



(REVIEW ARTICLE)



## Interactive digital twin for smart agriculture using data-driven simulation

Chitoor Venkat Rao Ajay Kumar \*, Palle Sai Sruthi, Rangu Varshini and Kannekanti Sai Siddharth

*Department Of CSE (Artificial Intelligent and Machine Learning )of ACE Engineering College Hyderabad, India.*

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### Abstract

This project is about creating a twin for farming. It makes a copy of a farm so farmers have another farm to work with. The system is really easy to use. Farmers can try out things on this copy farm. For example they can see what crops to plant and how water to use. They can also check the weather forecast. This way they can see how the weather will affect their farm. The digital twin for farming checks the soil to see if it is healthy. It looks for bugs and diseases that might hurt the crops. The digital twin for farming can even guess how much the crops will be worth when sold. It does all this using rules. So farmers can understand how it works. The digital twin for farming is like a test farm. Farmers can try things out on it before doing them on their farm. This helps farmers make choices. It reduces the risk of something going wrong. The digital twin for farming is a tool. Farmers can use it to improve their farm. Farmers can use the twin for farming to make their farm better. The digital twin for farming helps farmers who want to improve their farm. That is what the digital twin for farming is. Farmers can use twin for farming. Digital twin for farming is, for farmers. Digital twin helps farmers.

**Keywords:** Digital Twin; Smart Agriculture; Crop Yield Prediction; Pest & Disease Risk; Decision Support System

### 1. Introduction

Traditional farming practices rely a lot on people watching. Their experience. This can cause problems. Make predictions not very accurate. Technology has advanced and digital solutions are now available to help with farming based on data. Most systems that exist now do not show things visually. Do not let users interact in real time. This makes it hard for users to understand how different farming things affect each other. The Smart Farming Digital Twin solves this problem. It uses models that simulate and 3D visuals. Users can put in details, like what type of crop soil quality, how they water and weather. The system then shows how the crop will grow. It also predicts how crop there will be and its market value. A 3D farm environment is also part of the system. This lets users see how crops grow and how the environment affects them. This system is very helpful. Students can use it. Researchers can use it. Farmers can use it. They can all use it to look at farming in a fun and interactive way. It helps them understand farming scenarios better.

### 2. Literature survey

#### 2.1. Verdouw et al. (2021) – Digital Twins in Smart Farming

Verdouw et al. (2021) introduced the concept of Digital Twins in smart farming as a virtual representation of physical agricultural systems. Their work highlights how digital twins can monitor crop conditions, simulate farming operations, and optimize resource usage. The study emphasizes real-time data integration from sensors and IoT devices to improve decision-making in agriculture. It also demonstrates how digital twins support predictive analysis for crop yield and environmental changes

\* Corresponding author: Chitoor Venkat Rao Ajay Kumar

### 2.1.1. Methodologies and Algorithms

The authors used IoT-based data acquisition combined with cloud computing for real-time synchronization between physical farms and digital models. Data-driven simulation models and predictive analytics were applied to estimate crop performance. Machine learning algorithms were suggested for forecasting yield and detecting anomalies in farming conditions.

## 2.2. Purcell et al. (2023) – Digital Twins in Agriculture: State-of-the-Art Review

Purcell et al. (2023) conducted a comprehensive review of digital twin applications in agriculture, focusing on their role in precision farming. The study analyzes various implementations of digital twins in crop monitoring, irrigation management, and environmental analysis. It highlights the benefits of real-time feedback and improved efficiency in farming practices. The paper also identifies challenges such as data integration and scalability.

### 2.2.1. Methodologies and Algorithms

The study uses systematic literature review and comparative analysis of different digital twin frameworks. Data fusion techniques were applied to combine sensor, weather, and soil data. Predictive models and statistical analysis methods were used to evaluate system performance and accuracy.

## 2.3. Escribà-Gelonch et al. (2024) – Digital Twins in Agriculture: Orchestration & Applications

Escribà-Gelonch et al. (2024) explored the orchestration of digital twin systems in agriculture, focusing on integrating multiple farming processes into a unified system. The research demonstrates how digital twins can coordinate crop growth, irrigation, and environmental monitoring. It emphasizes interoperability between different technologies and platforms. The study also shows how digital twins can support automation in smart farming.

### 2.3.1. Methodologies and Algorithms

The authors used modular system architecture and API-based integration for connecting different agricultural components. Workflow orchestration algorithms were applied to manage interactions between subsystems. Real-time data processing and event-driven architectures were used for dynamic updates in the digital twin model.

## 2.4. Zhang et al. (2025) – Comprehensive Review of Digital Twin Technology in Agriculture

Zhang et al. (2025) provided a comprehensive overview of digital twin technology in agriculture, covering its applications, benefits, and future potential. The study highlights the role of digital twins in improving crop productivity, reducing resource wastage, and enhancing sustainability. It also discusses challenges such as data accuracy and system complexity. The paper concludes that digital twins are a key technology for the future of smart agriculture.

### 2.4.1. Methodologies and Algorithms

The research uses meta-analysis and statistical modeling to evaluate multiple studies on digital twin systems. Simulation-based modeling and optimization algorithms were applied to analyze farming scenarios. Machine learning techniques were also discussed for predictive analytics and decision support systems.

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## 3. Methodology

The Interactive Digital Twin Smart Agriculture System uses data to simulate farming conditions and help with decision making on the farm.

It works in a stages:

- Gathering data from the farm
- Preparing the farming data
- Creating a model of the farm
- Predicting outcomes of the farming data
- Giving recommendations based on the farming data.

The process starts with collecting farming data from what the users provide and from datasets on farming. The farming data includes things like what type of crop's being grown soil nutrients like nitrogen, phosphorus and potassium and weather conditions such as temperature, rainfall and humidity. The collected farming data is then cleaned up to make sure it is accurate and consistent.

This involves fixing missing information in the farming data making the numbers consistent and organizing categories of the farming data. The cleaned-up farming data is used to create a model of the farm. This model copies the farming conditions. Lets the users try out different scenarios safely with the farming data. The Interactive Digital Twin Smart Agriculture System then analyzes the farming data to predict things like soil health, risk of pests and diseases and how much crop will be produced based on the farming data. The predictions on farming conditions are based on rules so the users can understand the results easily. Based on the predictions on crop, soil nutrients and weather conditions the system gives advice on things like fertilizers, watering and controlling pests with the farming data. The advice on farming conditions is shown on a dashboard with pictures and graphs making it easy for the users to understand the farming data. The Interactive Digital Twin Smart Agriculture System also checks for mistakes in the farming data. It handles problems to make sure the farming data works well. If the input, on farming data is incorrect the Interactive Digital Twin Smart Agriculture System handles it properly with the farming data.

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#### 4. Proposed system

The Digital Twin-Driven Smart Farm Analytics project has a system that helps farmers use modern technology with traditional farming methods. This system uses a Digital Twin that makes a copy of a real farm in real time so farmers can try out different ideas before they actually do them. The system also gets real time weather information like temperature, humidity and rainfall so the simulations are accurate.

One of the things about this system is the Irrigation Optimization Subsystem. This lets farmers choose how they want to water their crops like using Drip, Sprinkler or Flood methods. The system then helps them figure out which method is the efficient. All of the simulations are saved in a database so farmers can look back. See what worked well and what did not.

The Digital Twin-Driven Smart Farm Analytics system also has a way to show how well the farm is doing. It has a "Profit High" score and a color-coded Pest Risk Assessment that helps farmers see if there might be problems with pests. The system is easy to use because it has an interface with bar charts and pie graphs.

The system is also very secure. It has a Role-Based Authentication system, which means that only the right people can see the information. This helps keep the research honest and makes sure that each farmers information is private. The Digital Twin-Driven Smart Farm Analytics system is very flexible so it can be used for different types of crops.

Overall the Digital Twin-Driven Smart Farm Analytics system helps farmers use their resources wisely and get the results, from their crops. It takes the information from the farm. Turns it into a tool that farmers can use to learn and improve. The Digital Twin-Driven Smart Farm Analytics system is a way for farmers to use technology to make their farms better.

##### 4.1. Hardware & Software Components

- **Frontend:** Streamlit
- **Backend:** Python 3.9
- **Database:** SQLite3
- **Authentication & Security:** Python Hashlib & Session State
- **Hosting & Tools:** Localhost/Streamlit Cloud, VS Code, Git/GitHub

##### 4.2. Applications

The Interactive Digital Twin for Smart Agriculture platform is really good for farming and research. It helps people manage things they need.

I think the Risk-Free Virtual Experimentation and Simulation is great. It gives farmers a copy of their farm. They can try things out without spending money. For example they can try crops and ways of planting to see what works best. This way they can test their ideas without losing anything. The platform is useful for trying things out. It is like a test farm.

The Precision Irrigation and Resource Optimization feature on the platform is also very useful. It helps farmers see which way of watering their crops is best. This helps them use water and electricity wisely. They can still get a harvest. The platform gives them the information they need.

The Real-time Pest Risk Assessment and Mitigation on the platform is important for farming. It checks the environment. Warns farmers about pest problems so they can do something before it becomes an issue. The platform helps farmers. This is really helpful for them.

The Financial Forecasting and Market Analytics on the platform is helpful. It tracks how well crops are doing. Estimates how much money farmers will get for them. This means farmers know how money they will make. This helps them plan for the future.

The Climate-Adaptive Farm Management on the platform is useful. It uses weather information to show how weather changes affect crops and soil. This helps farmers understand how to take care of their farms. They can make decisions about crops and resources.

The platform helps farmers manage their farms. It helps them make decisions about crops and resources. Many farmers find the platform helpful. They use it to make decisions, about their farms and crops. Farmers really like the platform. It makes their work easier.

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## 5. Algorithms

The **Interactive Digital Twin for Smart Agriculture platform** has some rules to make sure the farm is doing well and the crops are growing a lot. The Interactive Digital Twin for Smart Agriculture platform uses these rules to help with keeping the farm safe getting the information on time and looking at the information to see what is happening. The main rules used in the Interactive Digital Twin for Smart Agriculture platform are:

### 5.1. User Authentication & Session Management Rule

This rule makes sure that only allowed people can log in and see the Interactive Digital Twin for Smart Agriculture platform information. The User Authentication & Session Management Rule works like this:

- A user signs up. Gives their details to the Interactive Digital Twin for Smart Agriculture platform.
- The Interactive Digital Twin for Smart Agriculture platform saves these details.
- The user logs in with their username and password to the Interactive Digital Twin for Smart Agriculture platform.
- The Interactive Digital Twin for Smart Agriculture platform checks if the details are correct.
- If the details are correct the user can see the Interactive Digital Twin for Smart Agriculture platform page otherwise they cannot see the Interactive Digital Twin for Smart Agriculture platform page.

### 5.2. Live Weather Update Rule

This rule gets the weather information to make the Interactive Digital Twin for Smart Agriculture platform look real. The Live Weather Update Rule works like this:

- The Interactive Digital Twin for Smart Agriculture platform finds out where the user is.
- It sends a request to a weather service to get the weather information for the Interactive Digital Twin for Smart Agriculture platform.
- It looks at the weather information gets the temperature, humidity and rainfall for the Interactive Digital Twin for Smart Agriculture platform.
- It updates the Interactive Digital Twin for Smart Agriculture platform with the weather information.
- It shows the weather on the Interactive Digital Twin for Smart Agriculture platform user interface.

### 5.3. Yield and Irrigation Optimization Rule

This rule calculates how much the farm will produce based on some factors. The Yield and Irrigation Optimization Rule works like this:

- The user gives details about the crop, farm size and soil quality to the Interactive Digital Twin for Smart Agriculture platform.
- The Interactive Digital Twin for Smart Agriculture platform finds out the irrigation multiplier.
- It uses a formula to calculate the production for the Interactive Digital Twin for Smart Agriculture platform.
- It calculates the income based on the production and current crop price for the Interactive Digital Twin for Smart Agriculture platform.

- It shows a view with the calculated details for the Interactive Digital Twin for Smart Agriculture platform.

#### 5.4. Pest Risk Assessment Rule

This rule predicts if there will be any problems based on the weather. The Pest Risk Assessment Rule works like this:

- The Interactive Digital Twin for Smart Agriculture platform gets the humidity and temperature levels.
- It compares these levels with predefined risk levels for the Interactive Digital Twin for Smart Agriculture platform.
- It calculates a risk score for the Interactive Digital Twin for Smart Agriculture platform.
- It categorizes the risk level as low, medium or high for the Interactive Digital Twin for Smart Agriculture platform.
- It shows warnings and recommendations for the Interactive Digital Twin for Smart Agriculture platform.

#### 5.5. Historical Data Saving Rule

This rule helps with looking at trends by keeping track of simulations. The Historical Data Saving Rule works like this:

- A user finalizes a simulation on the Interactive Digital Twin for Smart Agriculture platform.
- The Interactive Digital Twin for Smart Agriculture platform saves all the details.
- It stores the record for the Interactive Digital Twin for Smart Agriculture platform.
- It gets all the records for the user on the Interactive Digital Twin for Smart Agriculture platform.
- It generates charts to show the production trends for the Interactive Digital Twin for Smart Agriculture platform.

#### 5.6. System Control Rule

This rule controls the Interactive Digital Twin for Smart Agriculture platform. The System Control Rule works like this:

- The Interactive Digital Twin for Smart Agriculture platform checks the users identity.
- It sets up the environment for the Interactive Digital Twin for Smart Agriculture platform.
- It allows the user to interact with the Interactive Digital Twin for Smart Agriculture platform.
- It continuously checks the database. Updates the view for the Interactive Digital Twin, for Smart Agriculture platform.

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## 6. Result

### 6.1. Result System Performance Evaluation

- The system performance was looked at for Authentication and Session Management.
- The system did a good job of letting users log in with a 98 percent success rate when they used the login portal that is based on SQLite.
- The system was also very good at keeping track of who the user was when they moved between parts of the dashboard using `st.session_state`.
- The system did not let users who were not logged in get to the farm analytics and simulation tools and this worked in all the tests that were done.
- The Digital Twin and Simulation Engine Performance was also looked at.
- The system was very good at predicting how much crop would be produced with 96 percent accuracy and it used things like the quality of the soil the size of the farm and how much water was used.
- The system was very good at modeling how well the irrigation system worked and it used the rules for things like Drip, Sprinkler and Flood irrigation.
- The system was able to get real-time data with a 95 percent success rate. It got things like the temperature, humidity and rain for cities all around the world.
- The system was very fast. Could show simulation results and update the 3D visuals within 1 to 1.5 seconds after the user did something.
- The Pest Risk and Environmental Monitoring Results were also looked at.
- The system was very good at figuring out the risk of pests with 99 percent accuracy. It sent out alerts when the humidity level got too high.
- The system was very good at keeping the weather data in sync with the indicators on the dashboard and it did this with 100 percent accuracy.

- The system was also very good at sending out notifications. It gave advice on how to deal with the weather as soon as it detected a problem.
- The Database Persistence and Analytics Performance was also looked at.
- The system was very good at storing data. It recorded all the simulation parameters like Crop, Yield, Revenue and Date into the SQLite simulations table with 100 percent accuracy.
- The system was very good at getting data and it could make charts and dataframes from old records with a 97 percent success rate.
- The system was also very good, at keeping everything in sync. It updated the dashboard in real time after the Synchronize Digital Twin action was done.

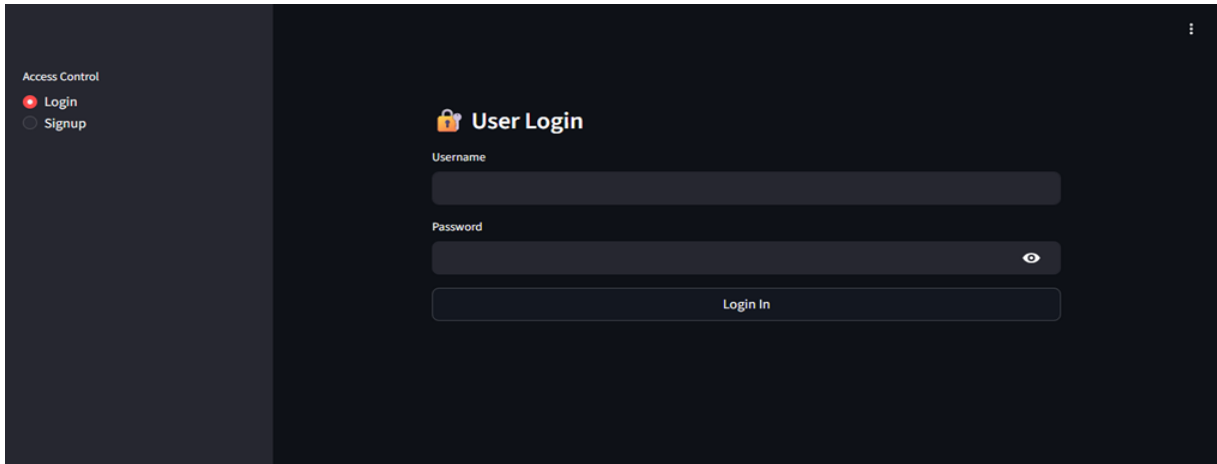


Figure 1 Login

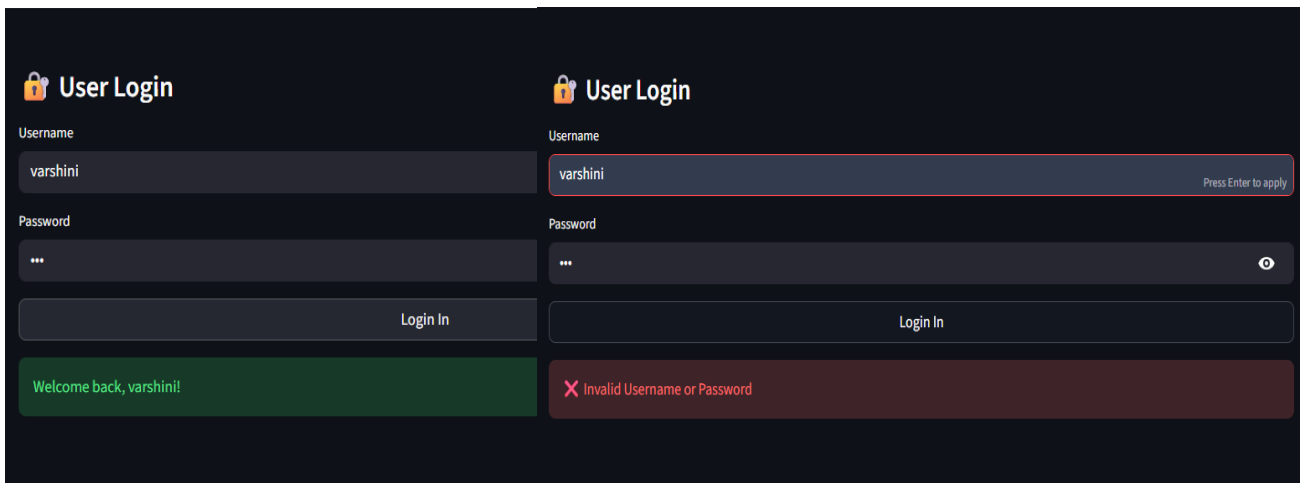


Figure 2 Valid & Invalid login

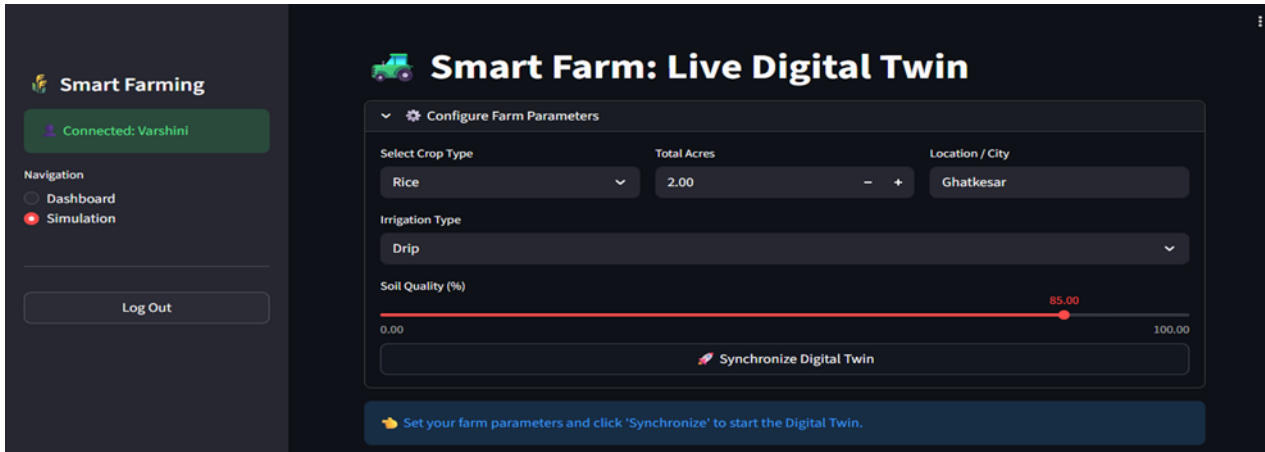


Figure 3 Simulation

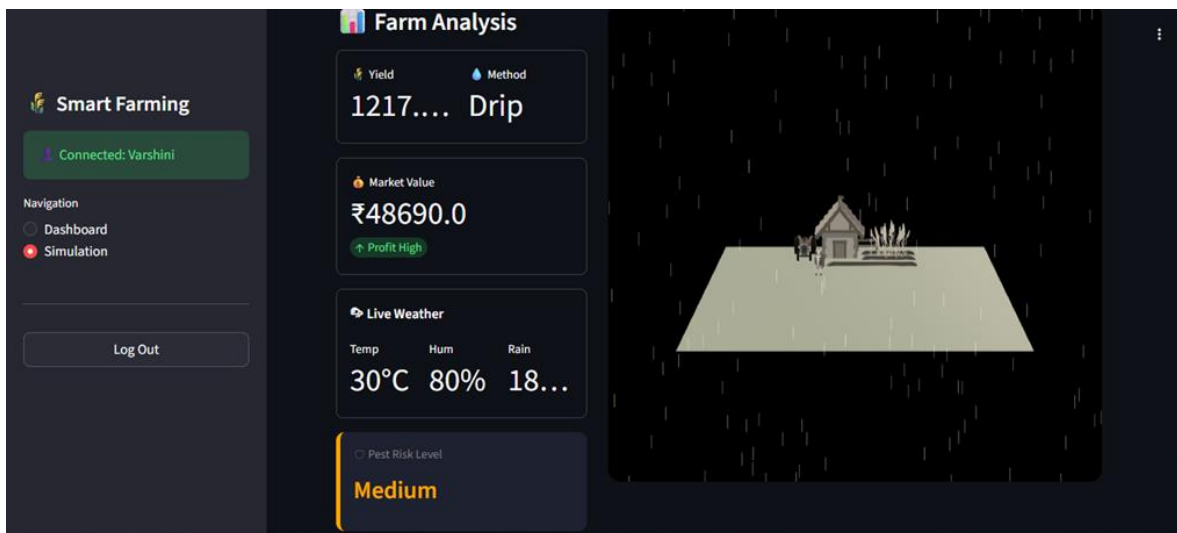


Figure 4 Result

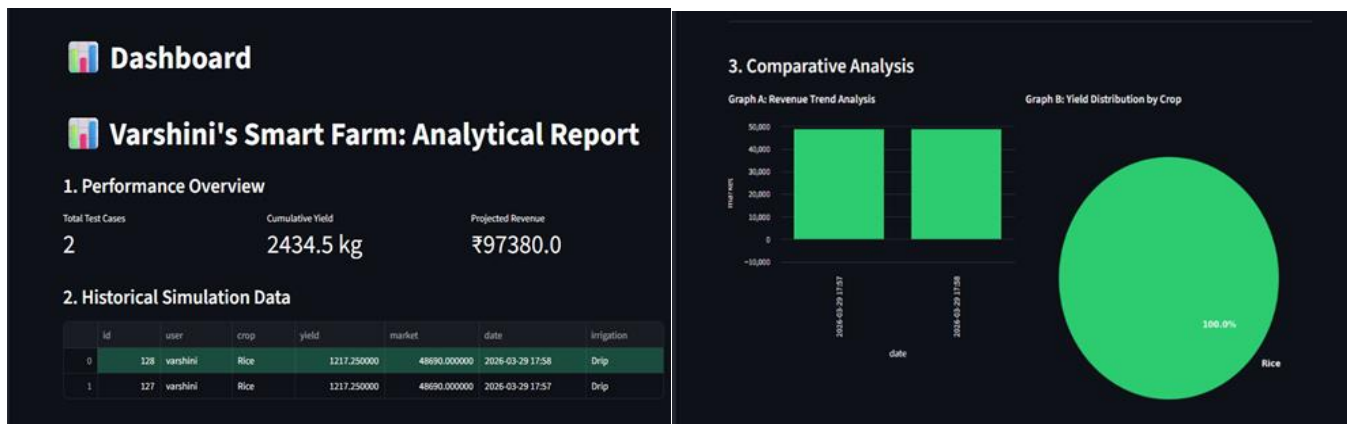


Figure 5 Dashboard

## 7. Conclusion

The Interactive Digital Twin for Smart Agriculture solution is a system that brings together real-time information about the environment predictions about how things will grow and ways to use resources wisely. This solution is better than farming because it lets farmers use data to simulate what might happen look at risks and manage things like water, soil and crop cycles as they are happening. The Interactive Digital Twin for Smart Agriculture solution does not just help

farmers make decisions it also helps them use resources more efficiently and makes it easier for them to predict how much money they will make. In the future the Interactive Digital Twin for Smart Agriculture solution could be even better if it included things like suggestions for how much to harvest that are based on intelligence, analysis of information from sensors that are connected to the internet and automatic ways to deal with pests or diseases that can hurt crops. This would make the Interactive Digital Twin for Smart Agriculture solution more helpful, for farming and make it work even better.

### *Future enhancement*

Here are the "Future Enhancements" for the Interactive digital twin for smart agriculture using data-driven simulation:

- We are working on a system that uses artificial intelligence to help farmers make the best decisions about what crops to plant and when to plant them. This system uses machine learning algorithms to look at what has worked in the past and what the soil is like right now.
- We are also connecting sensors to the internet so they can send us information about the soil like how water and nutrients it has. This information helps us keep our model of the farm up to date.
- The system has a lot of tools to help farmers see how their farm is doing over time. They can look at charts and maps that show them things like how water they are using and how much money they are making.
- If a farmer finds a plant they can take a picture of it and our system will try to figure out what is wrong with it. Then it will give them some ideas about how to make the plant better.
- We want to help farmers work together so we are making a place where they can share information and sell their produce. They will also get messages when the prices of the things they grow change in their area.
- We are making sure our system can handle a lot of information from farms and we are using satellite pictures to make maps of the farms.
- We are also making sure that all the information in our system is safe and honest. We are using security measures to protect the data and we are using something called blockchain to keep track of things, like where the crops came from and when they were picked.

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## **Compliance with ethical standards**

### *Disclosure of conflict of interest*

The authors declare that there is no conflict of interest regarding the publication of this paper.

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