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Towards Circular Controlled Environment Agriculture: A Living Lab Framework for Integrating Water, Energy and Nutrient Management

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Abstract

The transition towards Circular Controlled Environment Agriculture (CEA) has emerged as a strategic priority for enhancing resource efficiency, climate resilience, and food security. While considerable advances have been achieved in individual technological domains—including water reuse, nutrient recovery, renewable energy integration, precision irrigation, artificial intelligence (AI), and digital farming—these innovations are typically developed and evaluated independently. Consequently, the lack of integrated validation under commercial production conditions remains a major barrier to their large-scale adoption. This paper proposes a Living Lab framework for accelerating the transition towards circular CEA by integrating water, energy, nutrient, and digital management within a single collaborative innovation ecosystem. The proposed framework combines closed-loop water and nutrient management, renewable energy utilization, advanced sensing technologies, Internet of Things (IoT) networks, AI-based decision support, and Digital Twin modelling under real greenhouse operating conditions. Equally important, the framework incorporates growers, researchers, technology providers, SMEs, public authorities, and other stakeholders throughout the co-design, implementation, validation, and assessment process, ensuring that technological innovation is aligned with practical needs and market adoption. This approach is consistent with the multi-actor Living Lab philosophy adopted within the Horizon Europe THRIVE-CEA project, where five regional Living Labs are being established to validate integrated CEA solutions under diverse climatic and production conditions. Greece hosts one of these Living Labs, focusing on Mediterranean greenhouse systems and circular production practices. Beyond technology demonstration, the proposed framework establishes a methodology for evaluating circular greenhouse systems using integrated environmental, agronomic, technical, and socio-economic indicators. By simultaneously addressing water and nutrient recirculation, renewable energy use, digital decision support, and stakeholder engagement, the Living Lab creates the conditions required for the practical implementation of circular greenhouse production. The framework presented here provides a scalable pathway for supporting the transition towards resilient, resource-efficient, and digitally enabled CEA systems across Mediterranean regions and beyond.

Keywords: Circular economy, Controlled Environment Agriculture, Living Labs, Water reuse, Nutrient management, Digital Twin, Artificial Intelligence, Hydroponics

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