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Digital Twins: A Futuristic Agricultural Momentum

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Over millions of years, agriculture has been proving as a major source of survival to all species on earth. A sustainable future depends on innovation, and cutting-edge technologies have the potential to have a beneficial global influence (A. Kolekar *et.al*., 2023). The sustainability of the growing population can reach its pace through some comprehensive approaches *viz*. precision farming, conservation agriculture, smart agriculture etc. From early agricultural tools to the newest of rotavators, science has been making tremendous acceleration in the field of agriculture. According to C. Stefano *et al*., 2023 the revolution of agriculture over years can be summed up as-

- Until 1920, agriculture was 1.0, involving physical labor and animal traction.
- Agriculture 2.0 (1920–1960) saw the development and spread of tractor advancements (diesel engine, three-point hitch, tires), as well as motorization, but the manual labor force remained significant.
- 3.0 Agriculture (1960–1980): fast replacement of manual labor, genetic advancements, mechanization, and improved tractors (greater power, operating machinery for all agricultural tasks).
- Agriculture 4.0 (precision agriculture) (1980–2000): introduction of on-board electronic control systems in tractors, enhanced machine operation, increased focus on the human-machine relationship (safety and ergonomics), and early attempts at computerized/digitized farm management (never fully and widely consolidated, except in specific sectors like zootechnics).
- After 2000, agriculture 5.0 (smart agriculture) included the following: the integration of automation and electronics (especially in mobile user-point processes), the spread of sensors for activity monitoring and tractor on-board location systems, and communication protocols between various tools, deep learning to boost agricultural output, and in-silico simulations for gene modelling and traceability.

The digital world stops at nothing to make progresses in this concern. Agriculture 4.0 counts digitalization such as use of robotic arms, Artificial Intelligence (AI), Internet of Things (IoT) on its finger tips while talking about digital algorithms (W. Purcell and T. Neubauer, 2023). It has also been noted that the development of agricultural knowledge and innovation systems (AKIS) is being propelled by digitalization (Klerkx *et.al*., 2019). These virtual hopes form the building blocks of sustainability.

Artificial Intelligence is currently a key force in the evolution of modern agriculture with researchers striving to upgrade all phases of agricultural production system by its use (J. Nie *et al*., 2022). Conversely, farmers stubble upon disagreement involving its cost relations and high data entries. In addition, they tend to frequently overlook thorough understanding of agricultural production and a detailed analysis of error patterns missing the links between theoretical and practical application. In order to combat this, "digital twins" can be a new introduction in smart agriculture (C. Verdouw *et.al*., 2021) which is thought to be a fundamental component of the metaverse (H. Hassani *et.al*., 2022).

Background

It was during the NASA Apollo missions over 50 years ago that DTs were first observed. The company constructed two identical spacecraft, one which would send the crew into space and the other would safely rest on Earth simulating the space-bound twin unit (G. Dyck *et.al*., 2023). Later, the “mirror space model”, a prototype first put forth by Michael Grieves in 2003, laid the groundwork for digital twins (M. Attaran and B. G. Celik, 2023; C. Pylianidis *et.al*.,2021; E. Symeonaki *et.al*., 2024; G. Goldenits *et.al*., 2024). Presently, it is utilized in sectors of manufacturing, agricultural, healthcare, smart cities. Additionally, researchers are constantly developing its’ concept by making it more accurate, scalable and usable in a variety of complexes.

Definition

Digital twins have been defined in a variety of ways by different scholars. For example, a link between the digital and physical worlds; a sophisticated tool for immersive data analysis; or virtual or simulated models that accurately represent tangible assets (J. Nie *et al*., 2022).

Digital twins seem to be a constantly evolving concept and definition, but the simplest way to describe them is as dynamic virtual objects that are copies of physical objects, systems, or processes that allow for real-time monitoring, analysis, and simulation of their real-world counterparts by combining data from sensors or machines (C. Pylianidis *et.al*.,2021). Anything that looks, connects and behaves like something in the real world can be replicated quite realistically using digital twins (A. Kolekar *et.al*., 2023).

Role of digital twin with respect to agriculture

The development of agricultural digital twin systems enables the seamless integration of digital cyberspace with physical agricultural activities such as yield forecasting, monitoring, intercultural operation, seed bed preparation, and tillage techniques, enabling a single framework for "connection-perception-decision-control" configuration (J. Nie *et al*., 2022). Their fundamental roles include the concepts of:

- Real-time monitoring: The provision of real-time data from physical equivalents to facilitate ongoing observation and improved decision-making (C. Verdouw *et.al*., 2021).
- Simulation and Forecasting: DT mirrors real-world conditions to allow simulation that can predict how a certain system will perform, behave and its potential failures if any (A. Nasirahmadi and O. Hensel, 2022).
- Autonomous: DT function on its own, requiring no human interventions. It possesses complete control over the corresponding real-life counterpart (C. Verdouw *et.al*., 2021).
- Optimization and product development: They refine processes by assessing and evaluating processes, thus, streamlining suggestions for enhancements including efficiency and minimizing waste.
- Sustainability: DT can model energy usage, emissions and other elements aiding in the advancement of more sustainable and eco-friendly practices (H. Hassani *et.al*., 2022).

Applications

Different industries, sectors, and domains can use DT in very different ways. In agriculture, farmers can use virtual environments to test and improve their agricultural methods, giving them the chance to improve their methods before putting them into practice. The application of DT with particular relevance to agricultural activities is described in the following points:

- Crop cultivation practices- Land preparation, seed selection, sowing methods, fertilizer and water management, intercultural operations, and harvesting procedures are all included in this practice package. DT uses IoT sensors and satellite data to continuously monitor the health of the soil and crops. By providing comprehensive information on soil pH, nutritional levels, and other hazards like as disease and pest infestations, they allow for prompt crop protection measures. It can reduce stress caused by either too much or too little watering by optimizing irrigation schedules by modelling water needs. Furthermore, fertilizer and pesticide requirements can be appropriately included. It enables farmers to precisely forecast yields and harvest dates. This aids in managing supply chain requirements and scheduling manufacturing cycles (A. Nasirahmadi and O. Hensel, 2022).

- Controlled environment- Controlling plant development and the environment with the aim of increasing production efficiency, maximizing plant yields, and improving product quality is known as controlled environment agriculture, or CEA (Chaux *et.al*., 2021). The energy required to regulate the inside temperature of high-tech greenhouses is substantial. Many different pieces of technology, such as heat exchangers, aquifers, and windows for natural ventilation, are employed to save energy. Energy analysis is carried out by DTs, who can also help with decision-making (N. Slob and W. Hurst,2022). The objective is to maintain a climate that guarantees steady crop yields or even raises them in addition to reducing energy use (G. Goldenits *et.al*., 2024).
- Livestock farming-. Animal behavior, including social relationships, food habits, and movement patterns, can be analyzed using sensor data to identify stress, disease, or damage and to enable timely intervention (A. Kolekar *et.al*., 2023). The general health of livestock populations can be improved by predicting outbreaks, optimizing biosecurity measures, and reducing disease transmission through the simulation of disease spread and analysis of real-time health data (E. Symeonaki *et.al*., 2024). The control of temperature, humidity, and ventilation in barn or pasture settings enhances animal wellbeing and lowers the risk of respiratory problems, heat stress, and other problems. Each animal is given the proper amount of nourishment without being overfed or underfed thanks to DT (W. Purcell and T. Neubauer, 2023). Farmers may effectively manage trash, reducing pollution and optimizing the usage of fertilizer or biogas as byproducts. Also, DT can help them to select animals for reproduction that have the best genetic qualities.
- Post Harvest practices: After agricultural products are harvested, they go through a post-harvest process that may involve transporting, drying, cooling, storing, and marketing. Loss reduction, enhanced monitoring, and optimization of food processing, storage conditions, marketing, and transportation are all potential benefits of digital farming techniques for post-harvest operations (A. Nasirahmadi and O. Hensel, 2022).
- Aquaponics- The grow bed, where crops are planted, is connected to a water tank that holds fish via a network of pipes and pumps. A filtration system that removes solid waste moves water between these two primary locations. The system uses live bacteria that "nitrify" (turn ammonia into nitrates) to extract it for plant food from other fish waste products like ammonia that are dissolved in the water (Ghandar *et al*., 2021).
- Water management-A digital model of river basins interspersed with weather prediction models may enable risk-free in silico testing (computer-based simulation) of water distribution patterns. Long-term system optimization through enhanced efficiency is made possible by the employment of digital twins, which not only aid in problem anticipation but also foster agility in reaction (Taneja *et. al*.,2022).
- Sustainable agriculture- Through increasing climate resilience, decreasing environmental impact, improving resource efficiency, and assisting farmers in implementing eco-friendly practices, DT promotes sustainable farming (C. Stefano *et al*., 2023). It informs farmers about crop rotation, cover cropping and tilling practices. By analyzing soil moisture levels, weather patterns, humidity, relative CO_2 concentration, and other crop needs, DT provides effective irrigation methods in areas experiencing water constraint (Peladarinos *et.al*., 2023). Pollination, insect control, and soil regeneration are examples of ecosystem services that improve the impact of farming techniques on local biodiversity. DT lessens the environmental impact of farm operations by monitoring their full lifetime, including greenhouse gas emissions, water use, and chemical use. This can assist farmers in implementing environmentally beneficial techniques like precision farming, which reduces soil erosion and hazardous runoff.
- Supply Chain Optimization- As was the case during the global COVID-19 crisis, when businesses speculated on the supply side, lowering it to enhance margins owing to client

demand, people who are impacted by possible shortages of supplies are at serious danger (S. Gallego-García *et.al*., 2023). Risk and resilience, supplier cooperation, end-to-end visibility, transportation and logistics efficiency, cost reduction, and more are all provided by DT (Angin *et.al*., 2020). It guarantees that farmers' operations are tracked in real-time for improved transparency and coordination, including inventory levels, appropriate production status, and transportation. This enables companies to simulate different risk scenarios, such supplier delays, equipment breakdowns, or natural disasters, and identify possible disruptions in the supply chain and develop contingencies if necessary.

AgriLora

Utilizing a wireless sensor network and cloud servers, AgriLora is a low-cost digital twin framework for smart agriculture that assists farmers in identifying plant illnesses, weed clusters, and nutrient deficiencies. Its aim is to attain a low-overhead WSN communication model that does not require long-range cellular access in the field. Also, development of a field-based WSN node placement and activation approach that is flexible enough to operate in a variety of situations and ensures a long battery life for the sensor nodes (P. Angin *et.al*., 2020).

Challenges

The extremely dynamic character of ecosystems creates special difficulties for DTs to accurately reproduce dynamic behavior, going beyond what is needed in many other industries (Tagarakis *et.al*., 2024). For the connection to provide the data that the service requires, there must be sufficient bandwidth (Melesse *et.al*., 2023). Absence of a dependable internet connection is another issue in rural and village regions. Risks related to DT-based systems' socio-ethics, like privacy issues and expensive expenses, may exacerbate socioeconomic divides (A. Kolekar *et.al*., 2023). In terms of water management, a one-size-fits-all approach might not work because water basin distribution and applications differ greatly (Taneja *et.al*., 2022).

Conclusion

Following the COVID-19 pandemic, people's life, education, access to food, and economic well-being have all suffered significantly. Despite the fact that agriculture is the foundation of almost everything, the reality that it is contributing to greenhouse gas emissions, water pollution, and biodiversity loss suggests that most major agricultural systems are moving in an unsustainable area. Energy consumption and pollution rises in tandem with the population. Innovation in agricultural production systems should focus on raising output while using less resources in order to guarantee food security. Digital twins and controlled environment agriculture might be key instruments for achieving productivity optimization and enhancing global food security. Growing automation demands across a range of sectors are the variables that are expected to contribute to the strong demand for the Digital Twin platform throughout the projection period.

Although digital twins have drawn a lot of public attention, their scalability remains uncertain since the implementation of digital twin technology would demand more mathematical resources for more complex physical things. until the agricultural community can completely profit from DT, there is still a long way to go. Agricultural researchers and interested parties should try to keep abreast of technology developments and look for connections between issues facing agriculture and issues resolved by DT in other fields. Farmers are better able to understand feeding habits, stressors, and ideal breeding practices by combining cutting-edge technologies and data-driven decision-making, which guarantees both production and the welfare of the cattle while advocating for environmentally friendly agricultural methods. Digital twin ideas, the next wave of digitization in agriculture, might make use of a variety of digital farming paradigms found in the literature. To create a system that benefits all people today and in future, it is necessary to bring people together.

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