

accurate predictive models and their coupling with advanced control architectures such as model predictive control, underscoring that model quality depends on sensing quality (Bersani et al., 2022).

5.3 Smart agriculture systems for real-time disease control

Smart agriculture systems extend prediction into real-time action by linking humidity sensing, data transmission, and automated control of greenhouse conditions. An IoT- and wireless-sensor-network platform collected temperature, humidity, and soil-moisture data, sent them to a Raspberry Pi processing unit, and used a fuzzy-logic controller to generate climate and irrigation decisions, with testing showing effective platform performance (Benyezza et al., 2023). This type of architecture is attractive for cucumber disease prevention because it supports continuous regulation of humidity-sensitive microclimates rather than intermittent manual correction. Recent IoT greenhouse research also shows that remote management and cloud-connected sensing are now technically mature enough for practical humidity control. Web-based and smartphone-linked systems can display greenhouse status and send commands to actuators for humidity, temperature, and irrigation management, while NB-IoT sensor nodes can upload environmental data such as humidity in real time with stable transmission success rates that meet management requirements (Bersani et al., 2022). These capabilities matter for disease control because they enable timely response to short-lived humidity spikes that often precede infection events.

A further step is the integration of monitoring, forecasting, and disease detection into one control loop. IoT reviews describe automated systems that monitor temperature and humidity while also inspecting crop health by image analysis, and these systems have been reported to enhance yield through immediate control and monitoring without requiring direct farmer analysis. More generally, IoT-based greenhouse monitoring provides high-detail spatial and temporal data at reasonable cost, which supports more accurate models of plant environments and better control decisions at the level of individual crops or zones (Bersani et al., 2022). The emerging frontier is digital-twin disease control, although evidence here is still early. A recent digital-twin framework for greenhouse downy mildew combined intelligent air-quality sensing, optimization, and a three-dimensional disease model to generate real-time hotspot maps, and simulation experiments reported 96.7% hotspot coverage together with a 31% reduction in spraying path length and a 53% decrease in fungicide use. However, those gains remain simulation-based and require real-world validation, so digital twins appear promising for adaptive humidity-linked disease control but are not yet established as routine production tools (Wu, 2026).

6 Case Study: Humidity Control Strategies for Reducing Disease Occurrence in Greenhouse Cucumber Production

6.1 Experimental design and environmental data collection

A case-study design for greenhouse cucumber humidity control should combine continuous environmental sensing with repeated disease observation from transplanting to symptom onset. In solar-greenhouse downy mildew studies, indoor monitoring nodes have been placed at fixed canopy-relevant heights, with temperature, relative humidity, soil temperature, and water-related variables recorded at 15 min intervals, while disease surveys were conducted weekly before symptom appearance and then every 3-4 days after onset (Liu et al., 2022). A related early-warning experiment coupled climate monitoring from transplanting to primary infection with model-based forecasting, showing that short-horizon climate prediction can be directly linked to disease detection workflows in production greenhouses.

To strengthen spatial representativeness, environmental data collection should also account for within-greenhouse heterogeneity in humidity and leaf wetness. A chessboard deployment of sensors across nine sampling points in solar greenhouses showed that leaf wetness duration varies systematically by position, with longer wetness in southern canopy zones and on rainy days, which is directly relevant because wetness duration is a key input for cucumber disease forecasting (Liu et al., 2020). Field trials for cucumber powdery mildew likewise used hourly inside and outside greenhouse weather measurements across multiple seasons, with disease onset recorded when first symptoms appeared and fungicides withheld to allow natural epidemic development, providing a strong template for unbiased humidity-disease assessment.