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Carbon-Smart Crop Production: Agronomic Strategies for Reducing Greenhouse Gas Emissions

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Agriculture feeds the world, supports rural livelihoods and sustains economies. Yet, it also faces a growing challenge it's climate change. Rising temperatures, irregular rainfall, droughts, floods and declining soil health are increasingly threatening agricultural productivity. At the same time, agricultural activities contribute to greenhouse gas (GHG) emissions, including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). This creates a critical challenge for modern agriculture: how can we produce more food while reducing the environmental footprint of crop production? The answer lies in *carbon-smart crop production*—an approach that combines scientifically informed agronomic practices to reduce greenhouse gas emissions, improve soil carbon storage, conserve natural resources and maintain crop productivity for sustainable agriculture.

Carbon-smart agriculture seeks to improve the environmental performance of farming while sustaining yields and enabling a gradual transition from conventional practices. Instead, it means making better decisions about how crops are grown, nutrients are supplied, water is managed and agricultural residues are utilized.

Understanding the Carbon Footprint of Crop Production

Greenhouse gas emissions from agriculture arise through several interconnected processes. Excessive or poorly timed nitrogen fertilizer application can increase nitrous oxide emissions from agricultural soils. Continuously flooded rice fields create oxygen-deficient conditions that favour methane production. Tillage, residue burning, fuel consumption and the manufacture of agricultural inputs also contribute to the overall carbon footprint. Among these processes, rice cultivation deserves particular attention because flooded paddy soils are source of emission of agricultural methane. The Intergovernmental Panel on Climate Change (IPCC) identifies improved water management, fertilizer management and residue management as important mitigation options in rice systems. Importantly, not all agricultural practices affect emissions in the same way. A practice that increases soil organic carbon may also increase methane emissions under certain conditions. Therefore, carbon-smart farming requires a whole-system approach rather than focusing on a single indicator.

Right Nutrient, Right Time: A Precision Approach to Crop Nutrition

Adequate nitrogen availability is fundamental for healthy crop development, chlorophyll synthesis, and the formation of proteins. However, nitrogen applied beyond crop requirements or at inappropriate times may be lost through leaching, volatilization and gaseous emissions. Precision nutrient management aims to synchronize between nutrient availability with crop demand. Soil testing, crop-based fertilizer recommendations, split nitrogen application, leaf colour charts, sensor-based nitrogen management and site-specific nutrient application can help improve nitrogen-use efficiency. For example, applying nitrogen in appropriate splits according to sensitive crop growth stages can reduce the amount of nitrogen exposed to loss when crop uptake is low. Leaf colour charts and crop sensors can further assist farmers in

deciding when additional nitrogen is required. Enhanced-efficiency fertilizers and suitable nitrification inhibitors may also help reduce nitrogen losses in specific cropping systems. Their effectiveness, however, depends on soil properties, weather, fertilizer placement and crop management. Efficient nitrogen management aims to convert a greater proportion of applied nitrogen into crop productivity while limiting losses to the environment.

Water-Smart Rice Cultivation: Reducing Methane Emissions

Rice is a staple food for millions of people, particularly in Asia. However, prolonged flooding creates anaerobic soil conditions that favour methane production by microorganisms. One promising approach is alternate wetting and drying (AWD), in which rice fields are allowed to drain and undergo controlled drying between irrigation events rather than remaining continuously flooded condition. Where soil, water availability and crop conditions permit, this practice can reduce methane emissions and irrigation requirements. Other options include suitable direct-seeded rice systems, improved irrigation scheduling and carefully planned mid-season drainage. A 2026 global synthesis of 91 meta-analyses reported that water-saving technologies reduced methane emissions by approximately 50% on average, although outcomes varied with the intervention and production system. Some non-flooded systems also experienced yield reductions, emphasizing the importance of locally appropriate management. For farmers, the objective should be to achieve a practical balance among water savings, crop yield, greenhouse gas reduction and production costs. AWD should be adopted only where irrigation infrastructure, soil conditions and crop water requirements allow safe implementation.

Conservation Agriculture: Protecting Soil and Storing Carbon

Soil is more than a medium for plant growth; it is also a major reservoir of organic carbon. Practices that increase carbon inputs and reduce soil disturbance can contribute to soil carbon sequestration and improve soil structure.

Conservation agriculture generally emphasizes three principles:

- ✓ **Minimum soil disturbance:** Reducing unnecessary tillage can help protect soil structure and reduce fuel consumption.
- ✓ **Permanent soil cover:** Retaining suitable crop residues or using cover crops protects soil against erosion and excessive temperature fluctuations.
- ✓ Crop diversification: Growing a variety of crops in rotation can enhance soil biological activity and promote diverse sources of carbon input into the soil.

These practices may enhance infiltration, reduce erosion, improve aggregate stability and support soil biological processes. However, the amount of carbon retained depends on climate, soil type, cropping history, residue management and the duration of adoption. No-till farming is not automatically carbon-neutral, and its benefits should be assessed over the full production system, including fuel use, fertilizer requirements and changes in soil carbon stocks.

Crop Residue Management: Turning Agricultural Waste into a Resource

Crop residue burning contributes to greenhouse gas emissions and air pollution while depriving the soil of valuable organic matter that could be recycled to improve soil health. Residues can instead be managed through mulching, incorporation where appropriate, composting, livestock feed, bioenergy production or other locally suitable uses. Retaining crop residues on the soil surface can reduce evaporation, moderate soil temperature and protect against erosion. Over time, residue inputs can contribute to soil organic matter. However, residue incorporation into flooded rice fields can increase methane emissions because decomposable organic material supplies carbon to methane-producing microorganisms. The timing and method of residue management therefore matter. A carbon-smart approach considers the entire cropping sequence. For example, residue retention may be beneficial in one crop or season but require different management before flooded rice cultivation. The aim is not simply to retain every residue in every field; it is to use agricultural biomass in ways that support soil fertility while minimizing total greenhouse gas emissions.

Diversified Cropping Systems and Cover Crops

Monocropping can limit crop diversity and leave soil exposed during fallow periods. Crop rotations, intercropping, pulse legume rotation and cover cropping offer opportunities to diversify agricultural production and improve resource use. Legumes can contribute biologically fixed nitrogen, potentially reducing the need for some externally supplied nitrogen fertilizer. Cover crops can protect the soil, suppress weeds, retain soil moisture, capture residual nutrients and add biomass to the soil. For example, suitable legume-based rotations can support soil fertility while providing additional farm products. Cover crops grown between main crops may also reduce erosion and improve soil cover. Nevertheless, these practices should be selected according to local rainfall, soil moisture, crop calendars and market opportunities. Cover crops require water and their residues can influence methane and nitrous oxide emissions depending on subsequent soil and water conditions. Thus, diversification is most effective when integrated with nutrient, water and residue management rather than treated as an isolated intervention.

Biochar and Organic Matter Management

Biochar is a carbon-rich material produced by heating biomass under limited oxygen conditions. Depending on the feedstock and production process, it can contain relatively stable forms of carbon that may persist in soil for long periods. When applied appropriately, biochar may improve certain soil properties, nutrient retention and water-holding capacity. Research has also identified potential benefits for crop productivity and greenhouse gas mitigation in some cropping systems. A 2026 synthesis of rice-field research reported that biochar was associated with yield improvements and reductions in methane, nitrous oxide and greenhouse gas emission intensity across the studies analysed. These findings are promising, but they should not be interpreted as universal outcomes for every soil or biochar product. Biochar quality, production emissions, application rate, transport costs and soil conditions all influence its net environmental benefit. Organic manures and composts also remain important tools for nutrient recycling, but their effects on greenhouse gas emissions depend on their composition, application method and the receiving soil. The most appropriate option is the one that delivers measurable agronomic benefits and a positive overall environmental balance.

Digital and Precision Agriculture: Making Climate-Smart Decisions

Emerging technologies are creating new opportunities to reduce agricultural emissions. Remote sensing, drones, soil sensors, geographic information systems and artificial intelligence can help farmers and researchers make better-informed crop management decisions.

These tools can support:

- ✓ Monitoring crop nitrogen status and identifying nutrient deficiencies.
- ✓ Mapping within-field variability and targeting fertilizer applications.
- ✓ Scheduling irrigation according to crop and soil water requirements.
- ✓ Estimating crop biomass and monitoring crop stress.
- ✓ Evaluating soil carbon and greenhouse gas mitigation interventions.

For example, satellite imagery combined with field observations can identify areas with different crop growth patterns. Farmers can then investigate whether these differences are associated with nutrient limitations, water stress or other constraints before deciding on corrective measures. Digital tools can improve the precision of agronomic interventions, but they cannot replace sound field-level agronomic knowledge. Their usefulness depends on affordability, data quality, farmer training and access to reliable advisory services.

Measuring Success: Beyond Yield per Hectare

An important challenge in carbon-smart agriculture is determining whether a practice actually reduces climate impacts.

A farming system may reduce emissions per hectare but increase emissions per kilogram of grain if yields decline substantially. Conversely, higher yields can reduce emission intensity even when total emissions do not decline.

Therefore, assessment should consider several indicators together:

- ✓ Greenhouse gas emissions per hectare.
- ✓ Greenhouse gas emissions per unit of crop yield.
- ✓ Soil organic carbon stocks over time.
- ✓ Nitrogen-use and water-use efficiency.
- ✓ Crop productivity and profitability.
- ✓ Energy use and emissions associated with agricultural inputs.

Methane and nitrous oxide must both be considered, particularly in rice-based systems where changes in water and residue management can reduce one gas while increasing the other.

Reliable measurement, reporting and verification are also necessary before claiming that a farming practice has achieved a particular emissions reduction or generated carbon credits.

Challenges and the Way Forward

Despite its potential, carbon-smart crop production faces several challenges. Small and marginal farmers may lack access to precision equipment, reliable irrigation infrastructure, quality inputs and technical guidance. Initial investment costs, labour requirements, uncertain market incentives and limited awareness can slow adoption. Furthermore, greenhouse gas mitigation is strongly influenced by local conditions. A practice suitable for irrigated rice in one region may not be appropriate for rainfed rice or another crop elsewhere. Future efforts should therefore focus on region-specific agronomic recommendations, long-term field experiments, affordable precision technologies, farmer training and better measurement of both emissions and soil carbon changes. Agricultural research institutions, extension agencies, policymakers and farmers must work together to develop practices that are practical, profitable and environmentally sound. Carbon-smart agriculture should also be integrated with climate adaptation. Practices that conserve soil moisture, improve soil structure, diversify crops and use nutrients efficiently can help strengthen resilience to droughts, heavy rainfall and other climatic stresses.

Conclusion: Growing More Food with a Lighter Climate Footprint

- ✓ The future of agriculture will depend not only on how much food we produce, but also on how efficiently and sustainably we produce it. Carbon-smart crop production offers an opportunity to connect agronomic productivity with climate responsibility.
- ✓ Precision nutrient management, water-saving rice cultivation, conservation agriculture, suitable residue management, diversified cropping systems and emerging digital technologies can all contribute to reducing the climate footprint of agriculture when implemented appropriately.
- ✓ However, there is no single practice that works everywhere. The greatest benefits are likely to come from combining locally suitable interventions, measuring their outcomes and adapting recommendations to farmers' needs.

The future of sustainable agriculture lies in a simple but powerful principle: produce more efficiently, protect the soil, use resources wisely and reduce avoidable emissions**.** Carbon-smart farming is not merely an environmental concept—it is an opportunity to build productive, resilient and responsible agricultural systems for generations to come.

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