

Plant Breeding for Carbon-Smart Agriculture

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INTRODUCTION

Agriculture is both a contributor to and a victim of climate change. Conventional agricultural practices involving intensive tillage, excessive fertilizer use, residue burning, and inefficient resource management contribute significantly to greenhouse gas emissions, particularly carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). At the same time, increasing temperature, irregular rainfall patterns, droughts, and extreme weather events threaten global food production.

Carbon-smart agriculture is an innovative approach that aims to transform agricultural systems from carbon-emitting systems into carbon-storing systems. It emphasizes three major strategies:

1. Reducing greenhouse gas emissions
2. Increasing carbon sequestration in plants and soils
3. Maintaining or improving crop productivity under changing climates

Plants are the primary biological agents responsible for atmospheric carbon capture through photosynthesis. Therefore, improving plant genetic traits associated with carbon fixation, biomass production, and soil carbon storage is a key strategy for carbon-smart agriculture.

Plant breeding provides powerful tools for developing crop varieties capable of absorbing more carbon, storing carbon efficiently in biomass and soil, and maintaining yield under environmental stresses.



2. Concept of Carbon-Smart Agriculture

Carbon-smart agriculture refers to farming practices and technologies that optimize carbon cycling within agricultural ecosystems. The approach focuses on increasing carbon inputs into soil while minimizing carbon losses.

The major principles include:

2.1 Carbon Sequestration

Carbon sequestration is the process of capturing atmospheric carbon dioxide (CO₂) by plants and storing it in biomass and soil organic matter. Improved crop varieties enhance carbon storage through greater biomass production, extensive root growth, increased crop residue retention, and improved soil organic carbon accumulation. These traits help increase carbon storage capacity, improve soil health, and support sustainable agricultural systems.

2.2 Reduction of Agricultural Emissions

Carbon-smart crops contribute to reducing agricultural greenhouse gas emissions by improving resource-use efficiency and promoting sustainable production practices. These crops require less external inputs due to better nitrogen-use efficiency, thereby reducing fertilizer-related emissions. Improved water-use efficiency minimizes energy consumption for irrigation, while compatibility with conservation agriculture practices helps reduce soil carbon losses, fuel use, and overall environmental impacts.

2.3 Climate Resilience

Carbon-smart crop varieties are developed to withstand changing climatic conditions and maintain productivity under environmental stresses. These varieties possess improved tolerance to drought, heat stress, salinity, flooding, and nutrient limitations. Climate-resilient crops ensure stable yields, enhance resource-use efficiency, and support sustainable agricultural systems by reducing production losses and improving adaptation to future climate challenges.

3. Role of Plant Breeding in Carbon-Smart Agriculture

Plant breeding has traditionally focused on improving yield, disease resistance, and quality traits. However, modern breeding programs increasingly target environmental sustainability traits.

The role of plant breeding includes:

- Developing high-carbon-sequestering crops
- Improving root architecture
- Enhancing photosynthetic efficiency
- Increasing nutrient-use efficiency
- Developing stress-tolerant varieties
- Reducing greenhouse gas emissions from cropping systems

4. Breeding Traits Important for Carbon-Smart Agriculture

4.1 Enhanced Photosynthetic Efficiency

Photosynthesis is the fundamental process through which plants capture atmospheric CO₂ and convert it into organic biomass. Plant breeding for improved photosynthetic efficiency focuses on selecting varieties with higher chlorophyll content, increased photosynthetic rate, improved carbon fixation pathways, and efficient stomatal regulation. Crops with enhanced photosynthetic capacity produce greater biomass, contributing to increased carbon storage. C₄ crops such as maize, sorghum, and millets naturally exhibit higher carbon fixation efficiency compared with C₃ crops.

4.2 Improved Root System Architecture

Roots play a vital role in transferring atmospheric carbon into the soil through root biomass and organic matter formation. Plant breeding for carbon-smart agriculture focuses on developing crops with deep rooting ability, high root biomass, extensive root branching, and longer root longevity. Deep-rooted crops deposit carbon into deeper soil layers, where it remains stored for extended periods. Wheat, sorghum, and legume crops contribute significantly to soil carbon storage through

enhanced root growth and biological nitrogen fixation.

4.3 Increased Biomass Production

Higher biomass production is an important trait for enhancing carbon accumulation in agricultural ecosystems. Plant breeding programs aim to develop crops with greater above-ground biomass, higher residue production, and increased carbon content in plant tissues. Crop residues returned to the soil contribute to organic matter formation, improve soil fertility, and enhance carbon sequestration. Crops such as sorghum, maize, Miscanthus, and perennial grasses are highly suitable due to their superior biomass production potential.

4.4 Nitrogen Use Efficiency (NUE)

Nitrogen fertilizers contribute significantly to greenhouse gas emissions, particularly nitrous oxide (N₂O). Breeding nitrogen-efficient crops helps reduce fertilizer dependency, lower emissions, and improve nutrient utilization. Important traits include efficient nitrogen uptake, better nitrogen metabolism, and enhanced root absorption capacity. Nitrogen-efficient rice and wheat varieties utilize available nutrients more effectively, maintaining productivity with reduced fertilizer inputs and supporting environmentally sustainable carbon-smart agricultural systems.

4.5 Water Use Efficiency (WUE)

Climate change has intensified water scarcity in many agricultural regions, making water-use-efficient crops essential for sustainable production. Breeding crops with improved water-use efficiency helps maintain yield under drought conditions, reduce irrigation requirements, and enhance carbon balance. Important traits include deep root systems, efficient stomatal regulation, and drought-responsive genes. Drought-tolerant crops such as millet and sorghum are valuable carbon-smart crops due to their ability to produce stable yields with limited water availability.

5. Modern Breeding Approaches for Carbon-Smart Crops

5.1 Marker-Assisted Selection (MAS)

Marker-assisted selection (MAS) is a modern breeding approach that uses molecular markers associated with desirable traits to identify and select superior plants. It helps breeders efficiently transfer important traits such as drought tolerance, improved root architecture, and nutrient-use efficiency into crop varieties. MAS reduce breeding time, increases selection accuracy, and accelerate the development of climate-resilient and carbon-smart crop varieties with enhanced productivity and sustainability.

5.2 Genomic Selection

Genomic selection is an advanced breeding technique that uses thousands of genetic markers across the genome to predict the performance and breeding value of plants. It enables faster breeding cycles, improves selection accuracy, and helps identify complex traits associated with carbon-smart agriculture. This approach is particularly useful for improving biomass production, root characteristics, and stress tolerance, leading to the development of climate-resilient crop varieties with enhanced carbon sequestration potential.

5.3 Genome Editing

Genome editing is an advanced breeding technology that enables precise modification of specific plant genes using tools such as CRISPR-Cas systems. It allows targeted improvement of important traits related to carbon-smart agriculture, including enhanced photosynthetic efficiency, drought tolerance, root development, and nitrogen-use efficiency. Genome editing provides opportunities to design crop varieties with improved carbon capture capacity, reduced environmental impact, and better adaptation to changing climatic conditions.

5.4 High-Throughput Phenotyping

High-throughput phenotyping is a modern approach that enables rapid and accurate evaluation of large numbers of plants using advanced technologies such as drones, remote sensing, imaging systems, and artificial intelligence. These tools help measure important carbon-smart traits, including plant biomass, root characteristics, growth patterns, and stress responses. High-throughput phenotyping improves breeding efficiency by allowing precise selection of climate-resilient crops with enhanced carbon sequestration potential.

6. Carbon-Smart Crop Examples

6.1 Rice

Carbon-smart rice breeding aims to develop varieties with reduced methane emissions, improved nitrogen-use efficiency, and enhanced drought tolerance. These traits support sustainable rice production while minimizing environmental impacts.

6.2 Wheat

Carbon-smart wheat breeding focuses on developing climate-resilient varieties with improved root depth, heat tolerance, nitrogen-use efficiency, and higher biomass production. Deep roots enhance soil carbon storage, while efficient nutrient use reduces fertilizer dependence and greenhouse gas emissions. Heat-tolerant and high-biomass wheat varieties contribute to sustainable production and improved carbon sequestration under changing climatic conditions.

6.3 Maize

Maize is an important carbon-efficient crop because of its C₄ photosynthetic pathway, which enables efficient carbon fixation and high biomass production. Breeding programs focus on developing maize varieties with improved drought tolerance, higher biomass production, and enhanced nutrient-use efficiency. These traits help increase carbon sequestration, reduce resource requirements, and improve the sustainability of maize-based

cropping systems under changing climatic conditions.

6.4 Millets

Millets are climate-smart crops naturally adapted to harsh environmental conditions. They require less water, possess high tolerance to drought and other stresses, and exhibit efficient carbon fixation ability. Their resilience, low input requirement, and adaptability make them valuable crops for carbon-smart agriculture. Millets contribute to sustainable food production while supporting climate change adaptation and improved resource-use efficiency.

6.5 Legumes

Legumes play an important role in carbon and nitrogen cycling through biological nitrogen fixation. They improve soil fertility by converting atmospheric nitrogen into plant-available forms, reducing the need for synthetic nitrogen fertilizers. Legume crops also contribute to soil carbon storage through root biomass and organic matter addition. Important carbon-smart legumes include chickpea, lentil, soybean, and mungbean, which support sustainable and climate-resilient agricultural systems.

7. Integration of Plant Breeding with Sustainable Farming Practices

Plant breeding alone cannot fully achieve carbon-smart agriculture; it must be integrated with sustainable management practices to maximize carbon storage and reduce environmental impacts. Carbon-smart crop varieties perform better when combined with conservation agriculture practices such as zero tillage, residue retention, and crop rotation, which enhance soil organic carbon and improve soil health. Integrated Nutrient Management (INM) practices, including biofertilizers, organic amendments, and balanced fertilization, improve nutrient efficiency and reduce greenhouse gas emissions. Agroforestry systems involving tree–crop integration increase biomass production and long-term carbon storage. Precision agriculture

technologies, such as sensor-based nutrient application and efficient irrigation management, optimize resource use and minimize losses. The combined application of improved genetic traits and sustainable farming practices enhances crop productivity, soil carbon sequestration, climate resilience, and overall ecosystem sustainability, making carbon-smart agriculture more effective and economically viable for farmers.

8. Challenges in Plant Breeding for Carbon-Smart Agriculture

Despite significant advancements in developing carbon-smart crop varieties, several challenges limit the effectiveness and widespread adoption of plant breeding approaches. Carbon-related traits are complex, require advanced evaluation methods, and are strongly influenced by environmental conditions.

8.1 Complexity of Carbon Traits

Carbon sequestration and storage traits are controlled by multiple genes and involve complex interactions between plants and the environment. Traits such as root growth, biomass production, and carbon allocation are quantitative in nature, making their identification and improvement through breeding challenging.

8.2 Limited Phenotyping Methods

Accurate measurement of important carbon-related traits, particularly root architecture, biomass accumulation, and soil carbon contribution, remains difficult. Advanced phenotyping tools are required to efficiently evaluate large numbers of genotypes under different environmental conditions.

8.3 Long Breeding Period

Development of new carbon-smart crop varieties requires several years of selection, evaluation, and multi-location testing. The lengthy breeding process increases time and investment requirements before improved varieties reach farmers.

8.4 Farmer Adoption

Successful adoption of carbon-smart varieties depends on farmer awareness, availability of high-quality seeds, accessibility of improved technologies, and clear economic benefits. Lack of knowledge and limited seed distribution systems may restrict their widespread use.

8.5 Climate Uncertainty

Future climate conditions are difficult to accurately predict due to changing temperature patterns, rainfall variability, and extreme weather events. This uncertainty makes it challenging to define breeding objectives and develop varieties suitable for diverse future environments.

9. Future Prospects

Future plant breeding programs will increasingly focus on developing crop varieties specifically designed for carbon-smart agriculture. Advances in biotechnology, genomics, and digital technologies will provide new opportunities to improve carbon capture, resource-use efficiency, and climate resilience. Artificial intelligence-based breeding, digital phenotyping, gene editing, multi-omics approaches, and climate modeling integration will enhance the identification and development of superior plant traits.

Future carbon-smart crops are expected to possess enhanced carbon capture capacity, improved contribution to soil carbon storage, reduced greenhouse gas emission potential, and greater tolerance to climate-related stresses. Integration of molecular breeding tools with sustainable agricultural practices will accelerate the development of resilient cropping systems. These advancements will help achieve higher productivity while maintaining environmental sustainability, improving soil health, and supporting global efforts toward climate change mitigation and food security.

CONCLUSION

Plant breeding is a powerful tool for achieving carbon-smart agriculture by developing crop varieties that capture more carbon, store carbon efficiently, and maintain productivity under climate stress. Improvements in photosynthesis, root architecture, biomass production, nutrient-use efficiency, and stress tolerance can significantly enhance agricultural sustainability. Modern breeding technologies such as genomic selection, genome editing, artificial intelligence, and high-throughput phenotyping provide new opportunities to develop climate-resilient crops. By integrating improved varieties with conservation agriculture, precision farming, and sustainable nutrient management, plant breeding can contribute significantly to climate change mitigation, soil health improvement, and global food security.

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