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# Soil Health and Carbon Dynamics under Rice–Wheat Cropping Systems in Eastern Uttar Pradesh

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**Abstract: -**

*The primary agricultural production method in the Indo-Gangetic Plains is the rice-wheat cropping system, which is essential to maintaining rural livelihoods and guaranteeing food security in Eastern Uttar Pradesh. However, soil degradation and soil organic carbon depletion have resulted from decades of intensive cultivation that included frequent puddling, conventional tillage, excessive use of chemical fertilizers, burning of crop residue, and limited application of organic manures. This has negatively impacted soil structure, nutrient availability, microbial activity, and overall soil health, endangering the long-term sustainability of the production system. In addition to being an important indication of soil quality, soil organic carbon is essential for carbon sequestration, aggregate stability, water-holding capacity, and nutrient cycling. The equilibrium between carbon inputs from organic amendments and crop residues and carbon losses from decomposition, tillage, erosion, and residue burning controls its dynamics. According to recent research, conservation agriculture, residue retention, zero tillage, integrated nutrient management, and green manuring are examples of sustainable management techniques that greatly improve soil health, improve carbon sequestration, boost resource efficiency, and lower greenhouse gas emissions. The current state of soil health and carbon dynamics under the rice-wheat cropping system in Eastern Uttar Pradesh is highlighted in this review, which also stresses sustainable management techniques for raising agricultural output and environmental sustainability.*

***Keywords:*** *Rice–wheat cropping system, Soil health, Soil organic carbon, Carbon dynamics, Conservation agriculture, Eastern Uttar Pradesh, Carbon sequestration.*

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❖ **Introduction:**

India's economy depends heavily on agriculture since it creates jobs, ensures food security, and sustains rural livelihoods. The rice-wheat cropping system, which covers roughly 13 to 14 million hectares in northern India, is the most significant cereal-based production system in the Indo-Gangetic Plains. It is essential to the nation's food security and makes a substantial contribution to the production of wheat and rice. Due to its rich alluvial soils, ideal climate, sufficient rainfall, and rising irrigation infrastructure, Eastern Uttar Pradesh, which is situated in the eastern Indo-Gangetic Plains is one of the main areas for growing rice and wheat During the Green Revolution, the Rice–Wheat Cropping Systems productivity significantly rose thanks to the introduction of fertilizer, irrigation, mechanization, and high-yielding cultivars. However, ongoing intensive farming has created a number of sustainability issues. Declining soil fertility, depletion of soil organic matter, nutrient imbalance, and decreased biological activity have all been caused by practices like frequent puddling for rice, intensive tillage for wheat, overuse of chemical fertilizers, burning of crop residue, and decreased application of organic manures. The capacity of soil to operate as a living ecosystem that promotes plant development while preserving environmental quality is

known as soil health, and it is a crucial indicator of sustainable agriculture. Because it controls nutrient cycling, aggregate stability, water-holding capacity, microbial activity, and total soil productivity, soil organic carbon is regarded as the most significant indicator of soil health. The equilibrium between carbon losses from decomposition, erosion, tillage, and residue burning and carbon inputs from crop residues, roots, and organic supplements determines the dynamics of soil organic carbon. In Eastern Uttar Pradesh, soil carbon dynamics and greenhouse gas emissions are significantly impacted by alternating flooded conditions during rice culture and aerobic conditions during wheat production. A significant obstacle to preserving soil fertility and agricultural yield is declining soil organic carbon. Conservation agriculture, zero tillage, residue retention, integrated nutrient management, green manuring, and crop diversification are examples of sustainable management techniques that have demonstrated a great deal of promise to improve soil health, improve carbon sequestration, and boost resource-use efficiency. The present state of soil health and carbon dynamics under the rice-wheat cropping system in Eastern Uttar Pradesh is summarized in this review, emphasizing the significance of soil organic carbon and sustainable management techniques for raising agricultural productivity and guaranteeing long-term environmental sustainability.

❖ **Rice–Wheat Cropping System in Eastern Uttar Pradesh.**

The foundation of regional agriculture, food security, and rural livelihoods is the rice-wheat cropping system, which is the most common cereal-based production system in Eastern Uttar Pradesh. The area's rich alluvial soils, humid subtropical climate, 900 to 1,200 mm of annual rainfall, and growing irrigation infrastructure make it ideal for growing wheat during the rabi season and rice during the kharif season. During the Green Revolution, the productivity of both crops was significantly raised by the adoption of high-yielding cultivars, irrigation, mechanization, and better crop management techniques. Continuous intensive cultivation has raised questions about the system's long-term sustainability despite its extraordinary success. Soil degradation, nutrient imbalance, depletion of soil organic carbon and decreased microbial activity are the results of conventional practices like frequent puddling for rice, intensive tillage for wheat, overuse of chemical fertilizers, burning of crop residues, and decreasing use of organic manures. The fertility, general production, and soil structure have all suffered as a result of these changes. In addition to contributing to greenhouse gas emissions and air pollution, burning crop


residue, which is frequently done to enable timely wheat sowing, results in large losses of organic carbon and vital nutrients. In a similar vein, rising groundwater extraction and climate change have made it harder to produce rice and wheat sustainably. Thus, maintaining soil health now depends on maintaining soil organic carbon through better residue management and balanced nutrient application. Conservation agriculture, zero tillage, residue retention, integrated nutrient management (INM), crop diversification, and effective water management are examples of sustainable management techniques that have demonstrated significant promise to increase soil fertility, improve carbon sequestration, improve water and nutrient use efficiency, and lower greenhouse gas emissions. In addition to restoring soil health, these climate-smart strategies increase system resilience in the face of shifting climate circumstances. For the rice-wheat cropping system in Eastern Uttar Pradesh to remain productive and sustainable over the long run, its widespread adoption is essential.

- **Concept of Soil Health**

The ability of soil to support biological diversity, preserve environmental quality, and sustain plant productivity is referred to as soil health. Soil health encompasses the physical, chemical, and biological characteristics of soil as well as their interactions, in contrast to soil fertility, which is mainly concerned with nutrient availability. In addition to supporting beneficial microbes, increasing resilience to environmental challenges, improving water and nutrient availability, and fostering root growth, healthy soil also boosts carbon sequestration. Sustainable agricultural productivity in Eastern Uttar Pradesh's rice-wheat cropping system depends on the condition of the soil. The alluvial soils in the area are naturally fertile, but decades of intense farming have progressively deteriorated the quality of the soil. Declining soil organic carbon, nutritional imbalance, and decreased microbial activity are the results of practices including frequent puddling, heavy tillage, overuse of chemical fertilizers, burning of crop residue, and decreased application of organic manures. Therefore, maintaining crop yield and environmental quality in the area depends on enhancing soil health through conservation agriculture and integrated soil management.


➢ **Physical Indicators of Soil Health**

They affect root development, water transport, aeration, and soil structure, the physical characteristics of soil are essential to plant growth. Bulk density, porosity, aggregate stability, infiltration rate, and water-holding capacity are significant physical markers. These qualities have been negatively impacted by repeated tillage for wheat and continual puddling for rice in the rice-wheat cropping system. In addition to destroying soil aggregates, reducing macro porosity, and limiting root growth in the subsequent wheat crop, puddling produces a compact layer that lessens water loss during rice cultivation. In a similar vein, frequent conventional tillage raises the danger of erosion and moisture loss, impairs soil structure, and speeds up the breakdown of soil organic matter. These modifications lower soil productivity overall, water infiltration, and nutrient availability.

### ➢ Chemical Indicators of Soil Health

The availability of nutrients, soil fertility, and total crop productivity are all influenced by chemical characteristics. Soil pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon and the availability of macronutrients are important chemical markers of soil health. Eastern Uttar Pradesh's alluvial soils are ideal for crop growth because they are typically neutral to slightly alkaline. However, nutrient imbalances and deficits of micronutrients like zinc, sulfur, boron, and iron have been caused by ongoing rice-wheat agriculture and excessive use of nitrogenous fertilizers without balanced nutrient management. The most limiting resource in the rice-wheat system is nitrogen, however because of losses from volatilization, leaching, and denitrification, its usage efficiency is still poor. In many farmed soils, phosphate and potassium deficits have also resulted from ongoing fertilizer loss without sufficient replenishment. Because it increases nutrient availability, cation exchange capacity, buffering capacity, and overall soil fertility, soil organic carbon is the most significant chemical indicator. When compared to applying only chemical fertilizers, long-term studies have demonstrated that integrated nutrient management (INM), which combines mineral fertilizers with farmyard manure, compost, crop residues, and green manures, effectively increases soil organic carbon improves nutrient availability, and sustains soil fertility.

### ➢ Biological Indicators of Soil Health.

The activity of soil organisms involved in nutrient cycling, organic matter breakdown, and general ecosystem functioning, biological indicators are crucial for evaluating soil health. Enzyme activity, earthworm populations, and soil microbial biomass are significant biological indicators. These organisms are essential for maintaining soil fertility, fixing nitrogen, sequestering carbon, and mineralizing nutrients. Continuous tillage, burning of crop residue, and overuse of agrochemicals lower microbial biomass and biological activity in the rice–wheat cropping system (RWCS) by hastening the loss of soil organic matter. Soil productivity declines as a result of less effective nutrient cycling. On the other hand, organic substrates that promote microbial growth and boost soil biological health are provided by sustainable techniques like conservation agriculture, residue retention, compost application, green manuring, and integrated nutrient management (INM). Active microbial communities and effective nutrient cycling are indicated by higher activity of soil enzymes such phosphatase, urease, and dehydrogenase. In a similar vein, higher earthworm populations enhance water infiltration, soil aggregation, and aeration. In order to preserve biological activity, enhance soil health, and guarantee the long-term viability of the rice-wheat cropping system in Eastern Uttar Pradesh, conservation-based management approaches must be implemented.

- **Soil Health Degradation in Eastern Uttar Pradesh**

The rice-wheat cropping system in Eastern Uttar Pradesh has gradually degraded the soil. Soil organic carbon has decreased, soil structure has been damaged, and nitrogen cycling has been disrupted by frequent tillage, puddling, overuse of chemical fertilizers, burning of crop residue, and sparing use of organic manures. The decline of soil health has also been driven by nutrient imbalances, decreased microbial activity, and increased climate variability. Crop productivity is negatively impacted by declining soil health because it increases soil compaction and production costs while decreasing water-holding capacity, nutrient-use efficiency, and root development. To boost soil organic carbon, restore soil health, and guarantee the long-term sustainability of the rice wheat cropping system in Eastern Uttar Pradesh, sustainable methods like conservation agriculture, residue retention, integrated nutrient management, and balanced fertilization are crucial.

- **Soil Organic Carbon and Carbon Dynamics under Rice–Wheat Cropping Systems**

- **Soil Organic Carbon: Definition and Importance**

Soil Organic Carbon is one of the most important indicators of soil health because it determines the physical, chemical, and biological aspects of soil. It is the carbon

component of soil organic matter produced from decomposed plant remains, roots, microbes, and other organic components. soil organic carbon plays a key role in nutrient cycling, aggregate stability, water-holding capacity, cation exchange capacity, microbial activity, and overall soil fertility. Additionally, it serves as a substantial terrestrial carbon reservoir and makes a substantial contribution to both climate regulation and global carbon sequestration. The alluvial soils of the Indo-Gangetic Plains in Eastern Uttar Pradesh often have low to moderate levels of soil organic carbon because of high temperatures, quick organic matter decomposition, extensive rice-wheat agriculture, and insufficient addition of crop wastes or organic amendments. Soil structure, nutrient availability, and crop yield have all declined as a result of continuous cultivation using conventional methods, which has further decreased soil organic carbon levels. In Eastern Uttar Pradesh's rice-wheat cropping system, maintaining and improving soil organic carbon through crop residue retention, integrated nutrient management, conservation agriculture, and organic amendments is crucial for enhancing soil fertility, boosting carbon sequestration, maintaining crop productivity, and reducing climate change.

- **Sources of Soil Organic Carbon in Rice–Wheat Systems**

In the rice-wheat cropping system, the equilibrium between carbon imports and losses determines the amount of soil organic carbon. The main sources of soil organic carbon include organic additions, root biomass, and crop leftovers. Straw from rice and wheat, stubbles, leaves, and roots are examples of crop residues that break down in the soil to produce soil organic matter and increase nutrient availability. But in Eastern Uttar Pradesh, residue removal or burning is a popular technique that speeds up soil organic carbon depletion and lowers carbon inputs. Farmyard manure (FYM), compost, vermicompost, green manures, chicken manure, and biochar are examples of organic amendments that are significant sources of soil carbon. Regular application promotes soil organic matter, strengthens soil structure, boosts microbial activity, and provides vital nutrients. In particular, green manuring with legumes like Sesbania aculeata (dhaincha) improves soil fertility and sustains crop yield by adding both organic carbon and biologically fixed nitrogen.

### ➢ Carbon Cycling in Agricultural Soils

The constant flow of carbon between the atmosphere, plants, soil, and microbes is known as carbon cycling. Through photosynthesis, rice and wheat plants in agricultural settings take up atmospheric carbon dioxide ($CO_2$) and transform it into plant biomass. Crop leftovers, roots, and root exudates restore carbon to the soil after harvest, where microbes break them down.

### ➢ Factors Influencing Soil Organic Carbon Dynamics

Several environmental and management factors influence soil organic carbon dynamics in the rice–wheat cropping system of Eastern Uttar Pradesh. Climate plays a major role, as high temperatures accelerate microbial decomposition of organic matter, while monsoon rainfall and soil moisture regulate carbon mineralization. Flooded rice fields create anaerobic conditions that slow decomposition, whereas aerobic conditions during wheat cultivation promote faster oxidation of organic matter. Soil texture also affects soil organic carbon storage. Fine-textured clay soils retain more organic carbon because clay particles protect organic matter from decomposition, whereas sandy soils generally contain lower soil organic carbon due to their limited carbon stabilization capacity. The biggest impact on soil organic carbon dynamics comes from managerial approaches. While residue retention, conservation agriculture, integrated nutrient management, organic amendments, and crop variety improve carbon inputs and long-term soil organic carbon storage, intensive tillage and burning crop residues increase carbon losses. In order to maintain the productivity of the rice-wheat cropping system, improve soil health, and increase carbon sequestration, it is imperative that these sustainable practices be adopted.

### ➢ Carbon Sequestration under Rice–Wheat Cropping Systems

Carbon sequestration is the process of capturing atmospheric $CO_2$ and storing it as soil organic carbon. In the rice–wheat cropping system, soil organic carbon is increased through crop residues, root biomass, and organic amendments. However, conventional practices such as intensive tillage, puddling, and crop residue burning accelerate organic matter decomposition and reduce soil carbon storage. Sustainable practices including conservation agriculture, zero tillage, residue retention, integrated nutrient management (INM), and the application of farmyard manure and compost enhance carbon sequestration by increasing organic matter inputs and reducing carbon losses. Fine-textured alluvial soils of Eastern Uttar Pradesh also favor long-term carbon stabilization. Improved carbon sequestration not only mitigates climate change but also enhances soil fertility, water-holding capacity, nutrient availability, and overall productivity of the rice–wheat cropping system.

- **Long-Term Fertilizer Experiments and Soil Carbon Dynamics**

long-term fertilizer experiments sustaining soil health and raising soil organic carbon (need balanced nutrient management. Continuous application of chemical fertilizers alone may initially boost yields but eventually lower soil quality, microbial activity, and soil organic carbon. In contrast, Integrated Nutrient Management (INM), which combines mineral fertilizers with farmyard manure, compost, crop residues, and green manures, significantly improves soil organic carbon, nutrient availability, soil structure, and microbial biomass. These studies demonstrate that integrating organic and inorganic nutrient sources enhances carbon sequestration, improves soil fertility, and supports the long-term sustainability of the rice–wheat cropping system in Eastern Uttar Pradesh.

- **Carbon Dynamics in Eastern Uttar Pradesh**

Eastern Uttar Pradesh's rice-wheat systems are seeing a decrease in soil organic carbon as a result of inadequate organic matter inputs, excessive plowing, residue burning, and intense cropping. Soil fertility, microbial activity, and carbon storage are all enhanced by conservation agriculture techniques like zero tillage, residue retention, integrated nutrient management, and green manuring. Climate variability affects carbon loss through variations in moisture and temperature. For rice-wheat systems to remain healthy, productive, and climate resilient, soil carbon must be increased through sustainable methods.

❖ **Sustainable Management Practices for Improving Soil Health and Carbon Dynamics**

In Eastern Uttar Pradesh's rice-wheat systems, sustainable management techniques are crucial for raising soil organic carbon and increasing soil health. Soil fertility and sustainability have been diminished by intensive farming, excessive tillage, residue burning, and uneven fertilizer application. Restoring soil quality, increasing carbon sequestration, and enhancing climate resilience are all made possible by techniques including conservation agriculture, residue recycling, integrated nutrient management, organic amendments, effective water management, crop diversity, and precision agriculture.

- **Conservation Agriculture**

The zero tillage, conservation agriculture preserves soil cover, encourages crop variety, and lessens soil disturbance. It lowers production costs while enhancing soil structure, microbial activity, moisture conservation, and soil organic carbon buildup.

- **Crop Residue Management**

Crop residue recycling increases microbial activity, soil organic matter, nutrient availability, and water retention. Avoiding residue burning promotes sustainable farming by lowering carbon losses and greenhouse gas emissions.

- **Integrated Nutrient Management**

To preserve soil fertility, INM blends fertilizers, organic manures, crop residues, and biofertilizers. It improves long-term productivity, microbial activity, soil organic carbon storage, and nutrient availability.

- **Organic Farming and Biochar**

Organic inputs and biochar improve soil structure, nutrient retention, microbial diversity, and carbon sequestration. Biochar provides long-term carbon storage and enhances soil fertility.

- **Water Management**

Efficient irrigation practices such as Alternate Wetting and Drying and laser land leveling reduce water use, methane emissions, and nutrient losses while improving crop sustainability.

- **Crop Diversification**

Including legumes, oilseeds, and cover crops improves biodiversity, nutrient cycling, soil fertility, and climate resilience while increasing soil organic carbon levels.

- **Precision Agriculture**

Precision technologies such as GPS, remote sensing, and soil testing optimize fertilizer, water, and input use. These practices improve resource efficiency, productivity, and soil carbon management.

## ❖ Future Perspectives

Future research should focus on long-term monitoring of soil organic carbon, the role of soil microorganisms in carbon stabilization, and the development of climate-resilient rice and wheat varieties. Greater emphasis should be placed on conservation agriculture, crop diversification, biochar application, precision nutrient management, and efficient residue management to improve soil health and carbon sequestration. The use of remote sensing, GIS, and precision agriculture technologies can further support site-specific soil management. Strengthening farmer awareness, soil testing, extension services, and policy support will be essential for promoting sustainable soil management and ensuring the long-term productivity and environmental sustainability of the rice–wheat cropping system in Eastern Uttar Pradesh.

## ❖ Conclusion

The rice–wheat cropping system is the backbone of agricultural production and food security in Eastern Uttar Pradesh. However, continuous intensive cultivation, excessive tillage, crop residue burning, imbalanced fertilizer use, and declining application of organic manures have led to soil degradation and depletion of soil organic carbon. The decline in soil organic carbon has adversely affected soil structure, nutrient availability, microbial activity, and overall soil productivity, posing a major challenge to the long-term sustainability of the production system. Sustainable management practices such as conservation agriculture, zero tillage, residue retention, integrated nutrient management (INM), balanced fertilization, and efficient water management have proven effective in improving soil health, enhancing carbon sequestration, increasing nutrient- and water-use efficiency, and reducing greenhouse gas emissions. These practices not only restore soil fertility but also improve crop productivity and resilience under changing climatic conditions.

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