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Article

Study of the Possibility of a Conceptual Framework for Digital Twin and Cyber-Physical Systems to Enhance Sustainable Agricultural Management

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Abstract

Modern agriculture demands innovative, scalable solutions for sustainability and resource optimization under changing climate conditions. This conceptual framework leverages Digital Twin and Cyber-Physical Systems (CPS) to enable integrated management across diverse crops. Combining real-time sensor data with manual inputs, it supports traceability, reduces chemical use, and enhances decision-making, providing a flexible foundation for future research and practical implementation of smart farming practices.

Keywords: digital twin; smart agriculture; sustainable farming; precision agriculture; cyber-physical systems

1. Introduction

Agriculture faces growing challenges as it transitions toward more sustainable, efficient, and resilient practices. Climate change, resource scarcity, and the need to reduce the environmental footprint of farming are driving demand for innovative solutions that improve management decisions [1]. Chemical inputs such as fertilisers and pesticides are under increasing regulatory and social scrutiny, with strategies like the European Union's Farm to Fork aiming to reduce their use significantly while maintaining productivity and quality [2]. Policymakers also play a crucial role in supporting the adoption of these solutions, and our proposed framework can offer them a roadmap for developing sustainable agricultural policies.

One promising approach to meet these challenges is the integration of advanced digital technologies, including Internet of Things (IoT) sensors, Artificial Intelligence (AI), and Cyber-Physical Systems (CPS). These technologies enable real-time monitoring of environmental and crop conditions, predictive modelling of needs such as irrigation and fertilisation, and more precise interventions. Among them, the Digital Twin concept—creating a virtual representation of a real-world system that evolves with data inputs—provides a compelling framework for managing agriculture in a holistic and data-driven way [3].

While Digital Twin technologies are well-established in industry and manufacturing, their application in agriculture remains at an early stage. Current implementations often focus on narrow functions or single crops without offering a flexible, scalable model that can adapt to different farming systems and contexts [4]. This paper proposes a conceptual framework to address this gap, envisioning a Digital Twin and CPS-based approach for supporting sustainable, traceable, and optimised management across diverse agricultural operations. For example, the framework can be adapted to large-scale commercial farms, small family-owned farms, or even urban vertical farms. By combining real-time sensor data with manually introduced observations and laboratory analyses, the proposed framework aims to help farmers make informed, data-driven decisions that reduce chemical inputs, improve resource efficiency, and enhance overall sustainability.

2. Literature Review

The integration of digital technologies in agriculture has received growing attention in recent years, with research highlighting the benefits of using Internet of Things (IoT) sensors, Artificial Intelligence (AI), and Cyber-Physical Systems (CPS) to improve farming efficiency and sustainability [6]. Digital Twin approaches, which create virtual representations of physical systems updated in real time with sensor data, have shown success in industry and infrastructure management but remain less explored in agriculture.

Recent studies have demonstrated the use of IoT-based monitoring for optimising irrigation scheduling, detecting plant diseases, and improving soil health assessment. Machine learning models have been applied to predict crop yields, estimate nutrient requirements, and reduce chemical inputs. CPS frameworks have enabled the integration of diverse data sources and automated decision support systems, allowing farmers to respond more precisely to changing field conditions.

Previous work has also explored practical approaches for improving traceability in orchard production, implementing QR code systems, RGB image recognition for fruit sorting, and AI-powered dashboards to support decision making in precision farming [7,8]. Other studies have examined strategies for reducing chemical inputs by leveraging real-time soil analyses and predictive modelling to optimise the timing and quantity of interventions. These efforts underline the growing need for integrated, data-driven management systems that can support sustainable agricultural practices.

Despite these advances, existing solutions often remain tailored to specific crops, regions, or technologies, limiting their general applicability. There is a clear need for a flexible, scalable framework that can be adapted to various farming contexts and technological levels. The conceptual framework proposed in this paper seeks to address this gap by outlining a Digital Twin and CPS-based approach designed to support diverse agricultural systems in making more sustainable, efficient, and traceable management decisions [9].

The aim of this work is to outline a conceptual framework for applying Digital Twin and CPS technologies in agriculture. By integrating sensor-based monitoring and user-entered data, this approach seeks to model field conditions, predict management needs, and support informed, sustainable decision-making. It is designed to be adaptable across different crops, production scales, and farming systems (Figure 1).

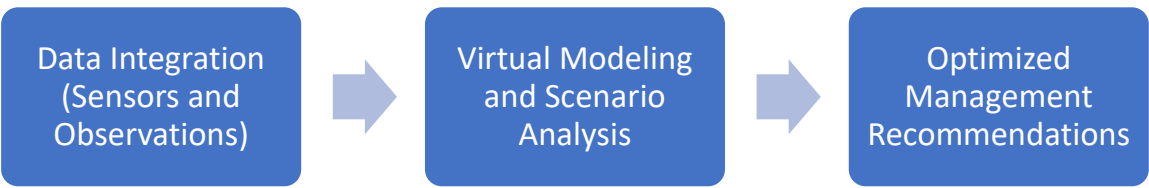


Figure 1. Simplified representation of the Digital Twin and CPS framework for smart agriculture.

3. Materials and Methodology

This conceptual study does not report experimental results, but instead outlines a flexible approach for applying Digital Twin and Cyber-Physical Systems (CPS) in agriculture. The framework is designed to be adaptable across diverse crops, production systems, and technological levels.

3.1. Materials

The proposed system empowers users by integrating diverse data sources into a unified management platform. This platform is designed to support informed agricultural decision-making, putting the control in the hands of the users. It incorporates a sensor network for real-time monitoring of key environmental parameters such as soil moisture, temperature, electrical conductivity, and pH.

This automated data collection is complemented by manual data entry, which includes laboratory analyses, expert assessments, and field observations provided by the operator to enrich and validate the system's dataset.

A data management and processing unit serves as the core of the system, offering centralised storage, secure handling, and advanced processing capabilities for all collected information. This component may utilise cloud-based infrastructure to ensure scalability and accessibility. Notably, the system features an interactive user interface, envisioned as a user-friendly dashboard that allows farmers and agronomists to visualise data trends over time, receive tailored management recommendations, and maintain comprehensive records of historical interventions.

3.2. Methodology

The proposed methodology adopts an integrated, modular approach to enable the effective application of Digital Twin and Cyber-Physical Systems (CPS) in agriculture. It is conceptually organized into five interrelated stages that together facilitate the systematic collection, integration, analysis, modeling, and utilization of diverse data sources to support informed, sustainable management decisions.

The process begins with **data acquisition**, which relies on IoT sensors strategically deployed in the field to continuously monitor key environmental parameters such as soil moisture, temperature, electrical conductivity, and pH. This automated data collection is complemented by **manual data entry**, incorporating laboratory analyses, expert assessments, and field observations to systematically enrich and validate the dataset, ensuring its completeness and accuracy.

During the **integration and centralization** stage, all collected data—both automated and manual—are consolidated into a unified, secure database. This ensures consistency, traceability, and interoperability with existing digital tools, while enabling long-term storage and standardized access for subsequent analyses.

The **data analysis and model calibration** stage involves processing this comprehensive dataset to identify patterns, trends, and relationships among variables. Advanced statistical methods and machine learning techniques are employed to develop and iteratively calibrate predictive models, ensuring they remain reliable across varying environmental conditions and production systems [10].

Building on this foundation, the **predictive modeling** stage applies techniques such as multivariate regression and neural networks to estimate critical management needs, including irrigation scheduling and fertilization requirements. These models are designed to continuously learn and adapt over time, capturing complex interactions among environmental variables and management practices to optimize resource use [11].

Finally, the **decision-support** stage provides actionable recommendations to farmers and agronomists through an interactive user interface. This interface is designed to facilitate user engagement and support informed decision-making aimed at reducing chemical inputs, improving resource efficiency, and enhancing overall sustainability, while maintaining comprehensive traceability of all interventions over time.

By structuring the methodology into these five stages, the framework offers a flexible and scalable approach that can be adapted to various crops, farm sizes, and technological contexts, supporting the broader goals of sustainable and data-driven agricultural management (Figure 2).

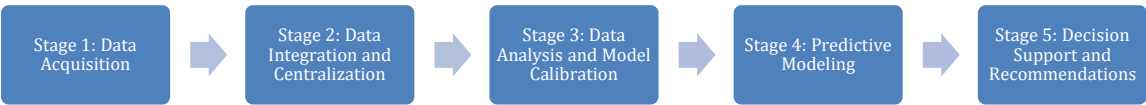


Figure 1 Conceptual workflow illustrating the five stages of the proposed Digital Twin and CPS framework for sustainable agricultural management

4. Results (Conceptual)

As this work presents a conceptual framework rather than empirical data, this section emphasises the potential impact and anticipated benefits of the proposed Digital Twin and Cyber-Physical Systems (CPS) approach in agricultural management. The framework is designed to enable more precise, efficient, and sustainable farming practices through integrated, data-driven decision-making.

Anticipated outcomes include improved irrigation and fertilisation scheduling, resulting in reduced chemical inputs and enhanced resource-use efficiency. The system's predictive modelling capabilities are expected to help farmers optimise interventions by accounting for dynamic environmental conditions and crop-specific requirements. By integrating real-time sensor data with manual observations and laboratory analyses, the framework also aims to strengthen the traceability of agricultural practices, supporting compliance with sustainability standards and evolving market demands.

The adaptable and scalable design of the framework facilitates its application across diverse crops, production systems, and technological contexts—from smallholder farms to large commercial operations. It also provides a foundation for developing interactive dashboards and decision-support tools that deliver clear, actionable recommendations. Over time, this approach has the potential to reduce environmental impacts, improve productivity, and contribute meaningfully to the broader goals of sustainable agriculture and food security.

While these results remain conceptual, they highlight the importance of continued research and development efforts to validate and implement such systems in real-world agricultural settings, ensuring that the potential benefits of the proposed framework can be fully realised.

5. Conclusions

This conceptual work introduces a flexible and scalable framework for applying Digital Twin and Cyber-Physical Systems (CPS) technologies to support sustainable agricultural management. By integrating real-time sensor data with manually entered observations and laboratory analyses, the approach aims to create a dynamic virtual representation of field conditions, enabling predictive modelling and data-driven decision-making.

The framework is structured in five interrelated stages: data acquisition, integration, analysis, predictive modelling, and decision support. This design emphasises adaptability across diverse crops, production systems, and technological contexts, ranging from smallholder farms to large commercial operations. Anticipated benefits include improved irrigation and fertilisation scheduling, reduced chemical inputs, enhanced traceability, and overall improved resource-use efficiency.

While this work remains conceptual and does not provide empirical validation, it offers a solid foundation for future applied research and development. Further studies will be necessary to implement, test, and refine such systems in real-world agricultural settings, ensuring that the potential benefits outlined here can be effectively realised. Ultimately, this framework seeks to contribute to the broader goals of sustainable, data-driven agriculture by enabling more precise, efficient, and environmentally responsible management practices.

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