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Digital Twins in Greenhouse Vine Crops: A Smarter Way to Grow

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Imagine walking into a long, bright greenhouse full of tomato and cucumber vines. Clusters of fruits hang at eye level, irrigation lines deliver nutrient solution drop by drop, and fans hum softly in the background. Now imagine that, at the same time, a virtual copy of this greenhouse is running on a computer or tablet, watching every change in temperature, humidity, light, and plant growth. This virtual copy of a digital twin is beginning to change the way vine crops are grown in protected cultivation.

What is a digital twin?

In simple words, a digital twin is a live digital model of a real system. The real greenhouse, with its structure, climate, and crops, is the physical side. The computer model that mirrors it, updated with fresh data from sensors and control systems, is the virtual side. Both are linked together so that when something changes in the greenhouse, it is reflected in the model, and when the model tests a new idea, it can suggest actions back to the greenhouse. Researchers in agriculture describe digital twins as a combination of sensing, simulation, and analytics. Sensors collect information, models and algorithms analyse it, and the results are displayed through dashboards or used to support automatic control. Unlike traditional decision-support tools that work on historical data, a digital twin runs continuously and can even look ahead, forecasting what may happen if the weather changes or if irrigation is delayed.

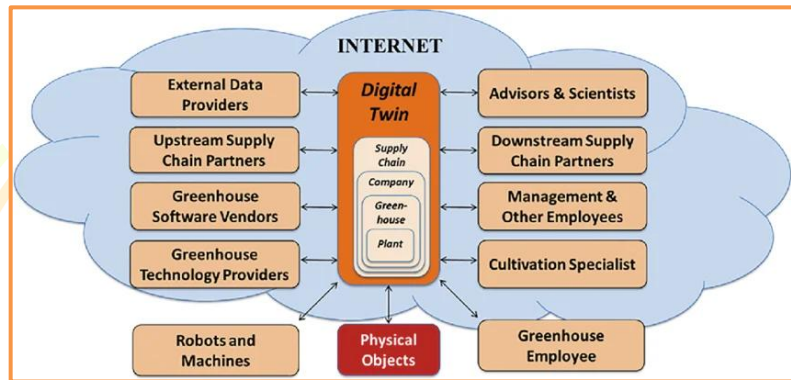


Fig: Digital Twin concept in greenhouse.

Why vine crops are a good match

Vine crops such as tomato, cucumber, capsicum, and greenhouse grapes are high-value crops that respond quickly to changes in their environment. Their yield and quality depend on a delicate balance among light, temperature, humidity, carbon dioxide, and water and nutrient supply. A few days of excessive humidity can increase disease risk, while a short period of water stress can reduce fruit size or cause blossom-end rot. In a large commercial greenhouse, keeping everything in balance every hour of the day is not easy. These characteristics make vine crops ideal candidates for digital twin systems. Because the crops are grown in a controlled space, sensors can be installed throughout the greenhouse, and climate devices like vents, fans, foggers, heaters, and screens can be managed through computerized control. The digital twin connects all these pieces into one coordinated view, helping the grower see how today's climate and irrigation decisions will influence plant health and production over time.

Inside a digital twin system

A digital twin for greenhouse vine crops can be imagined as three main layers: sensing, modelling, and interaction.

1. Sensing the greenhouse

The physical greenhouse is filled with instruments that measure the crop's growing environment. Common devices include:

Air temperature and relative humidity sensors to track the comfort of the crop canopy.

Light sensors to monitor solar radiation or photosynthetically active radiation.

Carbon dioxide sensors to check if enrichment is at the right level.

Substrate moisture and electrical conductivity sensors in soilless systems to follow water and nutrient status in the root zone.

Cameras or imaging systems that can estimate canopy development, leaf colour, or fruit load.

All of these sensors send data at regular intervals to a central platform or greenhouse computer. In advanced installations, wireless sensor networks and Internet of Things (IoT) devices are used, so that data can be accessed from anywhere with an internet connection.



Fig: Greenhouse Monitoring-Sensor Technology

2. Modelling crop and climate

The heart of the digital twin is the virtual model. It usually includes several types of models working together:

- ✚ Greenhouse climate models that describe how outside weather, ventilation, heating, and shading affect inside temperature, humidity, and carbon dioxide. Crop growth models that estimate how fast vines produce new leaves, flowers, and fruits based on light, temperature, and other factors.
- ✚ Water and nutrient balance models that simulate how much water the plants take up, how much is lost by evaporation, and how irrigation and fertigation should respond.
- ✚ Sometimes, disease and pest risk models relate microclimate and canopy structure to the probability of specific problems.

Some of these models are physics-based, relying on equations about heat, mass, and energy transfer in the greenhouse. Others are data-driven, using machine learning to recognize patterns from historical records of climate, irrigation, and yield. When combined, they give a realistic picture of how the crop and environment interact.

3. Interaction and decision support

The final layer is where growers and managers interact with the digital twin. Outputs are usually displayed in the form of dashboards, graphs, and alerts. For example, a screen might show current and predicted greenhouse temperatures, recommended irrigation volumes for each zone, or a risk index for fungal disease in the crop.

The system can also run "what-if" scenarios. A grower can ask questions such as:

- ✚ What happens to humidity if the vents are opened 10 minutes earlier?
- ✚ How much yield might be lost if the night temperature is reduced by 1 degree to save heating cost?
- ✚ Will reducing irrigation events during low radiation hours affect total daily water uptake?

The digital twin answers by simulating these scenarios with the underlying models and presenting likely outcomes. In some advanced systems, recommendations can be translated into automatic control actions, although growers usually prefer to maintain the final decision-making power.

A day in a greenhouse with a digital twin

To understand how this works in practice, consider a grower managing a large tomato greenhouse. Early in the morning, the grower checks the digital twin dashboard on a tablet. The system reports that, based on yesterday's radiation and today's weather forecast, the plants will require more water than on a typical day. It suggests increasing morning irrigation slightly and warns that, if afternoon ventilation is delayed, humidity may rise to levels favorable for disease. As the day progresses, clouds reduce the expected radiation. The digital twin updates its calculations and recommends adjusting irrigation timing so that the substrate does not stay saturated under lower light. Later, a sudden drop in outside temperature forces the greenhouse to close vents, which again increases humidity. The twin predicts that the risk of leaf wetness and fungal infection may increase and sends an alert proposing a short period of additional heating and dehumidification. In this way, the digital twin acts like an intelligent assistant. It does not replace the grower's experience, but it helps by processing thousands of data points and forecasting their combined effect on the crop. Over time, such support can reduce mistakes, improve consistency, and make it easier to train new staff.

Key applications in vine-crop greenhouses

Digital twin concepts are being tested and implemented in several important areas of greenhouse vine-crop cultivation.

Climate optimization

First, digital twins help manage climate more precisely. By linking climate models with real-time data, the system can recommend or implement adjustments in ventilation, shading, heating, cooling, and carbon dioxide dosing. The goal is to keep the crop in its optimum comfort range for as many hours as possible, which usually leads to healthier plants and better yield.

Irrigation and fertigation control

Second, digital twins improve irrigation and fertigation scheduling. For vine crops grown in substrates such as cocopeat, rockwool, or perlite, the timing and amount of drippers turning on is critical. A digital twin can estimate plant transpiration based on radiation and climate, compare it with sensor data from the root zone, and suggest irrigation doses that match plant demand closely. This approach helps to avoid both water stress and unnecessary drainage, saving water and fertilizers.

Early stress and disease detection

Third, digital twins support early detection of stress and disease. Because the system continuously monitors microclimate and sometimes crops' images, it can identify conditions that favour diseases such as powdery mildew or botrytis before symptoms are widespread. Alerts can prompt timely ventilation, dehumidification, or targeted crop protection measures, reducing both losses and chemical use.

Yield and harvest prediction

Finally, digital twins help with forecasting. By combining crop growth models and observations of flower and fruit development, they can provide estimates of likely yield and harvest timing. For greenhouse businesses that must plan labor, packaging, and market supply in advance, such predictions are extremely valuable.

Benefits for growers and the environment

When digital twins are applied effectively, growers can expect several practical benefits:

- ✚ Higher and more stable yields because the crop experiences fewer periods of hidden stress.
- ✚ Improved fruit quality and uniformity, which is important for both fresh markets and processing.
- ✚ Better resource-use efficiency, with more precise use of water, fertilizers, and energy. Reduced risk, as potential problems are detected earlier and can be corrected before serious damage occurs.

- More informed decision-making, especially for complex questions about climate and irrigation strategies.

From an environmental point of view, digital twins support more sustainable protected cultivation. Less over-irrigation means lower risk of nutrient leaching, and better control of climate can reduce unnecessary heating or cooling, which in turn can lower greenhouse gas emissions linked to energy use.

Challenges and limitations

Despite these advantages, digital twins are not a magic solution and face several challenges.

- First, they rely heavily on data quality. Faulty sensors, missing data, or poor calibration can weaken the model and lead to unreliable recommendations. Regular maintenance of sensors and careful setup of the system are essential.
- Second, integration is not always straightforward. Greenhouses often use devices and software from different manufacturers. Bringing all of them into a single digital twin platform requires technical expertise and can involve additional costs. Small and medium growers may find it difficult to invest in such advanced systems without external support or clear evidence of economic benefits.
- Third, there is a learning curve. Growers and technicians must understand at least the basics of how the digital twin works, what its limits are, and how to interpret its outputs. If the system is too complex or not transparent, users may lose trust and stop using it.

The road ahead

Future digital twins for vine-crop greenhouses are likely to become more intelligent and more specific. Progress in artificial intelligence and sensing will allow models to learn from each season and adapt to different cultivars, pruning systems, and local climate conditions. Integration with robotics and automation may also grow, for example, by linking digital twins with mobile robots for scouting, pruning assistance, or selective harvesting. At the same time, there is a strong interest in making digital twin technology accessible to smaller farms. Cloud-based platforms, open-source tools, and modular sensor kits may reduce costs and simplify installation. Training programs and advisory services will be important to translate advanced digital tools into practical field use.

Conclusion

Digital twins bring a new level of insight and control to greenhouse cultivation of vine crops. By building a living digital copy of the greenhouse and its crop, they help growers see beyond what is visible, anticipate problems, and fine-tune management for productivity and sustainability. While challenges remain in cost, integration, and training, ongoing research and innovation suggest that digital twins will play an increasingly important role in the future of protected cultivation.

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