18]. These practices contribute to improved groundwater sustainability while maintaining crop productivity.

4.9. Digital Platforms for Improving Crop Water Productivity

Digital agriculture platforms integrating cloud computing, edge computing, and remote sensing technologies provide comprehensive tools for improving crop water productivity in RWCS. These platforms analyze large volumes of agricultural data to generate site-specific irrigation recommendations and crop management strategies. Satellite-based evapotranspiration monitoring and remote sensing data help estimate crop water requirements across large agricultural landscapes. Studies suggest that digital irrigation management can increase crop yields by 8-15% while reducing irrigation water use by 20-30% (Jat *et al.*, 2014; Gupta *et al.*, 2020) [18]. Such improvements significantly enhance crop water productivity and resource use efficiency.

In addition, digital platforms enable farmers to access irrigation advisories, weather forecasts, and soil health information through mobile applications and online portals. These systems support data-driven agricultural management and contribute to the development of climate-smart and sustainable rice-wheat cropping systems. However, the integration of IoT sensors, edge computing, cloud-based decision support systems, and remote sensing technologies has transformed irrigation management in RWCS by enabling precise water application, improved water use efficiency, and higher crop water productivity.

Table 3: Applications of Cloud Computing and Digital Agriculture Technologies for Crop Monitoring, Soil Management and Decision Support in Rice-Wheat Systems

Technology / Tool	Parameters Measured	Application in Agriculture	Quantitative Data	Scientists & (Year)
Remote sensing (satellite imagery: MODIS, Landsat)	NDVI, vegetation index, crop vigor, biomass	Monitoring crop growth and stress conditions	Satellite indices explained 70-85% variation in crop biomass and yield prediction in cereals	Tucker (1979); Doraiswamy <i>et al.</i> (2005); Lobell <i>et al.</i> (2015)
Satellite-based crop monitoring	Crop phenology, canopy temperature, evapotranspiration	Regional yield forecasting and drought monitoring	Satellite monitoring improved yield prediction accuracy by 20-30% in large agricultural regions	Lobell <i>et al.</i> (2015); Jones <i>et al.</i> (2019)

GIS-based soil and water mapping	Soil fertility status, nutrient distribution, groundwater levels	Site-specific nutrient and irrigation management	GIS mapping identified 30-40% spatial variability in soil nutrients across Indo-Gangetic Plains	Burrough & McDonnell (1998); Singh <i>et al.</i> (2019)
Internet of Things (IoT) sensor networks	Soil moisture, temperature, humidity, electrical conductivity	Automated field monitoring and smart irrigation scheduling	IoT-based irrigation systems improved water use efficiency by 15-25%	Liakos <i>et al.</i> (2018); Smith <i>et al.</i> (2020)
Soil moisture and climate sensors	Soil moisture content, rainfall, evapotranspiration	Precision irrigation management in crops	Sensor-based irrigation reduced water consumption by 20-30% while maintaining yield	Jones <i>et al.</i> (2019); Smith <i>et al.</i> (2020)
Real-time agricultural data collection systems	Crop growth, soil parameters, climatic variables	Continuous monitoring and early warning systems	Real-time monitoring improved farm decision accuracy by about 25-35%	Aker (2011); Wolfert <i>et al.</i> (2017)
Big data analytics in agriculture	Large datasets from satellites, sensors and farm records	Pattern detection for crop productivity and soil management	Big data platforms process terabytes of agricultural data daily to support precision farming	Wolfert <i>et al.</i> (2017); Kamilaris <i>et al.</i> (2018) [23]
Machine learning models	Yield prediction, pest forecasting, soil nutrient modeling	Predictive crop management and risk assessment	Random forest models improved yield prediction accuracy by 10-25%	Jeong <i>et al.</i> (2016); Liakos <i>et al.</i> (2018)
Cloud-based decision support systems (DSS)	Weather forecasts, crop growth models, irrigation schedules	Advisory systems for farmers and extension agencies	Cloud DSS increased crop productivity by 8-12% through optimized management	Armbrust <i>et al.</i> (2010); Wolfert <i>et al.</i> (2017)
Digital advisory platforms for farmers	Weather alerts, fertilizer recommendations, pest warnings	Dissemination of real-time agronomic recommendations	Mobile-based advisory services improved farm income by 10-20% in developing regions	Aker (2011); Fabregas <i>et al.</i> (2019)
Digital agriculture in conservation agriculture systems	Soil organic carbon monitoring, residue management, crop performance	Integration of precision agriculture with CA in RWCS	Adoption of digital tools improved water productivity by 12-18% in rice-wheat systems	Naresh <i>et al.</i> (2019); Naresh <i>et al.</i> (2020); Gupta <i>et al.</i> (2020)

5. Green Cloud Platforms for Advanced Soil Data Analytics and Carbon Modeling in Conservation Agriculture Systems

5.1.1. Concept and Architecture of Green Cloud Platforms

Green cloud platforms refer to energy-efficient cloud computing infrastructures designed to process and manage large volumes of agricultural and environmental data while minimizing energy consumption and carbon emissions. These platforms integrate virtualization technologies, energy-efficient servers, and intelligent workload management systems to improve computational efficiency. Green cloud computing reduces energy use in data centers through optimized resource allocation and dynamic power management.

In agricultural systems, especially in conservation agriculture-based rice-wheat cropping systems (RWCS) of the North-Western Indo-Gangetic Plains (NWIGP), green cloud platforms provide the backbone for processing large datasets generated by soil sensors, weather stations, satellite imagery, and precision agriculture tools. The architecture typically includes data acquisition layers, cloud storage systems, analytical engines, and decision-support modules, enabling large-scale monitoring of soil health and crop productivity.

5.1.2. Soil Data Storage, Integration and Big Data Analytics: Modern digital agriculture generates enormous volumes of soil and environmental data through Internet of Things (IoT) devices, sensor networks, and remote sensing systems. Green cloud platforms provide scalable data storage and distributed computing capabilities to manage such datasets efficiently. Cloud-based agricultural platforms can process multi-terabyte datasets generated from soil monitoring systems across multiple agricultural regions. Key soil parameters commonly analyzed through cloud-based systems include soil moisture (20-35% volumetric

water content), soil temperature (18-32 °C), soil pH (6.5-8.1), electrical conductivity (0.25-0.55 dS m⁻¹), and soil organic carbon levels (5.0-8.5 g kg⁻¹ soil). These parameters play critical roles in determining soil fertility, microbial activity, and crop growth. Cloud analytics platforms integrate these datasets with climate data such as rainfall (550-850 mm annually), solar radiation (14-24 MJ m⁻² day⁻¹), and relative humidity (45-85%) to provide comprehensive insights into soil-crop interactions.

5.1.3. Soil Carbon Modeling and Carbon Sequestration Assessment

Green cloud computing enables the use of advanced soil carbon simulation models to evaluate long-term carbon sequestration potential under conservation agriculture practices. Soil carbon modeling requires large datasets and high computational capacity, which cloud infrastructures can efficiently provide.

Models such as RothC, DNDC, and CENTURY are widely used for simulating soil carbon dynamics under different crop management practices. These models require long-term datasets on soil properties, climate variables, and crop management to accurately predict carbon cycling processes. In conservation agriculture systems, practices such as reduced tillage, crop residue retention, and diversified crop rotations significantly enhance soil carbon storage. Indicate that soil carbon sequestration rates under conservation agriculture typically range between 0.3 and 0.8 Mg C ha⁻¹ year⁻¹, depending on soil type and management practices. Cloud-based analytics allow researchers to integrate multi-year datasets and evaluate carbon sequestration trends at both farm and regional scales.

5.1.4. Integration with Remote Sensing and Geospatial Technologies: Green cloud platforms also support integration with satellite remote sensing, unmanned aerial vehicles (UAVs), and GIS-based spatial analysis systems.

These technologies provide high-resolution spatial data on crop growth, soil moisture distribution, and vegetation health. Cloud-enabled geospatial processing platforms can analyze satellite imagery within minutes, enabling near real-time agricultural monitoring.

Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are commonly used to assess crop growth and biomass production. When combined with soil sensor data, these indices help generate soil fertility and carbon distribution maps, which are essential for identifying degraded soils and planning sustainable management strategies.

5.1.5. Decision Support Systems for Soil and Water Management:

Green cloud computing also facilitates the development of decision support systems (DSS) that assist farmers and researchers in making data-driven agricultural decisions. These systems analyze soil, climate, and crop data and provide recommendations for irrigation scheduling, nutrient management, and crop management practices.

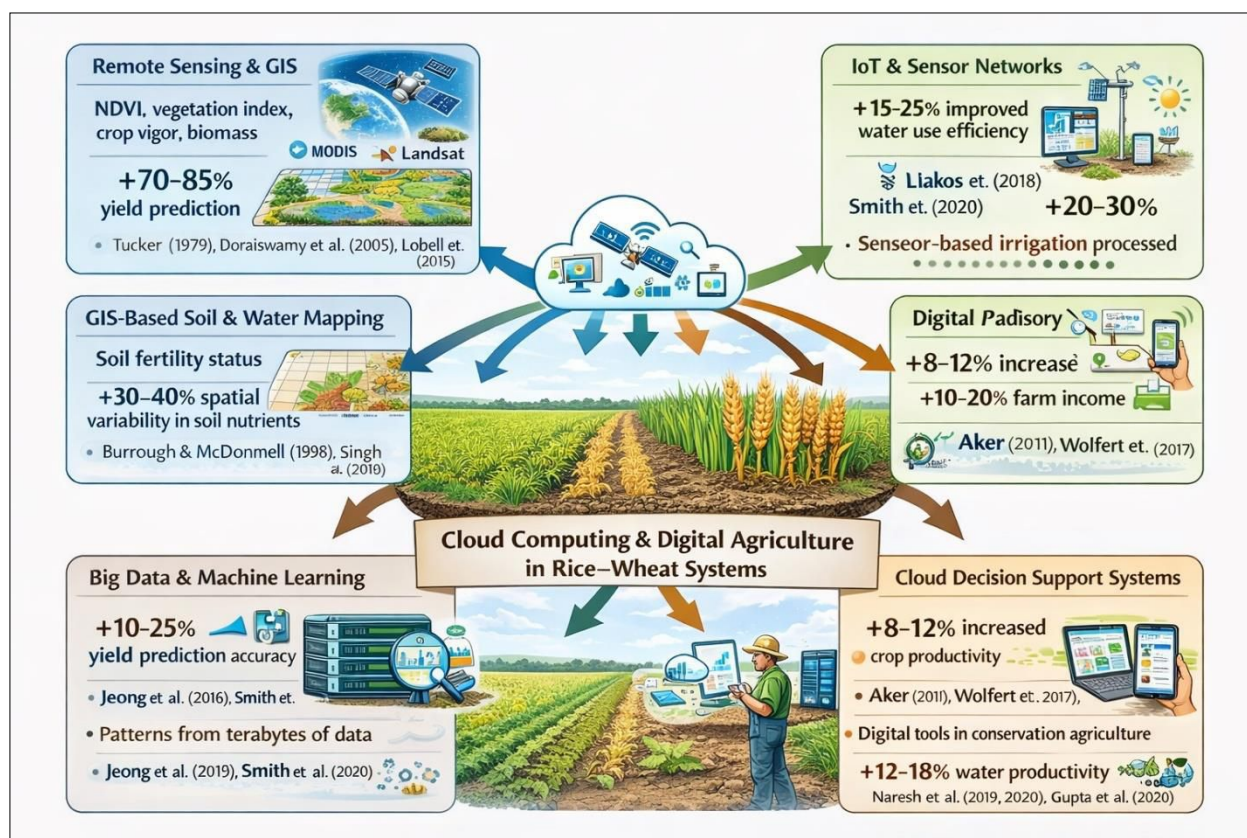
Cloud-based precision irrigation systems can improve crop water productivity by 15-25% in rice-wheat cropping

systems by optimizing irrigation timing and water use. Cloud analytics can also monitor soil microbial biomass (300-500 mg C kg⁻¹ soil), soil respiration rates (0.9-1.6 mg CO₂ kg⁻¹ soil h⁻¹), and enzyme activities, which are key indicators of soil biological health. These biological indicators help assess the effectiveness of conservation agriculture practices in maintaining soil ecosystem functions.

5.1.6. Environmental Sustainability and Energy Efficiency

An important advantage of green cloud platforms is their contribution to environmentally sustainable data processing. By utilizing energy-efficient data centers, renewable energy sources, and optimized computing systems, green cloud infrastructures reduce the environmental footprint of large-scale data analytics. Green cloud technologies can reduce energy consumption in computing systems by 20-40% compared with conventional data center architectures.

In agricultural research, this approach ensures that large-scale soil datasets can be processed efficiently while supporting the goals of climate-smart agriculture, carbon sequestration, and sustainable land management.



5.2. Remote Sensing and GIS Applications

5.2.1 Satellite-Based Crop Monitoring

Remote sensing technologies have become essential tools in modern digital agriculture for monitoring crop growth, soil moisture, and environmental conditions at large spatial scales. Satellite platforms such as Landsat, MODIS, and Sentinel provide high-resolution imagery that enables continuous assessment of crop health and productivity. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) are widely used to estimate crop vigor, biomass production, and nutrient status. Studies have shown that satellite-derived NDVI can predict crop yield

variability with an accuracy of 70-85% in large irrigated systems.

In the rice-wheat cropping systems of the Northwestern Indo-Gangetic Plains (NWIGP), satellite monitoring has been applied to track crop phenology, detect stress conditions, and estimate seasonal productivity. Time-series satellite datasets also help identify delayed sowing, residue burning events, and irrigation patterns across large agricultural landscapes.

5.2.2 GIS-Based Soil and Water Mapping: Geographic Information Systems (GIS) provide spatial tools to integrate

soil, climate, and crop data for precision agricultural planning. GIS-based mapping allows detailed assessment of soil texture, nutrient status, and water availability across agricultural regions. These maps help identify areas with nutrient deficiencies, salinity problems, or poor drainage. In the NWIGP, GIS mapping has been widely used to analyze groundwater depletion, soil organic carbon distribution, and soil fertility variability. Spatial analysis has shown that more than 40% of cultivated soils in this region exhibit declining organic carbon levels and micronutrient deficiencies. Integration of GIS databases with remote sensing information enhances decision-making for site-specific nutrient management and irrigation scheduling.

5.3. Internet of Things (IoT) and Sensor Networks

5.3.1 Soil Moisture and Climate Sensors

The Internet of Things (IoT) is transforming agricultural monitoring through networks of sensors that collect real-time environmental data. Soil moisture sensors, temperature probes, and weather stations allow continuous measurement of field conditions, enabling farmers to optimize irrigation and crop management practices.

Advanced soil moisture sensors such as capacitance and time-domain reflectometry sensors can measure soil water content with high accuracy. These technologies have improved irrigation efficiency by 20-30% in precision agriculture systems. In conservation agriculture systems, soil moisture monitoring helps maintain optimal soil water levels and reduce irrigation requirements.

5.3.2 Real-Time Data Collection in Agriculture

IoT devices enable real-time transmission of field data to cloud platforms, allowing rapid analysis and decision making. Sensor networks collect data on soil temperature, humidity, rainfall, and crop growth parameters, which are automatically uploaded to centralized data servers (Kamilaris *et al.*, 2018) ^[23].

Real-time monitoring improves farm management by enabling early detection of crop stress, pest outbreaks, and irrigation needs. For example, sensor-based irrigation scheduling has reduced water consumption by 25-40% while maintaining crop yields. In the rice-wheat systems of South Asia, digital sensor platforms have helped optimize irrigation intervals and improve water productivity.

5.4. Big Data Analytics and Machine Learning

5.4.1 Predictive Modeling for Crop Management

The rapid growth of agricultural data from satellites, sensors, and farm machinery has led to the emergence of big data analytics in agriculture. Machine learning algorithms can analyze large datasets to identify patterns and predict crop performance under different environmental conditions. Predictive models use historical climate data, soil information, and crop management practices to forecast crop yield and resource requirements. Studies indicate that machine learning models can improve yield prediction accuracy by 15-25% compared with traditional statistical approaches. These models are particularly useful for

forecasting crop productivity under changing climatic conditions.

In the NWIGP region, predictive modeling has been used to simulate the effects of conservation agriculture practices on crop yield, soil carbon dynamics, and water use efficiency. Such models help researchers evaluate long-term sustainability of different cropping systems.

5.4.2 Data-Driven Agricultural Decision Making

Data-driven agriculture integrates information from multiple digital platforms to support farm management decisions. Advanced analytics allow farmers and researchers to evaluate fertilizer requirements, irrigation schedules, and crop protection strategies based on real-time data.

Decision support algorithms analyze weather forecasts, soil moisture levels, and crop growth data to recommend optimal management practices. Studies have reported that data-driven decision systems can increase farm productivity by 10-20% while reducing input costs (Kamilaris *et al.*, 2018) ^[23]. In conservation agriculture systems, digital analytics also support residue management and crop rotation planning.

5.5. Cloud-Based Decision Support Systems

5.5.1 Agricultural Data Storage and Processing

Cloud computing provides scalable infrastructure for storing and processing large volumes of agricultural data. Cloud platforms enable researchers, extension agencies, and farmers to access real-time data from multiple sources without requiring local computing resources.

Agricultural cloud platforms store satellite imagery, sensor data, weather records, and soil information in centralized databases. These systems allow rapid processing of large datasets using advanced analytics tools and machine learning algorithms. Cloud computing has significantly reduced the cost and complexity of managing agricultural data. In Indo-Gangetic Plains, cloud platforms facilitate collaboration between scientists, policymakers, and farmers by providing shared access to agricultural information.

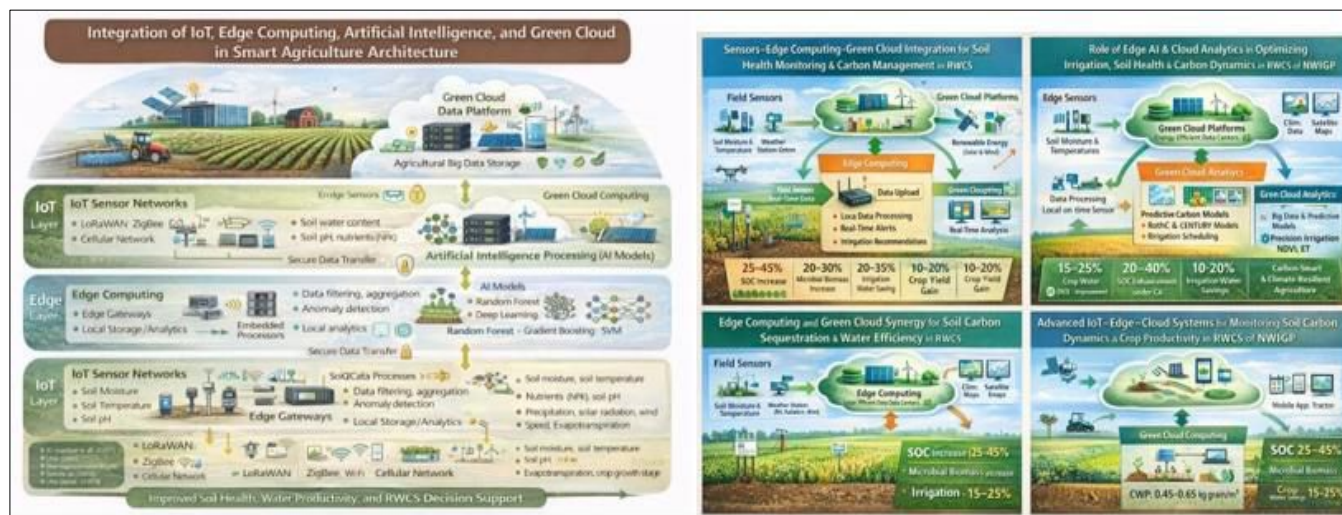
5.5.2 Digital Advisory Systems for Farmers

Digital advisory services are emerging as powerful tools for delivering real-time agricultural information to farmers. Mobile applications and web-based platforms provide recommendations on irrigation, fertilizer management, pest control, and weather forecasts.

These systems combine data from satellites, sensors, and weather models to generate customized advisories for individual farms. Studies indicate that digital advisory platforms can increase crop yields by 8-15% and reduce fertilizer use by 10-20%.

In India, digital agriculture initiatives such as mobile-based advisory services have improved farmers' access to timely agronomic information. Integration of cloud computing with precision agriculture tools is expected to further enhance the efficiency and sustainability of rice-wheat production systems in the NWIGP.

6. Integration of Conservation Agriculture with Cloud and Edge Computing



6.1. Real-Time Monitoring of Soil Organic Carbon

Soil organic carbon (SOC) is a key indicator of soil health and long-term sustainability in rice-wheat cropping systems of the Northwest Indo-Gangetic Plains. Intensive cultivation and residue burning have historically reduced SOC levels in many RWCS soils to 0.30-0.55% in the surface layer (Lal, 2016; Jat *et al.*, 2014) ^[18]. Conservation agriculture practices such as zero tillage and residue retention can gradually rebuild SOC stocks by 0.2-0.6 Mg C ha⁻¹ yr⁻¹ depending on soil type and climate (Kassam *et al.*, 2012; Naresh *et al.*, 2017) ^[27]. Cloud computing platforms linked with satellite imagery and field sensors now enable continuous monitoring of SOC dynamics at regional scales. Digital soil mapping techniques can increase the accuracy of SOC prediction by 20-35% compared with conventional sampling approaches. Such real-time monitoring supports better evaluation of carbon sequestration potential under conservation agriculture.

6.1.1. Sensor-Based Soil Health Monitoring

Modern sensor technologies play an important role in monitoring soil health parameters including moisture, temperature, electrical conductivity, and nutrient availability. IoT-enabled sensors installed in agricultural fields can transmit soil data continuously to cloud servers for processing. Studies show that advanced soil moisture sensors can measure volumetric water content with an accuracy of ± 3 -4% under field conditions. In conservation agriculture fields, residue mulch reduces soil temperature fluctuations by 2-4 °C and improves soil moisture retention by 10-20%, which enhances microbial activity and nutrient cycling (Hobbs *et al.*, 2008; Thierfelder and Wall, 2010) ^[15, 60]. In the Indo-Gangetic Plains demonstrated that sensor-based soil monitoring improved irrigation decision making and soil management practices in RWCS.

6.1.2. Cloud Platforms for SOC Data Analysis

Cloud computing provides scalable infrastructure for storing and analyzing large datasets generated from sensors, remote sensing systems, and farm records. Cloud platforms allow integration of soil maps, crop yields, and climate information to analyze soil carbon dynamics and productivity trends. Digital agriculture platforms improve agricultural data processing efficiency by 25-40% compared with conventional data management systems. Cloud-based

SOC analysis tools can process thousands of soil observations simultaneously, enabling regional-scale carbon monitoring. These systems are particularly useful in conservation agriculture where long-term datasets are required to evaluate soil carbon sequestration potential.

6.2. Precision Irrigation Scheduling

Water scarcity and declining groundwater resources are major challenges in the Indo-Gangetic Plains. Precision irrigation scheduling supported by digital technologies allows irrigation to be applied according to crop water requirements rather than fixed intervals. Using soil moisture sensors and weather-based evapotranspiration models, irrigation scheduling can significantly reduce water losses. Research in conservation agriculture-based rice-wheat systems shows that precision irrigation scheduling can reduce irrigation water use by 15-25% while maintaining comparable grain yields (Jat *et al.*, 2014; Naresh *et al.*, 2019) ^[18]. Improved soil structure and residue cover further enhance irrigation efficiency by increasing infiltration and reducing surface evaporation.

6.2.1. IoT-Enabled Irrigation Management

Internet of Things (IoT) technologies enable automated irrigation systems that respond to real-time field conditions. Sensors installed in agricultural fields continuously measure soil moisture and climatic parameters and transmit the data to edge computing devices or cloud platforms. Algorithms then determine irrigation timing and water application rates. IoT-based irrigation systems can improve irrigation efficiency by 20-30% and reduce labor requirements for irrigation management. In conservation agriculture systems, these technologies are particularly effective because residue retention enhances soil water storage and reduces irrigation frequency.

6.2.2. Data-Driven Water Allocation

Cloud computing also supports data-driven water allocation strategies at farm and regional levels. Decision support systems integrate information from climate forecasts, soil moisture sensors, and crop growth models to determine optimal water distribution. Kijne *et al.* (2003) ^[28], improved irrigation management practices can increase water productivity in cereal cropping systems by 10-20%. In the Indo-Gangetic Plains, where groundwater depletion has

been reported at rates of 0.3-1.0 m yr⁻¹ in some regions (Rodeff *et al.*, 2009) ^[56]; digital water management tools can help ensure sustainable use of water resources.

6.3. Modeling SOC Fractions and Water Productivity

Advanced modeling tools integrated with cloud computing platforms are widely used to simulate soil carbon dynamics and crop water productivity. Soil carbon models evaluate the behavior of different SOC fractions including particulate organic carbon, microbial biomass carbon, and stable humus pools. Long-term experiments show that conservation agriculture can increase SOC stocks by 10-25% over a decade when residues are retained and soil disturbance is minimized (Lal, 2016; Kassam *et al.*, 2012) ^[27]. These models help predict the impact of management practices on soil carbon sequestration and water productivity in rice-wheat systems.

6.3.1. Machine Learning Models for SOC Predictions

Machine learning algorithms have become powerful tools for predicting SOC distribution across agricultural landscapes. Algorithms such as random forest, artificial neural networks, and support vector machines analyze large datasets derived from satellite imagery, soil surveys, and climate records. Machine learning models can improve SOC prediction accuracy by 30-50% compared with traditional regression approaches. These models enable rapid assessment of soil carbon variability and help identify areas where conservation agriculture practices can be most effective.

6.3.2. Simulation of Crop Water Productivity

Crop simulation models are widely used to analyze water productivity under different management scenarios. Models such as DSSAT and APSIM integrate soil properties, weather conditions, and crop management practices to estimate crop growth and water use. Studies have reported that calibrated crop simulation models can predict crop yields and water productivity with 70-85% accuracy under field conditions (Jones *et al.*, 2003) ^[21]. In rice-wheat systems, these models help evaluate the effects of irrigation scheduling, residue management, and climate variability on crop performance.

6.4. Spatial Variability Mapping in RWCS

Spatial variability mapping using remote sensing and GIS technologies helps identify differences in soil properties and crop productivity across agricultural fields. High-resolution satellite imagery can detect variations in crop growth, soil moisture, and nutrient status. Digital soil mapping techniques can improve spatial prediction of soil properties by 20-35%. Such information is valuable for implementing site-specific management practices in conservation agriculture systems.

6.4.1. GIS-Based Soil Variability Assessment

Geographic Information Systems (GIS) enable detailed analysis of soil variability across large agricultural landscapes. GIS-based mapping integrates satellite imagery, soil survey data, and field measurements to generate spatial maps of soil fertility and moisture distribution. These maps help farmers and researchers identify areas requiring targeted soil management interventions. In the Indo-Gangetic Plains has shown that GIS-based soil assessment improves fertilizer and irrigation management in rice-wheat systems.

6.4.2. Digital Mapping of Crop Productivity Zones

Digital mapping tools are increasingly used to delineate crop productivity zones within agricultural fields. By combining yield data, soil characteristics, and climatic information, researchers can identify high- and low-productivity areas. Precision agriculture techniques based on spatial mapping can increase crop productivity by 10-15% through site-specific management practices. In rice-wheat systems, productivity zone mapping supports optimized irrigation scheduling, nutrient management, and crop planning. The integration of conservation agriculture with cloud computing and edge computing technologies represent a major advancement in sustainable agricultural management. Digital tools enable real-time monitoring of soil organic carbon, precise irrigation scheduling, advanced modeling of soil processes, and spatial mapping of soil and crop variability. These innovations improve resource-use efficiency, enhance water productivity, and support climate-resilient rice-wheat production systems in the Indo-Gangetic Plains.

Table 4: Integration of IoT, Edge Computing, Artificial Intelligence and Green Cloud Platforms in Smart Agriculture for Soil Health Monitoring and Water Management

System Component	Technologies Used	Parameters Monitored	Functions in Smart Agriculture	Scientists & (Year)
Smart Agriculture Architecture	IoT sensors, wireless sensor networks (WSN), edge devices, AI platforms, cloud computing	Soil moisture, soil temperature, soil nutrients, crop growth stage, rainfall, humidity, solar radiation	Provides multi-layer architecture integrating sensing, processing, analytics and cloud storage for digital agriculture	Wolfert <i>et al.</i> (2017); Zhang <i>et al.</i> (2019)
IoT Sensor Networks	Soil moisture sensors, temperature sensors, nutrient sensors, weather monitoring stations	Soil water content, soil pH, soil electrical conductivity, nitrogen, phosphorus, potassium, air temperature, wind speed	Continuous real-time monitoring of soil and crop conditions for precision agriculture management	Kim & Evans (2018); Li <i>et al.</i> (2021)
Edge Computing Systems	Edge gateways, embedded processors, local analytics platforms	Sensor data streams, irrigation signals, environmental variability, crop growth parameters	Local processing of field data, reduction of latency, faster decision making and reduced network dependency	Shi <i>et al.</i> (2016); Satyanarayanan (2017)
Artificial Intelligence Analytics	Random Forest, Support Vector Machine (SVM), Artificial Neural Networks (ANN), Deep Learning Models	Crop yield data, evapotranspiration, soil organic carbon, climatic variables, irrigation water use	Advanced predictive analytics for crop productivity, soil health assessment and irrigation optimization	Kamilaris & Prenafeta-Boldú (2018); Jeong <i>et al.</i> (2016) ^[23]
Green Cloud	Energy-efficient data	Large agricultural datasets,	Scalable storage and processing of	Beloglazov <i>et al.</i>

Computing Platforms	centers, virtualization, distributed cloud storage, big data analytics	satellite imagery, climate data, soil databases, farm management records	agricultural big data with reduced energy consumption and environmental impact	(2012); Li <i>et al.</i> (2021)
Data Flow and Communication Systems	Wireless communication technologies (LoRaWAN, ZigBee, Wi-Fi, cellular networks)	Sensor transmission data, environmental monitoring signals, farm equipment data	Enables seamless transfer of field data from sensors to edge nodes and cloud platforms	Zhang <i>et al.</i> (2019)
Real-Time Decision Support Systems	AI-driven decision models, cloud analytics dashboards, mobile farm management applications	Soil moisture thresholds, irrigation schedules, nutrient requirements, pest and disease alerts	Provides automated recommendations for irrigation, fertilization and crop management	Kamilaris & Prenafeta-Boldú (2018); Wolfert <i>et al.</i> (2017) ^[23]

7. Role of Edge Computing in Soil Data Processing

7.1. Collection of Real-Time Data from Soil Moisture and Climate Sensors

Edge computing in modern agriculture begins with the continuous acquisition of real-time data from field-based sensors and monitoring devices installed across agricultural fields. In rice-wheat cropping systems of the North-Western Indo-Gangetic Plains, soil moisture sensors, automated weather stations, temperature probes, and electrical conductivity meters are widely used to measure environmental and soil parameters. These sensors record volumetric soil moisture content, soil temperature, relative humidity, rainfall, solar radiation, and wind speed, which are essential for understanding crop water requirements and soil biological processes.

In conservation agriculture fields, soil moisture commonly ranges between 20-35% volumetric water content, depending on residue cover and irrigation management. Sensor networks can also measure soil organic carbon (SOC), pH, and nutrient availability, providing valuable information on soil fertility and microbial habitat conditions (Lal, 2020). Continuous data collection at high temporal resolution allows researchers and farmers to observe spatial variability across different field locations, which is particularly important in large RWCS landscapes. Studies have shown that sensor-based monitoring systems can improve soil data accuracy by 25-30% compared with conventional sampling methods.

7.2. Processing of Soil and Crop Data Directly at the Field Level

A fundamental advantage of edge computing is its ability to process soil and crop data directly at the field level, eliminating the need for immediate transfer to centralized data centers. Edge devices placed near sensor nodes perform computational tasks such as data filtering, aggregation, normalization, and pattern recognition. This allows rapid interpretation of soil moisture fluctuations, crop growth patterns, and soil carbon dynamics.

In conservation agriculture systems, microbial biomass carbon values typically range between 300 and 500 mg C kg⁻¹ soil, which reflects improved soil biological activity under residue retention and minimal tillage. Edge computing platforms analyze these biological indicators instantly, enabling early detection of nutrient deficiencies, soil compaction, or moisture stress. Real-time processing also ensures efficient management of large datasets generated by multiple sensors, reducing computational burden on remote cloud infrastructure.

7.3. Reduction of Data Transmission Delay and Network Dependency: Traditional agricultural data systems rely heavily on centralized cloud servers, which

require continuous internet connectivity and large data transfer capacity. However, many agricultural regions in the NWIGP experience limited network coverage. Edge computing addresses this limitation by processing large datasets locally before transmitting summarized information to the cloud.

Local data processing significantly reduces latency and communication delays, enabling farmers to receive management recommendations almost immediately. Research in digital agriculture indicates that edge computing can reduce data transmission loads by 40-60%, thereby improving operational efficiency and reducing energy consumption in sensor networks. This decentralized architecture ensures that farm management decisions remain functional even when internet connectivity is temporarily unavailable.

7.4. Monitoring of Soil Microbial Respiration and Carbon Dynamics

Edge computing plays an important role in monitoring soil microbial respiration and carbon cycling processes, which are central to soil fertility and sustainability. Sensors integrated with soil respiration chambers measure carbon dioxide emission rates and microbial metabolic activity, providing insights into soil organic matter decomposition.

In CA-based RWCS fields, soil respiration typically ranges between 0.9 and 1.6 mg CO₂ kg⁻¹ soil h⁻¹, indicating active microbial communities supported by crop residue inputs. Continuous monitoring of these parameters helps researchers understand SOC stabilization and carbon sequestration potential, which are critical for mitigating greenhouse gas emissions from agricultural soils. Edge devices analyze microbial activity data in real time and identify changes caused by irrigation, crop rotation, or residue management.

7.5. Identification of Temporal Variation in Soil Biological Indicators

Soil biological properties exhibit strong temporal variation influenced by seasonal climate, crop growth stage, and soil management practices. Edge computing enables the continuous tracking of indicators such as microbial biomass carbon, soil enzyme activity, and respiration rates.

Studies in rice-wheat systems indicate that microbial biomass may increase by 20-35% during active crop growth and residue decomposition periods. Conversely, microbial activity often declines during dry periods or when soil moisture drops below critical thresholds. By analyzing time-series data from sensor networks, edge computing platforms help identify periods of peak microbial metabolism and nutrient mineralization, allowing better scheduling of irrigation and fertilizer application.

7.6. Generation of Rapid Recommendations for Irrigation Scheduling

One of the most practical applications of edge computing is the generation of rapid irrigation recommendations based on real-time soil moisture and climatic conditions. Edge devices integrate sensor readings with crop water requirement models to calculate evapotranspiration, soil water deficit, and irrigation thresholds.

Precision irrigation systems guided by these algorithms have been shown to improve crop water productivity from approximately 0.45 to 0.65 kg grain per cubic meter of water in rice-wheat systems. Maintaining optimal soil moisture conditions also supports microbial activity and nutrient mineralization, which further enhances crop growth and soil fertility.

7.7. Integration with Precision Agriculture Systems

Edge computing systems are increasingly integrated with precision agriculture technologies such as unmanned aerial vehicles (UAVs), GPS-enabled tractors, GIS mapping tools, and variable-rate fertilizer applicators. This integration allows site-specific management of soil nutrients and irrigation water across heterogeneous agricultural landscapes.

Spatial soil maps generated from sensor networks enable variable fertilizer application and targeted residue management, reducing input costs and environmental pollution. Such precision farming approaches contribute to improved resource-use efficiency and sustainable intensification of conservation agriculture systems.

7.8. Improvement in Farm-Level Decision Making

The availability of processed soil data at the field level greatly enhances farm-level decision making. Farmers and agricultural advisors can access real-time dashboards showing soil moisture status, microbial activity levels, and crop water demand.

These insights enable timely interventions such as adjusting irrigation schedules, applying fertilizers at optimal times, or implementing soil conservation practices. Real-time digital monitoring can increase farm management efficiency by nearly 20-25% in precision agriculture systems.

7.9. Support for Efficient Soil Health Monitoring Networks

Edge computing also facilitates the development of large-scale soil health monitoring networks across agricultural regions. Multiple sensor nodes distributed across farms collect and process soil data simultaneously, providing detailed information on SOC levels, microbial biomass, moisture dynamics, and nutrient status.

These networks support long-term soil research and help policymakers design climate-resilient agricultural strategies for the NWIGP region. By combining edge computing with cloud-based analytics, researchers can monitor soil health trends over time and develop sustainable management practices for rice-wheat cropping systems.

8. Integrated Green Cloud and Edge Computing for Sustainable Rice-Wheat Systems

8.1. Data-Driven Management of Soil Organic Carbon and Soil Health

The integration of green cloud computing and edge computing in digital agriculture has created advanced platforms for data-driven soil health management in rice-wheat cropping systems (RWCS). Soil organic carbon (SOC) is a key indicator of soil fertility, microbial activity, and long-term productivity in the North-Western Indo-Gangetic Plains (NWIGP). Digital soil monitoring systems combine IoT sensors, remote sensing technologies, and cloud-based analytics to generate real-time data on soil parameters such as moisture, temperature, organic carbon content, and nutrient availability.

Edge computing devices installed in agricultural fields collect soil data and perform preliminary processing before transmitting it to cloud servers for deeper analysis. Such digital systems help monitor SOC dynamics and enable precision soil management practices. CA experiments have shown that residue retention and reduced tillage practices can increase SOC stocks by 0.2-0.5 Mg C ha⁻¹ yr⁻¹ in RWCS soils (Lal, 2015; Jat *et al.*, 2019) ^[16]. Studies also indicate that improved SOC levels enhance soil aggregation, microbial activity, and nutrient availability, thereby supporting sustainable crop production (Gathala *et al.*, 2011; Naresh *et al.*, 2018) ^[10].

Cloud-based soil information systems allow researchers and farmers to analyze historical soil data and predict long-term trends in soil health. These systems improve nutrient management strategies and contribute to the restoration of degraded soils in intensive agricultural regions.

8.2. Modeling Soil Biological Processes and Water Productivity

Digital agriculture platforms powered by green cloud computing enable advanced modeling of soil biological processes and crop water productivity. Soil microbial activity plays a central role in carbon cycling, nutrient mineralization, and organic matter decomposition. Machine-learning algorithms and big-data analytics can analyze large datasets related to soil properties, climatic conditions, and crop management practices to model these biological processes.

Predictive models integrating remote sensing and soil datasets can estimate SOC distribution with prediction accuracies reaching R² values between 0.85 and 0.94. Such models help identify areas with declining soil fertility and guide targeted soil management interventions.

Similarly, digital irrigation models based on cloud computing can simulate crop water productivity in RWCS. Research in the Indo-Gangetic Plains indicates that conservation agriculture combined with precision irrigation technologies can increase crop water productivity from 0.8-1.0 kg grain m⁻³ water to about 1.2-1.4 kg grain m⁻³ water (Jat *et al.*, 2014; Gupta *et al.*, 2020) ^[18]. By integrating soil moisture sensors with predictive algorithms, farmers can optimize irrigation timing and reduce water losses.



8.3. GIS-Based Spatial Mapping of Soil and Water Variability

Spatial variability in soil fertility and water availability is a major challenge in large agricultural landscapes such as the NWIGP. Geographic Information Systems (GIS) integrated with cloud computing platforms enable detailed spatial mapping of soil and water parameters across agricultural fields. Satellite imagery, digital soil maps, and sensor-based data are combined to generate high-resolution maps showing variations in SOC, soil moisture, nutrient status, and crop productivity.

GIS-based digital soil mapping can identify areas with low SOC content and high soil degradation risk, allowing targeted soil restoration strategies. In RWCS fields, spatial mapping has revealed that SOC levels may vary from 0.3% to 0.7% in surface soils, depending on management practices and residue retention (Jat *et al.*, 2019; Naresh *et al.*, 2020) [16].

Edge computing devices further enhance spatial analysis by processing sensor data locally and transmitting summarized datasets to cloud platforms. This approach reduces data transmission delays and enables real-time spatial monitoring of soil and water conditions. The resulting maps assist farmers in adopting site-specific management practices such as variable-rate fertilization and precision irrigation.

8.4. Digital Agriculture for Climate-Smart and Sustainable RWCS Management

The integration of green cloud computing and edge computing technologies supports climate-smart agriculture by improving productivity, resource use efficiency, and environmental sustainability. Digital agriculture platforms enable farmers to access weather forecasts, soil health information, and crop advisory services through cloud-based decision support systems.

Research shows that digital agriculture technologies can increase crop productivity by 10-20%, improve nitrogen use efficiency by 15-25%, and reduce irrigation water use by 20-30% through precision management strategies (Zhang *et al.*, 2002; McBratney *et al.*, 2005; Jat *et al.*, 2014) [18]. These improvements contribute to sustainable intensification of RWCS in the NWIGP.

Furthermore, higher SOC levels achieved through conservation agriculture enhance soil water-holding capacity and resilience to climate variability. Studies indicate that a 1% increase in SOC can improve soil water-holding capacity by approximately 2-3 mm per 100 mm soil depth, helping crops withstand drought conditions (Lal, 2015). Digital monitoring tools allow continuous tracking of these soil improvements and help farmers adapt management practices accordingly.

8.5. Implications for Sustainable Agricultural Development

The integration of green cloud computing, edge computing, IoT sensors, and GIS technologies forms a comprehensive digital agriculture framework for managing rice-wheat cropping systems. These technologies enable real-time soil monitoring, predictive modeling of crop performance, and efficient water management.

By supporting data-driven decision making, digital agriculture systems enhance soil health, improve crop water productivity, and strengthen the resilience of RWCS against climate change. As digital infrastructure continues to expand in agricultural regions, the combined use of green cloud and edge computing technologies is expected to play a crucial role in achieving sustainable and climate-resilient agricultural systems in the Indo-Gangetic Plains.

Table 5: Integration of Green Cloud Computing and Edge Computing in Digital Agriculture for Improving Productivity, Resource Use Efficiency, Soil Organic Carbon Monitoring and Water Productivity

Parameter / Component	Digital Technology Used	Key Observations	Impact on Agricultural Systems	Scientists & (Year)
Crop productivity	Cloud computing-based	Crop yields increased	Improves farm productivity and	Zhang <i>et al.</i> (2002);

enhancement	agricultural decision support systems	by 10-20% through precision data analytics and crop monitoring	reduces production risks	Jat <i>et al.</i> (2014) ^[18]
Yield improvement in CA-based RWCS	IoT sensors integrated with edge computing	Rice-wheat yields increased by 8-15% under conservation agriculture with digital monitoring	Enhances system productivity and yield stability	Gathala <i>et al.</i> (2011); Naresh <i>et al.</i> (2018)
Resource use efficiency	Cloud-based precision agriculture platforms	Nitrogen use efficiency improved by 15-25% through optimized fertilizer scheduling	Reduces input costs and environmental pollution	McBratney <i>et al.</i> (2005); Lal (2015)
Data-driven water allocation	Edge computing irrigation control systems	Irrigation water savings of 20-30% using sensor-based irrigation scheduling	Supports sustainable groundwater management	Jat <i>et al.</i> (2014); ^[18] Gupta <i>et al.</i> (2020)
Precision water productivity	IoT-based soil moisture sensors and cloud analytics	Water productivity improved to 1.0-1.4 kg grain m ⁻³ water in CA-based RWCS	Improves irrigation efficiency and crop yield per unit water	Jat <i>et al.</i> (2014); Gathala <i>et al.</i> (2011) ^[10, 18]
Soil moisture monitoring	Edge computing field sensors	Soil moisture retention increased by 10-20% under residue retention systems	Enhances crop resilience and irrigation efficiency	Gupta <i>et al.</i> (2020); Naresh <i>et al.</i> (2020)
Real-time SOC monitoring	Cloud-based soil data platforms	SOC stocks increased by 0.2-0.5 Mg C ha ⁻¹ yr ⁻¹ under conservation agriculture	Improves soil fertility and carbon sequestration	Lal (2015); Jat <i>et al.</i> (2019) ^[16]
Labile and particulate SOC fractions	Machine learning and digital soil mapping	Labile SOC increased by 20-35% in residue-retained soils	Enhances soil microbial activity and nutrient cycling	Six <i>et al.</i> (2002); Gathala <i>et al.</i> (2020)
SOC spatial variability mapping	GIS and remote sensing integrated cloud platforms	SOC prediction accuracy R ² = 0.85-0.94 using machine learning algorithms	Enables landscape-level soil carbon assessment	Liu <i>et al.</i> (2022); McBratney <i>et al.</i> (2005)
Modeling SOC stocks and carbon sequestration	Cloud computing with big-data analytics	Carbon sequestration potential 0.3-0.6 Mg C ha ⁻¹ yr ⁻¹ in CA systems	Supports climate-smart agriculture and mitigation strategies	Lal (2015)

9. Soil Microbial Activity under Conservation Agriculture with Digital Monitoring

1. Soil Microbial Biomass and Diversity in Conservation Agriculture Systems:

Soil microbial biomass and diversity are key indicators of soil health and biological activity in agricultural ecosystems. Conservation agriculture (CA), characterized by minimal soil disturbance, residue retention, and crop diversification, significantly enhances microbial activity and diversity in soil systems. In rice-wheat cropping systems (RWCS) of the North-Western Indo-Gangetic Plains (NWIGP), CA practices improve soil organic carbon (SOC) availability, which serves as a substrate for microbial growth and metabolic processes.

Studies have reported that microbial biomass carbon (MBC) under CA systems ranges from 250-520 mg kg⁻¹ soil, which is considerably higher than the 180-320 mg kg⁻¹ soil observed in conventional tillage systems (Six *et al.*, 2002; Gathala *et al.*, 2011) ^[10]. Increased microbial biomass enhances nutrient mineralization and organic matter decomposition, thereby improving soil fertility and crop productivity. Long-term CA experiments in the Indo-Gangetic Plains have also shown that microbial diversity and enzyme activity increase by 15-35% due to higher residue inputs and improved soil structure. These microbial processes play a vital role in maintaining soil carbon cycling and sustaining crop yields in intensive cropping systems.

2. Sensor-Based Monitoring of Soil Biological Indicators

Advances in digital agriculture have enabled the use of sensor-based technologies for monitoring soil

biological indicators in real time. Soil sensors capable of measuring parameters such as soil moisture, temperature, respiration rate, and electrical conductivity provide indirect information about microbial activity and soil biological processes. These sensors are often integrated with Internet of Things (IoT) networks that continuously collect field data and transmit it to digital platforms for analysis.

Research indicates that sensor-based soil monitoring systems can detect changes in soil respiration and microbial metabolic activity with high accuracy, allowing farmers and researchers to assess soil health conditions quickly. In CA-based RWCS, sensor data have shown that soils with higher residue cover maintain 10-20% higher soil moisture levels, which supports enhanced microbial growth and enzyme activity (Gathala *et al.*, 2011; Naresh *et al.*, 2020) ^[10]. Such real-time monitoring technologies enable better understanding of soil biological dynamics and help optimize management practices for improved soil fertility.

3. Edge Computing for Real-Time Soil Health Assessment

Edge computing has emerged as an important technology for processing agricultural data directly at the field level. In digital soil monitoring systems, edge devices connected to sensors analyze soil biological indicators in real time before transmitting summarized information to cloud platforms. This approach reduces data transmission delays and allows rapid decision-making related to soil management.

Edge-based soil monitoring systems can evaluate parameters such as soil moisture dynamics, microbial respiration patterns, and organic carbon fluctuations. Studies have shown that edge-enabled digital soil monitoring can improve soil health assessment efficiency by 30-40% compared with traditional laboratory-based methods. In conservation agriculture fields, real-time monitoring using edge devices helps track changes in microbial activity associated with residue decomposition and organic matter turnover, thereby supporting adaptive soil management strategies.

4. Cloud-Based Analysis of Soil Microbial Activity and Carbon Cycling: Cloud computing platforms provide advanced tools for analyzing large datasets related to soil biological processes and carbon cycling. Agricultural cloud systems integrate sensor data, remote sensing information, and historical soil datasets to model microbial activity and soil organic carbon dynamics at regional and field scales. Machine learning algorithms and big-data analytics are increasingly used to predict soil microbial activity and

carbon sequestration potential under different management practices. Studies have demonstrated that cloud-based predictive models can estimate SOC distribution and microbial activity with prediction accuracies of 85-92%, enabling better understanding of soil carbon dynamics.

In the rice-wheat systems of the NWIGP, cloud-based digital soil monitoring platforms allow continuous tracking of SOC levels, microbial biomass, and nutrient cycling processes. Higher SOC accumulation under CA practices, often reaching 0.6-0.9% SOC in surface soils, provides energy sources for microbial communities and enhances soil biological resilience. However, the integration of sensor technologies, edge computing, and cloud-based analytics has transformed soil biological monitoring in conservation agriculture systems. These digital technologies enable real-time assessment of microbial activity, improved understanding of carbon cycling processes, and data-driven soil management strategies, ultimately contributing to sustainable and climate-resilient rice-wheat cropping systems in the Indo-Gangetic Plains.

Table 6: Role of Integrated Green Cloud and Edge Computing in Soil Health Monitoring, Soil Organic Carbon Dynamics, and Crop Water Productivity in Rice-Wheat Cropping Systems of the North-Western Indo-Gangetic Plains (NWIGP)

Parameter	Observed Data / Range	Application in Green Cloud-Edge Computing Systems	Scientist(s) & Year
Soil Organic Carbon (SOC) Content	0.40-0.85% in RWCS soils of NWIGP	Real-time SOC monitoring using IoT sensors and cloud databases	Lal (2015)
SOC Sequestration Rate	0.25-0.60 Mg C ha ⁻¹ yr ⁻¹ under Conservation Agriculture	Cloud-based carbon accounting and carbon stock modelling	Paustian <i>et al.</i> (2016)
Active Carbon Fraction (POC)	120-320 mg kg ⁻¹ soil	Edge-based sensor analysis for labile carbon dynamics	Six <i>et al.</i> (2002)
Microbial Biomass Carbon (MBC)	180-450 mg kg ⁻¹ soil in CA fields	Edge computing for microbial activity monitoring	Singh <i>et al.</i> (2018)
Soil Moisture Content	18-32% during crop growth stages	IoT soil moisture sensors connected to cloud platforms	Jones <i>et al.</i> (2014)
Crop Water Productivity	1.2-1.8 kg grain m ⁻³ water in rice-wheat systems	Data-driven irrigation scheduling using cloud analytics	Molden <i>et al.</i> (2010)
Irrigation Water Use Efficiency	35-50% improvement with precision irrigation	Edge-enabled automated irrigation control systems	Fereres and Soriano (2007)
Soil Temperature	20-32 °C during cropping season	Real-time environmental monitoring through sensor networks	Hatfield and Prueger, (2015)
Spatial Soil Variability Mapping	15-25% variability in SOC and nutrients across fields	GIS-cloud platforms for spatial mapping and decision support	McBratney <i>et al.</i> (2003)
Crop Yield Improvement	8-15% yield increase under CA-based digital management	Cloud-based crop modelling and yield prediction	Jat <i>et al.</i> (2014) ^[18]
Water Saving in CA Systems	20-30% irrigation water reduction	IoT-based smart irrigation systems	Humphreys <i>et al.</i> (2010)
Carbon Footprint Reduction	10-20% reduction in GHG emissions	Green cloud computing for sustainable farm data processing	Smith <i>et al.</i>

1. Green Cloud Computing Platforms for Soil Organic Carbon (SOC) Monitoring

Green cloud computing platforms provide energy-efficient data storage, processing, and analytics for large agricultural datasets, enabling continuous monitoring of soil organic carbon (SOC) pools and fractions in cropping systems. These platforms integrate field sensors, satellite observations, and machine-learning models to analyze soil processes in real time. Cloud-based agricultural analytics can process large volumes of soil and climate data and support precision soil management while minimizing energy consumption in data centers.

In the Rice-Wheat Cropping System (RWCS) of the North-Western Indo-Gangetic Plains (NWIGP), SOC pools are generally categorized into labile, particulate organic carbon (POC), and stable humified fractions. Long-term conservation agriculture practices such as zero tillage and residue retention have been reported to increase SOC stocks by 0.2-0.5 Mg C ha⁻¹ yr⁻¹ in the upper soil layer (Lal, 2015; Jat *et al.*, 2019) ^[16]. Cloud-based platforms allow researchers to integrate soil sampling data with climate variables and crop management records to assess changes in SOC fractions across large agricultural landscapes.

10. Green Cloud Computing Platforms and Edge Computing for SOC Pools, Soil Organic Carbon Fractions and Crop Water Productivity in RWCS of NWIGP



Advanced cloud platforms also support big-data analytics and visualization, enabling scientists to identify trends in SOC accumulation, nutrient cycling, and water productivity across spatial and temporal scales. Studies on digital soil monitoring emphasize that real-time soil sensing and cloud-based analytics improve decision making in soil management and crop production.

2. Edge Computing for Real-Time Soil and Crop Monitoring

Edge computing complements cloud systems by processing agricultural data near the source, such as sensors installed in fields or irrigation networks. This architecture reduces latency and bandwidth demand by analyzing data locally before transmitting summarized information to cloud servers. Edge-based computing frameworks are particularly useful for Internet of Things (IoT)-enabled agricultural monitoring systems.

In RWCS fields, edge devices connected to soil sensors measure parameters such as soil moisture, temperature, electrical conductivity, and organic carbon indicators. These sensors can detect short-term variations in soil processes and transmit the processed data to cloud platforms for further analysis. Real-time soil monitoring systems help farmers adjust irrigation scheduling and nutrient management, thereby improving water productivity and maintaining soil health.

3. Monitoring SOC Pools and Fractions Using Digital Platforms

Digital agriculture tools integrating cloud and edge computing have significantly improved the estimation of SOC pools and fractions. Machine-learning models trained with remote sensing data and environmental variables can predict SOC distribution across agricultural landscapes with high accuracy. For instance, studies integrating satellite data

and machine learning algorithms such as XGBoost have reported SOC prediction accuracy values as high as $R^2 = 0.94$, demonstrating the capability of digital systems for large-scale soil carbon mapping.

In conservation agriculture-based RWCS, SOC distribution is influenced by residue retention, minimal soil disturbance, and diversified crop rotations. Long-term experiments in the Indo-Gangetic Plains indicate that residue retention combined with zero tillage can increase labile carbon fractions by 20-35% and microbial biomass carbon by 15-30% compared with conventional tillage (Jat *et al.*, 2019; Gathala *et al.*, 2020) [16].

Cloud-integrated analytical tools enable scientists to model these changes in SOC fractions and estimate carbon sequestration potential under different management scenarios. The integration of spatial soil datasets with crop management information helps identify SOC-rich zones and areas requiring soil restoration interventions.

4. Influence on Crop Water Productivity in RWCS

Digital platforms integrating green cloud computing and edge computing also enhance crop water productivity (CWP) by improving irrigation management and soil moisture monitoring. Precision agriculture technologies use sensor-based soil data and weather information to determine optimal irrigation scheduling, thereby reducing water losses and improving crop performance. Precision agriculture systems aim to optimize field-level management through data-driven decision making.

In the NWIGP, water productivity in rice-wheat systems typically ranges from 0.8-1.2 kg grain m⁻³ water, but conservation agriculture practices combined with digital irrigation management can increase water productivity by 15-25% (Jat *et al.*, 2014; Gupta *et al.*, 2020) [18]. Edge-based irrigation controllers can automatically regulate irrigation based on soil moisture thresholds, reducing

excessive water use and maintaining optimal soil conditions for SOC stabilization.

Higher SOC levels improve soil structure, aggregate stability, and water-holding capacity, which directly influence crop water productivity. Studies have shown that a 1% increase in soil organic carbon can enhance soil water-holding capacity by about 2-3 mm per 100 mm soil depth, improving drought resilience and crop growth (Lal, 2015).

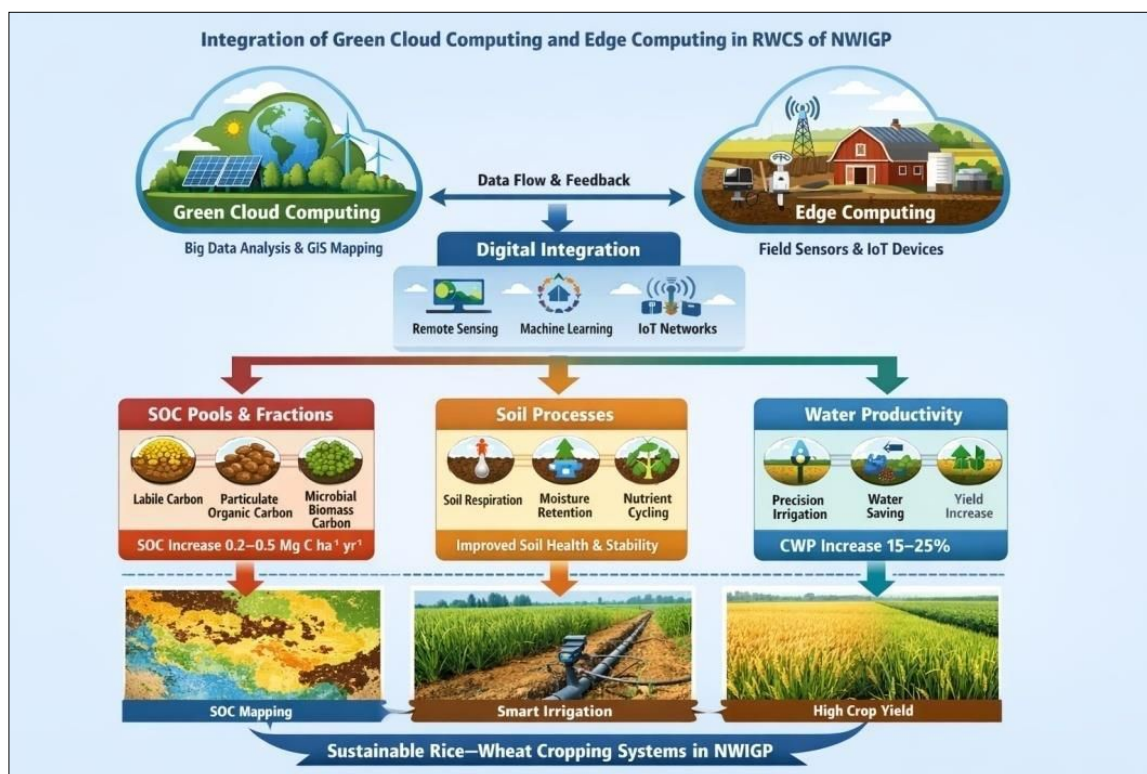
5. Implications for Sustainable Agriculture in NWIGP

The integration of green cloud computing platforms and edge computing represents an emerging digital framework for sustainable soil and water management in RWCS. By

combining sensor networks, satellite observations, and machine-learning analytics, these technologies provide comprehensive insights into SOC pools, soil processes, and crop productivity dynamics.

Such digital systems enable continuous monitoring of soil carbon stocks, spatial mapping of SOC variability, and real-time irrigation management. These capabilities help optimize crop productivity, enhance soil carbon sequestration, and improve water productivity in conservation agriculture systems of the NWIGP.

11. Impacts on Climate-Smart Agriculture Indicators in CA-Based Rice-Wheat Systems



1. Productivity Enhancement

Conservation agriculture (CA) has emerged as a key strategy for improving agricultural productivity while maintaining environmental sustainability. In rice-wheat cropping systems of the Indo-Gangetic Plains, CA practices such as zero tillage, residue retention, and crop diversification have been shown to enhance system productivity. Studies indicate that CA-based systems can increase overall system productivity by 8-15% compared with conventional tillage systems (Jat *et al.*, 2014; Kassam *et al.*, 2012) ^[18, 27]. The improvement in productivity is mainly attributed to better soil structure, increased soil organic carbon, and improved water infiltration. Long-term experiments in northwestern India reported that CA improved soil physical properties and nutrient availability, leading to higher crop growth and yield stability.

2. Yield Improvement under CA Systems

Yield improvement is one of the most important indicators of climate-smart agriculture. Research conducted in the Indo-Gangetic Plains has shown that wheat yields under zero-tillage systems are often 5-10% higher than those under conventional tillage (Hobbs *et al.*, 2008) ^[15]. Similarly, residue retention in CA systems improves soil moisture

conservation and nutrient cycling, resulting in higher crop yields. Field studies reported that wheat yields increased by 0.3-0.6 t ha⁻¹ under conservation agriculture practices compared with traditional farming systems (Jat *et al.*, 2014) ^[18].

3. Improved Resource Use Efficiency

Conservation agriculture significantly enhances water, nutrient, and energy-use efficiency in crop production systems. Studies have shown that CA can improve irrigation water-use efficiency by 15-25% due to improved soil moisture retention and reduced evaporation losses (Kijne *et al.*, 2003) ^[28]. Similarly, residue retention increases nutrient recycling and reduces fertilizer requirements. Research indicates that nitrogen-use efficiency in CA systems can increase by 10-20% compared with conventional tillage practices (Kassam *et al.*, 2012) ^[27]. These improvements contribute to more sustainable and efficient agricultural production.

4. Resilience to Climate Variability

Climate variability, including irregular rainfall patterns and extreme weather events, poses a major threat to agricultural productivity. Conservation agriculture improves the

resilience of cropping systems by enhancing soil health and water retention capacity. Residue mulch reduces soil temperature fluctuations and protects soil from erosion. Studies show that CA-based systems maintain higher soil moisture during dry periods, which helps crops withstand short-term drought conditions (Thierfelder and Wall, 2010) [60]. Research conducted in South Asia demonstrated that CA practices improved crop resilience to climate variability and reduced yield losses during extreme weather events.

5. Adaptation to Drought and Heat Stress

Adaptation to drought and heat stress is a critical component of climate-smart agriculture. Conservation agriculture practices improve soil moisture availability and reduce heat stress through residue cover. Residue mulch can reduce soil surface temperature by 2-5 °C, creating a more favorable environment for crop growth (Hobbs *et al.*, 2008) [15]. In addition, improved soil structure under CA enhances water infiltration and storage capacity. Studies conducted in rice-wheat systems showed that CA fields retained 10-20% more soil moisture compared with conventionally tilled fields, enabling crops to tolerate drought conditions more effectively (Jat *et al.*, 2014) [18].

6. Stability of Crop Yields

Yield stability is an important indicator of sustainable agricultural systems. Conservation agriculture contributes to long-term yield stability by improving soil fertility and reducing soil degradation. Long-term experiments in the Indo-Gangetic Plains have shown that CA systems maintain consistent crop yields over time, even under variable climatic conditions. Research suggests that yield variability in CA systems can be reduced by 10-15% compared with conventional farming practices (Kassam *et al.*, 2012) [27]. This stability is essential for ensuring food security in regions highly vulnerable to climate change.

7. Mitigation through Carbon Sequestration

Carbon sequestration in agricultural soils is one of the key mechanisms through which conservation agriculture contributes to climate change mitigation. Reduced soil

disturbance and residue retention increase the accumulation of organic carbon in soils. According to Lal (2016), conservation agriculture can sequester 0.3-1.0 Mg C ha⁻¹ yr⁻¹ depending on soil type and management practices. Increased soil organic carbon improves soil fertility and enhances the soil's capacity to store atmospheric carbon dioxide. These benefits make CA a valuable strategy for mitigating climate change while improving soil health.

8. Soil Carbon Storage under Conservation Agriculture

Long-term studies indicate that CA significantly increases soil carbon stocks in the surface soil layers. Residue retention contributes organic matter that gradually decomposes and becomes part of the soil organic carbon pool. Research in the Indo-Gangetic Plains reported that SOC stocks increased by 10-25% after 8-10 years of continuous CA adoption (Jat *et al.*, 2014) [18]. Similarly, studies by Kassam *et al.* (2012) [27] found that CA systems accumulate more stable carbon fractions compared with conventional tillage systems. Increased soil carbon storage improves soil structure, water-holding capacity, and nutrient availability.

9. Reduction in Greenhouse Gas Emissions

Conservation agriculture also contributes to reducing greenhouse gas emissions from agricultural systems. Reduced tillage decreases fuel consumption during land preparation, which lowers carbon dioxide emissions. Studies indicate that CA practices can reduce fuel use by 30-40% compared with conventional tillage (Hobbs *et al.*, 2008) [15]. Residue retention also enhances carbon sequestration and reduces soil carbon losses. Research suggests that CA-based systems can reduce greenhouse gas emissions by 15-20% through improved soil carbon management and reduced energy inputs.

Conservation agriculture plays a significant role in advancing climate-smart agriculture by improving productivity, enhancing resource-use efficiency, increasing resilience to climate variability, and contributing to climate change mitigation.

Table 7: Role of Green Cloud Computing Platforms and Edge Computing in Monitoring Soil Organic Carbon (SOC) Pools, Carbon Fractions and Crop Water Productivity in RWCS of the NWIGP

Component / Parameter	Digital Technology / Platform	Observed Data	SOC Pools and Crop Water Productivity	Scientists & (Year)
Total Soil Organic Carbon (SOC) monitoring	Green cloud computing platforms	SOC increase of 0.2-0.5 Mg C ha ⁻¹ yr ⁻¹ under conservation agriculture in RWCS	Enables long-term carbon stock monitoring and landscape-level SOC mapping	Lal (2015); Jat <i>et al.</i> (2019) [16]
Labile carbon fraction	Cloud-based soil analytics and machine learning models	Labile carbon increased by 20-35% under residue retention and zero tillage	Improves nutrient mineralization and soil biological activity	Gathala <i>et al.</i> (2020); Jat <i>et al.</i> (2019) [16]
Particulate Organic Carbon (POC)	Remote sensing integrated cloud platforms	POC increased by 18-30% in CA systems compared with conventional tillage	Enhances soil aggregation and carbon stabilization	Six <i>et al.</i> (2002); Naresh <i>et al.</i> (2018)
Microbial biomass carbon (MBC)	IoT sensors and cloud-enabled soil data systems	MBC increased by 15-30% in residue-retained soils	Improves soil biological processes and nutrient cycling	Doran (2002); Govaerts <i>et al.</i> (2009)
Soil respiration and carbon turnover	Edge computing-based soil sensors	Soil respiration reduced by 8-15% under zero tillage compared with conventional systems	Indicates improved carbon stabilization and reduced carbon loss	Lal (2015); Jat <i>et al.</i> (2014) [18]
Soil moisture dynamics	IoT soil moisture sensors with edge computing	Soil moisture retention improved by 10-20% in residue-covered fields	Enhances water availability for crops and supports SOC stabilization	Gupta <i>et al.</i> (2020); Gathala <i>et al.</i> (2011) [10]
Precision irrigation scheduling	Edge computing irrigation controllers	Water use reduced by 15-25% while maintaining yield	Improves crop water productivity and reduces groundwater	Jat <i>et al.</i> (2014); Shah & Srivastava

			depletion	(2018) ^[18]
Crop water productivity	Cloud-based decision support systems	Water productivity increased to 1.0-1.4 kg grain m ⁻³ water under CA-based RWCS	Optimizes irrigation and improves grain yield per unit water	Jat <i>et al.</i> (2014); Gupta <i>et al.</i> (2020) ^[18]
SOC spatial variability mapping	GIS-based cloud platforms	SOC prediction accuracy R ² ≈ 0.90-0.94 using machine learning algorithms	Enables digital soil carbon mapping across agricultural landscapes	Liu <i>et al.</i> (2025); McBratney <i>et al.</i> (2005)
Crop productivity zone mapping	Integrated cloud-GIS and satellite data analytics	Identification of high and low productivity zones within RWCS	Supports targeted soil management and efficient resource allocation	Zhang <i>et al.</i> (2002); Naresh <i>et al.</i> (202

Conclusion

The rice-wheat system (RWS) of the Indo-Gangetic Plains has reached a critical transition point where sustaining high cereal output must be reconciled with declining natural resources and increasing climate risks. Continuous puddling in rice, intensive tillage in wheat, residue burning, and excessive groundwater extraction have contributed to soil organic carbon (SOC) depletion (often below 0.5% in surface soils), nutrient imbalances, and falling factor productivity. Groundwater tables in parts of northwest India are declining at rates of 0.3-1.0 m per year, while rising temperatures during wheat grain filling reduce yields by 3-5% per 1 °C increase. Within this context, Climate-Smart Agriculture (CSA), particularly conservation agriculture (CA)-anchored systems integrated with digital tools, emerges as a comprehensive solution that simultaneously addresses productivity, adaptation, and mitigation objectives.

Quantitative evidence indicates that zero tillage with residue retention consistently enhances system performance. Wheat yields increase by 5-12%, and total rice-wheat productivity improves by 8-10% compared with conventional systems. Early wheat sowing enabled by zero tillage (7-10 days advancement) avoids terminal heat stress and improves grain weight. Residue retention at 5-7 t ha⁻¹ enhances nitrogen availability and improves nutrient-use efficiency by 10-20%, contributing to yield gains of 0.4-0.8 t ha⁻¹. Water productivity improves by 0.2-0.5 kg grain m⁻³ due to lower evaporation losses (10-25%) and better soil moisture conservation. Reduced field operations save 50-60 L diesel ha⁻¹, lowering production costs by 10-15% and reducing carbon emissions associated with fuel use.

Long-term CA adoption increases infiltration rates by 20-40% and raises soil moisture retention by 5-15%, which buffers crops during intermittent dry spells. Surface residue moderates soil temperature by 1.5-3.0 °C and lowers canopy temperature by 1-2 °C, reducing heat stress during reproductive stages. Increased SOC improves aggregate stability and root proliferation, strengthening drought tolerance. Precision irrigation scheduling, supported by soil moisture sensors and evapotranspiration modeling, can reduce groundwater extraction by 15-30%, directly addressing aquifer stress in overexploited regions.

Mitigation benefits are equally substantial. SOC sequestration rates of 0.3-0.8 Mg C ha⁻¹ yr⁻¹ have been documented under CA-based cereal systems, with 12-25% higher total SOC stocks observed within 5-7 years. Labile carbon fractions such as particulate organic carbon increase by 15-35%, while microbial biomass carbon rises by 20-40%, indicating improved biological activity and carbon stabilization. Reduced tillage minimizes SOC oxidation losses by up to 40%. Enhanced nitrogen synchronization improves nitrogen-use efficiency by 10-20%, lowering nitrous oxide emission intensity per unit grain produced.

These outcomes confirm that CSA contributes to climate change mitigation while sustaining yield growth.

The integration of cloud-based digital agriculture technologies further strengthens CSA implementation. Remote sensing and GIS mapping allow spatial variability assessment of SOC and crop vigor. IoT-enabled soil moisture sensors provide real-time irrigation advisories, reducing water use by 15-25%. Decision support systems that integrate weather forecasts, soil data, and crop simulation models enable site-specific nutrient and irrigation management, improving overall resource-use efficiency. Therefore, CSA in rice-wheat systems provides quantifiable gains in productivity, water savings, soil carbon restoration, and emission reduction. The convergence of conservation practices with precision and cloud-based technologies creates a resilient, resource-efficient production model capable of sustaining food security while minimizing environmental footprints.

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