

Mediterranean soilless cucumber production, fan ventilation improved transpiration by 60% relative to fan-pad cooling and reduced drainage outflows by 95%, while an irrigation regime of 0.24 L/m² minimized nutrient losses without compromising growth. Irrigation can also be part of a broader disease-resistance strategy when linked with plant material and resource-saving delivery systems. Greenhouse work on grafted cucumbers reported that combining an appropriate irrigation regime with a suitable rootstock prolonged fruiting by about 38-40 days and increased yield, suggesting that water management can strengthen crop persistence under stress-prone production conditions. More generally, reviews of sustainable greenhouse vegetable systems identify irrigation system choice, irrigation timing, and drainage-water management as key low-input tools for controlling the production environment while improving resource efficiency (Argento et al., 2024).

4.3 Integrated environmental control strategies

The strongest disease-prevention outcomes come from integrated environmental control, where humidity is managed together with temperature, airflow, light, and crop monitoring rather than in isolation. Greenhouse reviews emphasize that microclimatic stability determines infection probability and host susceptibility, and that integrating environmental sensing, biological control, and adaptive climate regulation offers a preventive pathway toward climate-smart pest and disease management (Fanourakis et al., 2026). This systems view is reinforced by general greenhouse-control research, which treats temperature, humidity, light, and CO₂ as jointly regulated variables and identifies multi-scale model coupling as the next step for more reliable environmental control. Sensor networks, automation, and predictive control are increasingly central to this integrated approach. Intelligent environmental control systems use real-time sensor data to continuously maintain target growing conditions, while AI can predict plant responses and support proactive rather than purely reactive climate management. At the control-algorithm level, model predictive control using heaters, humidifiers, and ventilation fans reduced relative RMS error for temperature and humidity deficit to 23.5% and 13.1%, respectively, and humidity control in this framework is explicitly expected to support photosynthesis while helping prevent plant disease (Ito and Tabei, 2021).

Integrated systems are also becoming more effective by linking environmental control with disease detection. AI-based greenhouse management platforms have been developed to combine disease-image classification with environmental information such as humidity, temperature, and light, and these systems can feed back into vent and screen control to improve greenhouse sustainability and intervention timing. In real greenhouse conditions, such an integrated system achieved 94% classification accuracy and was proposed as a way to reduce labor, lower pesticide use, and improve productivity through more precise pest and disease control (Kim et al., 2021). For cucumber production specifically, integrated control is most effective when disease suppression and crop performance are optimized together. In semi-closed greenhouse production, yield models showed that average nighttime relative humidity was significantly associated with cucumber yield, while the overall environmental dataset supported improved greenhouse management and forecasting. Across protected agriculture more broadly, internet-based remote control, efficient water management, temperature regulation, and optimized IPM are now treated as complementary parts of sustainable greenhouse operation, suggesting that next-generation cucumber disease prevention will depend on coordinated humidity control rather than single-factor interventions (Argento et al., 2024).

5 Computational and Predictive Approaches for Humidity-Based Disease Management

5.1 Data-driven modeling of humidity-disease relationships

Data-driven modeling has made humidity-based disease management in cucumber production more operational by converting greenhouse climate measurements into early-warning indicators of infection risk. An early warning model for primary cucumber downy mildew in solar greenhouses was built from monitoring data, epidemiological theory, and a limited set of practical inputs, and it could issue warnings more than two days before symptoms appeared, with a positive warning raising estimated disease occurrence probability from 0.68 to 0.96 (Zhao et al., 2022). This emphasis on parsimonious environmental variables is important because growth-environment data are relatively easy to collect at scale in facility agriculture, making them well suited for broad predictive use in