

Beyond the Cold Chain: Leveraging AI-Driven Digital Twins and Smart Technologies to Minimize Horticultural Carbon Footprints

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Introduction

The horticulture sector plays a vital role in global food systems, yet it remains highly dependent on energy-intensive infrastructure, particularly cold chain systems used for storage and transportation. Refrigeration, climate-controlled warehousing, and temperature-regulated logistics are essential for maintaining the quality and shelf life of fruits, vegetables, and ornamental crops. However, these systems contribute substantially to greenhouse gas (GHG) emissions due to high electricity demand and refrigerant leakage. As climate change intensifies and sustainability regulations become stricter, horticulture must transition beyond traditional cold chain management toward more intelligent, energy-efficient systems. Artificial Intelligence (AI), Internet of Things (IoT), and Digital Twin (DT) technologies are emerging as transformative solutions within climate-smart agriculture. A digital twin creates a continuously updated virtual model of a physical agricultural system, enabling real-time monitoring, simulation, and predictive optimization. These technologies facilitate data-driven decision-making that reduces resource waste, enhances productivity, and lowers carbon emissions across the horticultural value chain (Slob & Hurst, 2022; Gund et al., 2025).

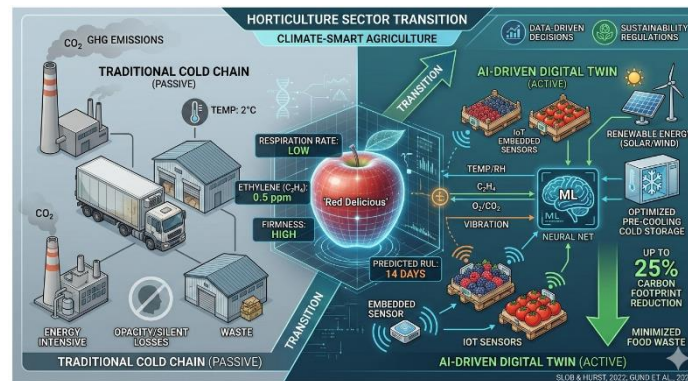


Fig.1 Climate smart agriculture

Digital Twins and Smart Technologies in Horticulture

A Digital Twin is not merely a simulation model but a dynamic, data-integrated virtual representation of a real-world system. It continuously receives information from IoT sensors embedded within the physical environment such as temperature probes, humidity sensors, soil moisture detectors, and CO₂ monitors. This bidirectional communication allows operators to test scenarios digitally before implementing changes in real systems. For example, a greenhouse manager can simulate adjustments in ventilation strategies to assess potential energy savings and crop growth outcomes without risking production losses. Such capabilities make digital twins powerful tools for operational optimization and sustainability improvement (Slob & Hurst, 2022). The integration of AI algorithms enhances the functionality of digital twins by enabling predictive analytics and machine learning based optimization. AI systems can analyze large volumes of historical and real-time environmental data to forecast crop growth patterns, disease outbreaks, and resource demands. According to Gund et al. (2025), the rapid expansion of digital twin research in agriculture reflects growing recognition of its potential to improve efficiency and environmental performance. In greenhouse horticulture specifically, advanced environmental control systems powered by digital twins have demonstrated the ability to reduce unnecessary heating and lighting while maintaining optimal crop conditions. These systems adapt dynamically to weather changes, plant developmental stages, and energy price fluctuations, resulting in measurable sustainability benefits (Van Mourik et al., 2022).

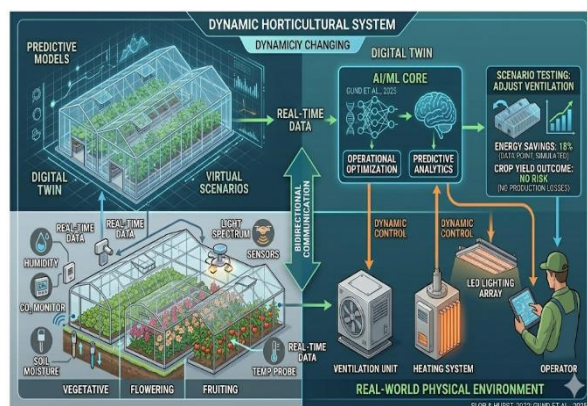


Fig.2 Dynamic horticulture system

Carbon Footprint Reduction Through Precision Climate Control

Greenhouses require continuous regulation of microclimatic conditions to ensure optimal crop growth. Traditionally, heating, cooling, and lighting systems operate based on fixed schedules or manual adjustments, often leading to overuse of energy. AI-driven digital twins change this paradigm by continuously analyzing environmental data and adjusting systems in real time. For instance, during periods of sufficient natural sunlight, artificial lighting can be reduced automatically. Similarly, predictive models can anticipate temperature drops and activate heating systems only when necessary, preventing energy oversupply. Studies indicate that such intelligent environmental control strategies significantly lower energy consumption while preserving crop yield and quality (Van Mourik et al., 2022; Slob & Hurst, 2022). By optimizing climate control operations, digital twins directly reduce electricity consumption and associated carbon emissions.

Optimized Irrigation and Nutrient Management

Water and fertilizer management represent major sources of emissions in horticulture. Excessive irrigation not only wastes water but also increases energy use for pumping and distribution. Over-application of nitrogen fertilizers contributes to nitrous oxide emissions, a potent greenhouse gas. Digital twins equipped with AI-based predictive models can assess plant water stress levels and nutrient uptake requirements in real time. By analyzing soil moisture data, evapotranspiration rates, and crop growth stages, these systems determine precise irrigation schedules tailored to plant needs. Elhariri et al. (2025) demonstrated that smart greenhouse systems integrating digital twins can significantly reduce water use without compromising productivity. Similarly, nutrient delivery systems integrated with digital twins can optimize fertigation practices by adjusting nutrient concentrations based on plant growth predictions. This precision reduces

fertilizer waste and lowers emissions associated with fertilizer production and soil nitrogen transformation processes (Gund et al., 2025). As a result, both direct and indirect carbon emissions are minimized.

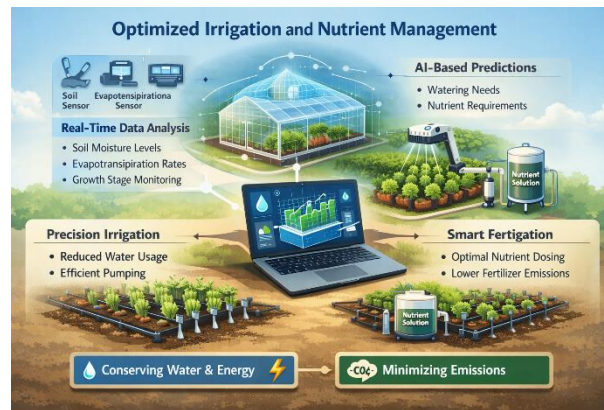


Fig.2 optimized irrigation and nutrient

Post-Harvest and Supply Chain Optimization

While production efficiency is crucial, a significant portion of horticultural emissions occurs during post-harvest storage and transportation. Cold chain systems are energy-intensive, and inefficiencies often lead to spoilage, requiring replacement production that further increases emissions. Digital twins can model entire supply chains, from packing facilities to distribution centers and retail outlets. By simulating various transport routes, storage temperatures, and delivery schedules, stakeholders can identify configurations that minimize energy use and reduce spoilage risks. Verdouw et al. (2022) highlight that digital twin enabled supply chain optimization improves logistics efficiency and reduces lifecycle emissions. Additionally, predictive analytics can forecast product shelf life based on real-time environmental exposure data. This capability allows distributors to prioritize shipments and reduce food waste, indirectly lowering the carbon footprint associated with lost produce.

Predictive Maintenance and Equipment Efficiency

Horticultural operations depend heavily on equipment such as HVAC systems, irrigation pumps, and automated conveyors. Equipment inefficiencies or unexpected breakdowns can increase energy consumption and disrupt production processes. AI-integrated digital twins monitor equipment performance continuously, analyzing parameters such as energy draw, vibration patterns, and operating temperatures. Predictive maintenance models detect anomalies and anticipate potential failures before they occur. This proactive approach prevents energy waste,

extends equipment lifespan, and reduces the need for carbon-intensive manufacturing of replacement components (Gund et al., 2025). Over time, these operational efficiencies contribute significantly to overall carbon footprint reduction.

Lifecycle Carbon Considerations

Despite their environmental benefits, digital technologies themselves carry embodied carbon costs. The manufacturing of sensors, servers, and computing infrastructure, along with data center energy consumption, contributes to emissions. Therefore, evaluating the net sustainability impact of digital twin deployment requires comprehensive lifecycle assessment. Li et al. (2024) emphasize that while digital agriculture infrastructure has an initial carbon footprint, long-term operational efficiencies generally offset these emissions, especially in large-scale horticultural systems. The key lies in ensuring that digital systems are powered by renewable energy sources and optimized for energy-efficient data processing.

Challenges and Future Perspectives

The widespread adoption of digital twin technology in horticulture faces several challenges. High initial investment costs can limit accessibility for small-scale growers. Furthermore, integrating heterogeneous data sources into unified platforms requires standardized protocols and robust cybersecurity frameworks. Limited technical expertise in rural regions may also slow implementation. However, future developments are promising. Integration with renewable energy systems such as solar-powered greenhouses can further reduce carbon intensity. Blockchain technologies may enhance supply chain transparency and carbon traceability, strengthening sustainability verification mechanisms (Tiwari, 2025). As research and technological maturity advance, digital twin ecosystems are expected to become central components of climate-resilient horticultural systems.

Conclusion

Moving beyond traditional cold chain optimization, AI-driven digital twins and smart technologies provide a comprehensive strategy for minimizing horticultural carbon footprints. Through precision climate control, optimized irrigation and nutrient management, supply chain simulation, and predictive maintenance, these systems enhance operational efficiency while reducing emissions across the value chain.

Although digital infrastructure entails embodied emissions, lifecycle assessments indicate that long-term sustainability gains outweigh initial environmental costs. With continued innovation

and supportive policies, digital twin-enabled horticulture can play a pivotal role in advancing low-carbon, climate-resilient agricultural production.

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