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Carbon-Smart Vegetable Production: Linking Nutrition with Climate Mitigation

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Vegetables are vital for achieving nutrition security, yet their production systems are often resource-intensive and contribute to greenhouse gas (GHG) emissions. With growing concerns over climate change, there is an urgent need to adopt carbon-smart strategies in vegetable farming that balance productivity with environmental sustainability. Carbon-smart vegetable production integrates practices such as organic amendments, biochar application, crop diversification, precision nutrient management and low-energy protected cultivation to enhance soil carbon sequestration and reduce carbon footprints. In the Indian context, where vegetable cultivation occupies nearly 10.86 million hectares, such approaches can play a transformative role in achieving dual goals *viz*., nutritional well-being and climate mitigation. This article highlights the mechanisms of carbon sequestration in vegetable-based systems, assesses their carbon footprints, explores innovative strategies for carbon-smart production and discusses challenges and opportunities for India in the context of its net-zero carbon targets.

Keywords: Carbon sequestration, Vegetable crops, Climate-smart agriculture, Carbon footprint, Sustainable farming.

Introduction

Agriculture contributes nearly 19% of India's greenhouse gas emissions, largely from fertilizer use, soil degradation and intensive resource inputs (MoEFCC, 2022). Vegetables, though crucial for balanced nutrition and income generation, are often cultivated in input-intensive systems involving high irrigation, fertilizers and plastic use in protected cultivation. This makes them vulnerable to criticism regarding their carbon footprint.

However, vegetables also present unique opportunities for climate mitigation: short-duration cycles allow multiple carbon-sequestering crops in year organic residues contribute to soil carbon build-up and innovative practices can reduce emissions. Thus, making vegetable cultivation *carbon-smart* can ensure food and nutrition security while contributing to India's commitment of achieving net-zero carbon emissions by 2070.

Carbon Sequestration Potential in Vegetable Systems

Vegetable systems can capture and store carbon through soil and biomass pathways:

a. **Soil Organic Carbon (SOC):** Vegetable residues, compost and organic manures enhance SOC content, improving both fertility and carbon storage.
b. **Root Biomass & Exudates:** Root systems of crops like okra, spinach and cole crops stimulate microbial activity, aiding soil carbon stabilization.
c. **Biochar Integration:** Biochar application in vegetable fields has shown increased carbon storage and improved nutrient-use efficiency (Verma *et al*., 2021).
d. **Diversified Cropping:** Vegetable-based rotations and intercropping (e.g., potato–okra–maize, tomato–legume systems) increase biomass returns and SOC accumulation.

Indian studies indicate that vegetable-based systems can sequester 0.3–0.8 t C/ha/year, depending on crop type and management (ICAR, 2022).

Carbon Footprints in Vegetable Cultivation

While vegetables sequester carbon, their production systems also emit GHGs:

- **High Fertilizer Use:** Nitrogen fertilizers contribute to nitrous oxide emissions, a potent GHG.
- **Irrigation Practices:** Pumping groundwater for vegetable irrigation consumes large amounts of energy, adding to carbon footprints.
- **Protected Cultivation:** Though yield-efficient, polyhouses rely on plastics and energy-intensive inputs, raising carbon costs.
- **Post-Harvest Emissions:** Cooling, storage and transportation of perishable vegetables add to life-cycle emissions.

A life-cycle analysis reveals that carbon footprints of vegetables range from 0.8 to 2.5 kg CO_2-eq/kg produce, depending on the crop and production system (FAO, 2021). Organic and diversified systems show significantly lower footprints compared to conventional intensive systems.

Strategies for Carbon-Smart Vegetable Production

To make vegetables climate-friendly, the following approaches can be adopted:

a) **Organic Amendments:** Using compost, farmyard manure and vermicompost reduces reliance on chemical fertilizers while improving soil carbon stocks.
b) **Biochar Technology:** Enhances carbon sequestration and boosts yield, especially in crops like tomato and brinjal.
c) **Cover Crops & Green Manures:** Leguminous cover crops fix nitrogen and improve soil carbon.
d) **Precision Nutrient Management:** Site-specific fertilizer recommendations, fertigation and slow-release fertilizers reduce emissions.
e) **Efficient Irrigation:** Drip and sprinkler irrigation reduce water and energy footprints by up to 40%.
f) **Low-Energy Protected Cultivation:** Using solar-powered greenhouses, biodegradable mulches and natural cooling systems.

Adopting these practices can reduce vegetable carbon footprints by **25–35%**, while increasing resilience and profitability (Singh *et al*., 2023).

Indian Context and Opportunities

India is the second-largest producer of vegetables (204.84 million tonnes in 2022–23) with states like West Bengal, Uttar Pradesh, Odisha and Bihar leading. With 10.86 million hectares under vegetable cultivation, the potential for carbon-smart practices is immense.

- **Smallholder Advantage:** High labor intensity and crop diversity in Indian vegetable systems provide natural resilience and lower footprints.
- **Carbon Credits:** Integrating vegetable growers into carbon markets can generate additional income. For example, adopting drip irrigation in tomato production in Maharashtra reduced emissions by **32%**, qualifying farmers for carbon credits.
- **Integration with Schemes:** Mission for Integrated Development of Horticulture (MIDH) and National Innovations in Climate Resilient Agriculture (NICRA) can incorporate carbon-smart vegetable farming models.

Challenges

Despite the potential, several challenges exist:

- **Measurement Difficulties:** Short-duration crops make it hard to assess net carbon sequestration accurately.
- **Yield vs. Carbon Trade-Offs:** Some carbon-saving practices may initially reduce yields, discouraging farmers.

- **Technology Costs:** Biochar units, solar-powered greenhouses and biodegradable mulches are costly.
- **Policy & Awareness Gaps:** Farmers lack incentives, knowledge and support for adopting carbon-smart methods.
- **Post-Harvest Issues:** Cold storage and logistics remain carbon-intensive, especially in rural India.

Way Forward

a. **Develop Vegetable-Based Carbon Farming Models:** Combining rotation organic inputs and efficient technologies.
b. **Carbon Credit Mechanisms:** Linking vegetable farmers to carbon trading systems through FPOs and cooperatives.
c. **Research & Data Collection:** Quantifying carbon sequestration in different vegetable systems for policy formulation.
d. **Capacity Building:** Training farmers in carbon-smart practices via Krishi Vigyan Kendras (KVKs).
    - **Policy Integration:** Including carbon-smart vegetables in India's National Action Plan on Climate Change (NAPCC).

Conclusion

Vegetables have long been valued for their nutritional and economic roles, but their hidden role in climate mitigation is now emerging. By adopting carbon-smart practices, vegetable production systems can become powerful contributors to India's climate goals while enhancing food and nutrition security. Carbon-smart vegetable farming is not just an environmental necessity, but also a pathway to sustainable livelihoods for millions of smallholders. If research, policy support and farmer participation align, India can lead the way in demonstrating how vegetables can be both a source of nutrition and a solution to climate change.

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