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Digital Twins in Agriculture: The Future of Farm Decision-Making

Samala Akhila[1], Saurabh Kumar Sinha[2], Rahul Machindra Somvanshi[3], Akanksha Sikarwar[4], Shiv Lal Kumawat[5]

[1]Ph.D Scholar, Department of Agricultural Extension Education, Professor Jayashankar Telangana Agricultural University.
[2]Guest Teacher, Department of Agricultural Extension, College of Horticulture and Research Station, Ramanuj Ganj, MGUVV Durg (C.G.).
[3]Ph.D Scholar, Department of Agricultural Extension Education, Dr. Panjab Rao Deshmukh Krishi Vidyapeeth Akola.
[4]Senior Research Fellow, Department of Soil Science, ICAR-IISS, Bhopal (Madhya Pradesh).
[5]Ph.D Scholar, Division of Agricultural Economics, ICAR-Indian Agriculture Research Institute PUSA, New Delhi.

*Corresponding Author
Samala Akhila*

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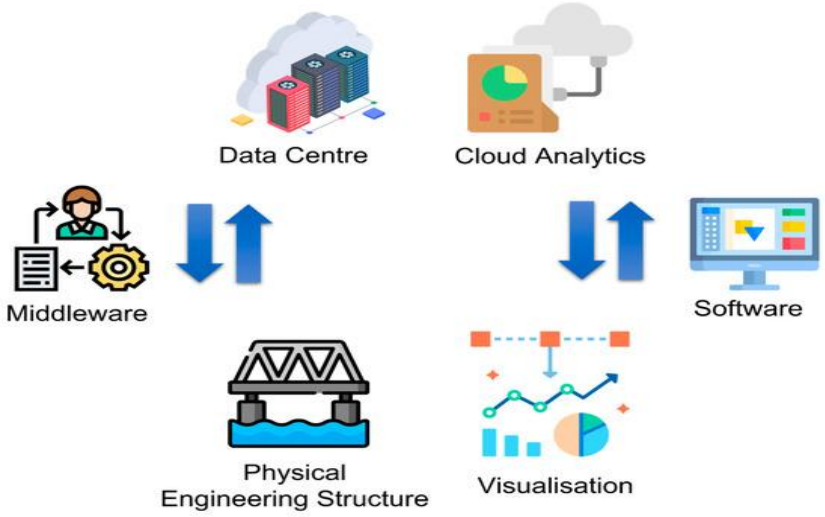
INTRODUCTION

Agriculture is experiencing a significant digital transformation powered by advancements in artificial intelligence (AI), the Internet of Things (IoT), remote sensing, drones, robotics, cloud computing, and big data analytics. New era of farming new era of farming Traditional field observations is no longer enough in modern farming, as farmers are becoming empowered by digital technology making decisions with it on a timely and informed manner. Among these emerging technologies, Digital Twin attracted attention globally as one of the most effective tools for precision / smart agriculture. A Digital Twin is a digital representation of a physical asset, process or system that is continuously updated with data from sensors and other digital sources. It is used in agriculture to build a digital real-time model of a farm, field, greenhouse, livestock, or irrigation system to enable farmers to observe conditions as they change, predict future scenarios, and test various management approaches before they apply them. Digit Twins are expected to be a critical piece of the puzzle for improving profitability, productivity and sustainability on the farm through risk reduction and better decisions, both for crops and livestock, now and moving into the future.

What is a Digital Twin

A Digital Twin is the dynamic virtual representation of a physical agricultural system with continuous updates through real-time data acquisition enabled by sensors, weather stations, satellites, drones, farm machinery, and farm management software. Digital Twins, unlike traditional computer models, are continuously updated to reflect changing field conditions, offering a real-time snapshot of crop growth, soil conditions, weather, and resource use.

The technology creates a two-way link between the physical farm and its virtual image. As new data are gathered, the virtual model is automatically updated, allowing farmers to run simulations on various management strategies, determine how crops would respond, spot trouble areas, and fine-tune farm operations prior to doing them.



How Does a Digital Twin Work

The functioning of a Digital Twin involves four major steps:

1. Data Collection

- Soil moisture sensors
- Temperature and humidity sensors
- Weather stations
- Drones and satellite imagery
- Farm machinery sensors
- IoT devices

2. Data Integration

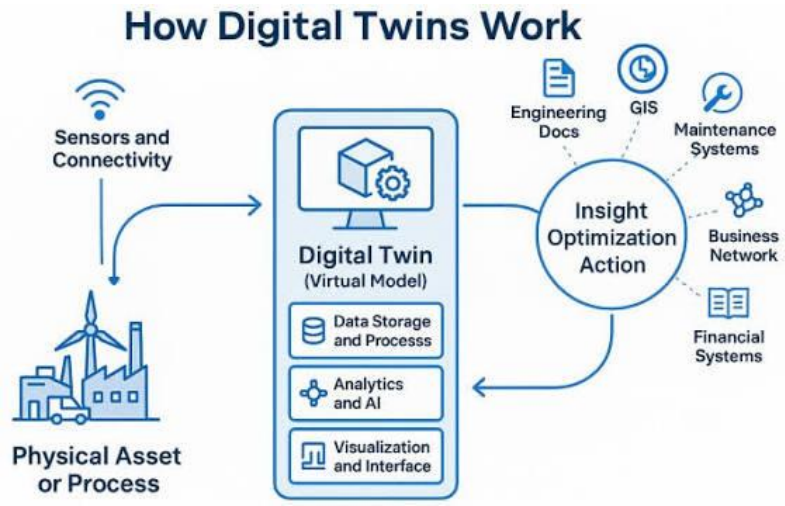
Information gathered by sensors, drones, weather stations, satellites, and farm equipment is sent via wireless communication networks to cloud platforms. The data is structured, stored and processed in real-time, creating a centralized data repository that allows for continuous farm monitoring and enables informed decision making.

3. Digital Simulation

Through AI, ML, and crop growth modeling, an integrated dataset is processed into a dynamic virtual representation of the farm. This DT is continuously self-updated and simulates crop growth, environmental conditions and management scenarios to foresee results prior to field application.

4. Decision Support

The Digital Twin processes live and historical information to deliver actionable advice on irrigation scheduling, fertilizer application, pest and disease management, harvest planning, and optimal resource use. These insights enable farmers to increase production, reduce costs, and become more sustainable.



Applications of Digital Twins in Agriculture

1. Precision Crop Management

Digital Twins make it possible to track the growth of crops in real-time by combining data related to weather, nutrients in the soil, moisture, and the health of the plants. Farmers are able to spot nutrient shortages, stress in crops, and apply those inputs in a targeted way, improving productivity, and reducing cost of production.

2. Smart Irrigation Management

Among the most difficult challenges in agriculture is water availability. Digital Twins model soil moisture evolution, crop water needs, and weather forecasts to predict the best irrigation date. Since this increases the efficiency of water use and avoids over-irrigation and water stress.

3. Nutrient Management

Through the study of the soil nutrient status, crop development stages, and nutrient requirements of the crop, Digital Twins support farmers in making nutrient application at the right time, at the right rate and at the right place. This improves nutrient use efficiency, reduces fate of the fertilizers and environmental pollution.

4. Pest and Disease Prediction

Digital Twins integrate environmental data, information on crop growth and historical records of diseases to estimate the probability of pest outbreaks and disease development ahead of the manifestation of visible symptoms. Early warning systems allow for interventions in due time and avoidance of pesticide applications when not necessary.

5. Greenhouse Automation

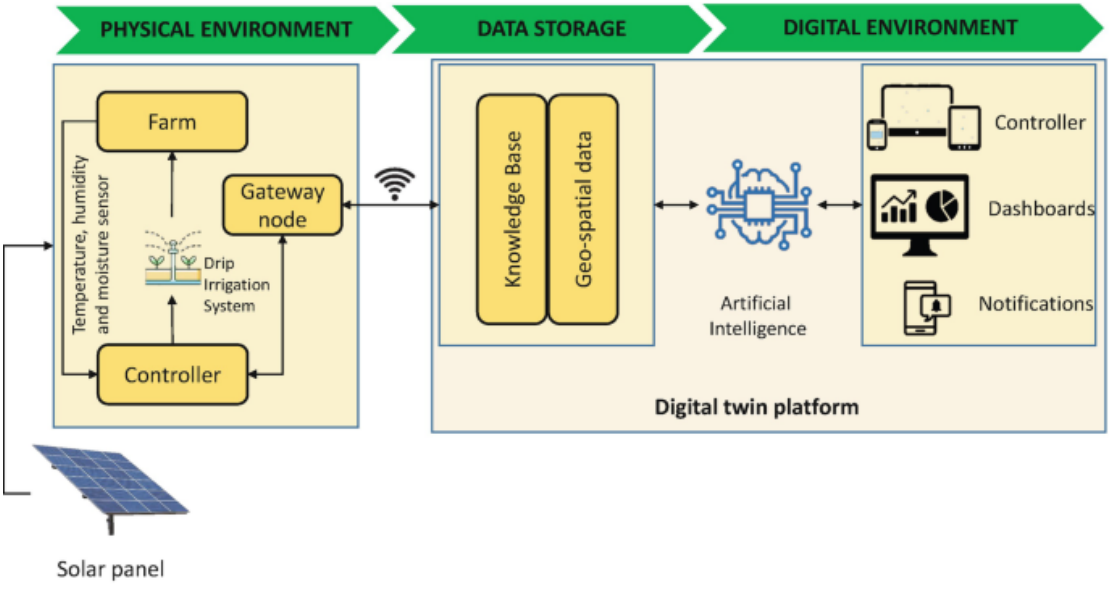
In protected cultivation, the Digital Twins keep track of temperature, humidity, concentration of carbon dioxide, light intensity, and irrigation systems in real time. They optimize environmental conditions automatically, bringing improved productivity and quality of crops with reduced energy consumption.

6. Livestock Management

Digital Twins are increasingly being applied in dairy and livestock farming to track animals' health, feed consumption, body temperature, activity and milk output. Farmers get diseases or health disorders alerts at early stage, leading to better animal welfare and farm profitability.

7. Farm Machinery Optimization

Today, tractors, harvesters and other farm machinery produce operational data that can be connected to Digital Twins. This enables an optimized performance of the machinery and fuel consumption, maintenance needs prediction, and equipment downtime reduction.



Benefits of Digital Twins in Agriculture

Digital Twin technology offers farmers a multitude of benefits, allowing them to base their decisions on facts and in real time farm status. It enhances crop yield and increases resource use efficiency through efficient farm operations, such as irrigation, fertilizer application and other. The technology enables detection of crop stress, pests, and diseases at an early stage, and its intervention reduces yield losses. Through the promotion of accurate use of inputs, Digital Twins also reduce the cost of production and the environmental pollution and the emission of greenhouse gases. This farming and advisory support helps farmers adjust to changing weather patterns, enhance operational planning, boost farm profits, and promote climate-resilient and sustainable precision agriculture.

Challenges in Adoption

Though there are great opportunities through digital twin technology, its mass use in agriculture is hindered by several challenges. The high upfront cost of sensors, IoT devices, and digital infrastructure makes the implementation expensive, especially for smallholder farmers. Poor rural internet access, a lack of trained personnel and low awareness of advanced digital technologies are also constraining adoption. Moreover, data privacy and cybersecurity issues, and absence of standardized digital platforms add complexity to data and system integration. Routine sensor maintenance and calibration, along with the difficulty of harmonizing various digital technologies, contribute to the complexity and cost of operation.

Future Prospects

The outlook of Digital Twins for agriculture is super bright. Advances in artificial intelligence, machine learning, cloud computing, robotics, 5G communications, edge computing, and satellite technology, will further contribute to making Digital Twin solutions more precise, cost-effective, and accessible. The next-generation platform may combine autonomous tractors, farm bots, drones, weather forecasting, and blockchain traceability in one seamless ecosystem.

Digital Twins are expected to also help the development of climate-smart agriculture enabling farmers to model impacts of shifting weather patterns, field maximum carbon efficient farming practices, conserve natural resources, and build climate variability resilience. With the decreasing sensor costs and expanding digital infrastructure, even small and medium-scale farmers are going to have increased access to this revolutionary technology.

CONCLUSION

The advent of Digital Twin technology is a giant step forward for contemporary agriculture. It allows the representation of farms, crops and agricultural systems as real-time virtual models, which farmers use to take precise, data-driven decisions that enhance productivity, resource use efficiency and sustainability. While issues of cost and infrastructure, along with the need for technical expertise still exist, the pace of technological development and increasing digital uptake will likely spur its use. Digital Twins will be an integral part of precision farming/smart agriculture in the near future, ensuring food security and environmentally sustainable farming systems