Special Issue: AI, The Agricultural Intelligence

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This special issue of *The International Journal of Intelligent Control and Systems* (*IJICS*) is dedicated to Agricultural Intelligence. In past years, smart agriculture has advanced rapidly from pilot demonstration to large-scale commercialization, driven by artificial intelligence (AI) integration, Internet of Things (IoT) densification, policy support, and cost reduction. Key progress spans five core dimensions: perception and connectivity, AI and digital twins (DTs), robotics and automation, system integration and policy, and sustainability and global outreach. The social dimension of smart agriculture has evolved in tandem with technological advancement, shifting from a technology-centric auxiliary role to a people-centric core focus over the past decade.

Among the core dimension of smart agriculture, agricultural digital twins are transitioning from research to field applications, delivering improvements in resource efficiency and yield gains. DT constructs a virtual, dynamic replica of real-world crops, fields, or agricultural systems that integrates plant models, real-time phenotyping data, IoT sensor data, and environmental data to create a virtual mirror that can simulate, predict, and optimize crop growth, turning the predictive insights from plant modelling into actionable decisions for farmers.

In this special issue of *IJICS*, we aim to highlight the advances of techniques in smart agriculture, with specific attention to DT and social dimension in smart agriculture. The accepted contributions are categorized into the following four groups.

(1) Perception of crop: Phenotyping in agriculture. Phenotyping is the systematic measurement, analysis, and quantification of the observable physical, physiological, biochemical, and structural traits of plants, including growth, development, morphology, yield, stress responses, and resource-use efficiency, as the joint outcome of genetic makeup (genotype) and environmental conditions. AI plays a transformative role in modern high-throughput phenotyping by automatically turning raw sensor data (images, spectra, and point clouds) into quantitative, biologically meaningful plant traits, in a scalable way. Phenotyping techniques provide objective, high-throughput, non-destructive, and quantitative measurements of plant traits, making autonomous agricultural systems possible.

Multispectral cameras are commonly used in phenotypic monitoring. Using unmanned aerial vehicles (UAVs) equipped with red-green-blue (RGB), multispectral, and thermal infrared sensors to capture multi-period images of high-latitude-adapted sugar beet varieties, prediction models for sugar beet sugar content, root fresh weight, and yield are built [1]. Perceived information also includes disease. A real-time intelligent pine wilt disease monitoring framework is proposed, integrating a fixed high-altitude sensing platform with YOLOv5-based deep learning, to achieve accurate, large-area, and continuous pine wilt disease-infected pine tree identification with low costs [2]. Real time monitoring applies to agricultural machinery autonomous driving: a multi-view camera fusion-based 3D object detection method is developed for unstructured/semi-structured tractor road scenes [3]. Low-cost, image-based plant phenotyping techniques for individual plants are reviewed for practical usage [4].

(2) Plant modelling and digital twins. While phenotyping and sensing technologies have been developed in this century, plant modelling, the basis of DT, is a multidisciplinary field that began in the 1960s and has progressed from simple empirical descriptions to complex mechanistic simulations. Data-driven models rely on large volume and type of data (phenotypic, environmental, and genomic) to learn growth patterns, without prior assumptions about mechanisms. Process-based (mechanistic) models simulate underlying physiological, biochemical, and ecological processes (e.g., photosynthesis, respiration, and transpiration) based on biological principles. Hybrid models combine mechanistic models and data-driven models, balancing interpretability and flexibility.

The GreenLab model originates from research in the early 1970s by Philippe de Reffye, who developed the first 3D simulations of coffee tree architecture. His approach, integrating original botanical architecture, extends to numerous plants, leading to develop the boTany and Modeling of Plant Architecture and vegetation (AMAP) series model in the 1990s. These works evolved into the GreenLab modelling approach, combining structural and process-based

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modelling concepts within a mathematical framework. Software plays a key role in model applications, diffusion, and usage. XPlantGL, a software implementing the simulation and calibration of the GreenLab model, in a generic version for crops, is presented [5]. Linking models at different scales can potentially realize the prediction of molecular outcomes in grain yield formation. A review is made on the leaf and canopy level photosynthesis models, and the connection between both types of models is discussed [6]. How can a plant model evolve into a digital twin? Integrating functional-structural plant models (FSPMs) with artificial intelligence is regarded as the way to build crop digital twins. Using high-precision field data, organ-level growth simulation, and AI analysis is considered to be helpful to clarify stress resilience mechanisms, identify key traits, and optimize cultivation, supporting decision-making for African food security [7].

(3) Decision support for robotics and automation. In smart agriculture, decision support plays a pivotal role as the brain center: it translates multi-source data (phenotypic, environmental, model-simulated) into actionable, autonomous operations, bridging data perception, model prediction, and practical agricultural execution. It transforms passive data collection (phenotyping) and simulation (digital twins) into active, precise, and scalable operations—reducing labor costs, improving resource-use efficiency, and accelerating the translation of research (e.g., crop models and phenotyping techniques) into practical agricultural productivity.

Decision support for irrigation in arid region can be achieved by deploying a digital twin system integrating the decision support system for agrotechnology transfer (DSSAT) crop growth model with a deep reinforcement learning (DRL) soft actor-critic (SAC) agent enhanced by bidirectional long short-term memory (BiLSTM) and dual-attention mechanisms. The result shows that water use efficiency is improved by 39.0% compared to a traditional fixed-schedule and soil moisture threshold method [8]. For a greenhouse irrigation scenario, a hybrid model is developed, where an XGBoost model is used to correct the residual between observed transpiration rates and physical predictions, balancing physical consistency and nonlinear fitting ability. The results show that the model-based on-demand scenario saved ~30.0% irrigation water compared to over-irrigation while maintaining crop water supply, thus improving water and energy use efficiency [9].

(4) System integration: Centralized or decentralized policy? System integration serves as the technical backbone to unify fragmented resources into efficient operational systems. It focuses on connecting data, technologies, equipment, and services across the agricultural value chain, addressing the pain points of fragmented smart devices, isolated data, and disjointed processes. On the other hand, policy acts as the guiding framework to clarify development directions, resolve institutional barriers, and stimulate market vitality, providing a stable environment for technology promotion and industrial upgrading. Only through the synergy of the two can smart agriculture break through technical, cost, and institutional barriers, achieve large-scale promotion, and ultimately realize the transformation of agriculture towards precision, efficiency, and sustainability.

Here, it is argued that industrial agriculture's crises stem from a long historical trend of information disembedding: agricultural value has been progressively separated from its socio-ecological context [10]. Digital platforms offer a potential remedy by re-embedding markets into their biological, social, and environmental contexts through cybernetic intelligence, representing a fundamental re-orchestration of agricultural value, but demanding careful consideration of who controls agronomic truth. Risks include centralized decision-making in proprietary algorithms, shifting control from farmers/states to transnational corporations. Interestingly, this challenge is being addressed by a decentralized blockchain-enabled agricultural contract fulfillment mechanism that proposes to address pain points of traditional contract farming (severe trust deficits, high legal enforcement costs, and the credit blind spot of smallholder farmers) by integrating decentralized identity, verifiable credentials, and smart contracts [11]. The mechanism transforms implicit social trust into transparent, liquid on-chain credit, achieving reduced information asymmetry and transaction friction, as well as effective constraint of opportunistic behavior via reputation penalties.

In the end, we would like to extend our sincere gratitude to all the authors, reviewers, and editorial team members who have made this special issue possible. We do hope that this collection of articles will inspire further research and collaborations in Agricultural Intelligence, a transdisciplinary field aimed at improving agricultural practices. We believe this research effort will continue to mobilize generations of researchers, pushing forward the vital transition towards sustainable and resilient farming systems. Finally, we wish to dedicate this special issue to Philippe de Reffye, pioneer of 3D botanical faithful digital plants, father of GreenLab, who has worked for 50 years in plant modelling, and is still contributing at the age of 80.

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