

7.3 Sustainable disease management under climate change

Under climate change, sustainable cucumber disease management must move beyond reactive spraying toward climate-informed integrated management. Rising temperatures, shifting moisture regimes, and combined abiotic stresses are changing host-pathogen interactions and increasing the unpredictability of disease outbreaks, which makes traditional single-factor control less reliable. In greenhouse cucumber specifically, erratic humidity promotes downy mildew outbreaks, and combined thermal and RH fluctuations can also reduce fungicide efficacy, further increasing the value of preventive environmental regulation (Fanourakis et al., 2025).

Future strategies therefore need to combine adaptive surveillance, precision agriculture, structural greenhouse adaptation, and economically viable cleaner production. Reviews of climate-resilient disease management emphasize early warning systems, precision tools, and resilient cultivars, while protected-cultivation research highlights smart climate control, insulation, and sustainable energy integration as practical adaptation pathways (Hossain et al., 2024). For greenhouse cucumber production, the most durable path is a preventive, data-driven IPM framework that couples humidity control with broader climate sensing, biological and agronomic measures, and farmer-usable decision tools.

8 Conclusions

Humidity regulation remains one of the clearest environmental levers for suppressing cucumber downy mildew in greenhouses because infection develops under high relative humidity and moderate temperatures, while drier conditions slow epidemic progress. Experimental evidence further shows that keeping greenhouse humidity below about 89% can protect cucumber plants from downy mildew, making RH control a practical disease-prevention target rather than only a descriptive risk factor. The practical value of humidity regulation is strongest when it is implemented through ventilation and integrated greenhouse management. Ventilation-based reduction of humidity lowered downy mildew infection and severity substantially, and in one greenhouse comparison the ventilated house also produced more fruit than the regular greenhouse. This matters agronomically because downy mildew can spread rapidly and cause major economic loss under favorable humid conditions, so environmental control reduces both disease pressure and dependence on repeated chemical intervention.

For precision cucumber production, the main implication is that humidity must be treated as part of a multi-sensor microclimate system rather than as a standalone variable. Greenhouse studies have shown that wireless nodes can collect temperature, humidity, soil, and external weather data at short intervals for disease-linked monitoring, while IoT platforms can automatically maintain target humidity ranges inside cucumber houses. This supports a production model in which disease prevention, crop growth, and resource control are managed through the same data infrastructure. That same infrastructure also improves production outcomes beyond disease suppression. IoT-based cucumber houses maintained more favorable daytime temperature and RH conditions and achieved a 41.6% yield increase per vine over conventional management, while cloud-based automated control improved cucumber yield, fruit quality, water-use efficiency, and energy performance. In this sense, humidity control contributes to precision production not only by lowering infection risk, but by stabilizing the broader greenhouse environment needed for consistent crop performance.

The strongest future opportunity is to shift from reactive humidity management toward predictive, AI-assisted prevention. LSTM-based greenhouse models have already predicted cucumber downy mildew occurrence with 90% accuracy from environmental time-series data, and CNN-LSTM models that combine disease and environmental information have also shown good agreement between predicted and observed disease severity. These results indicate that future systems can move from fixed RH thresholds to dynamic disease-risk forecasting. A second opportunity is to build smart prevention systems that combine environmental sensing with automated control, image analysis, and low-cost deployment. Emerging greenhouse platforms now integrate feedback loops for fans, pumps, and lighting, while future designs explicitly propose machine-learning image analysis for early disease detection and autonomous decision-making. At the same time, low-cost validated sensor systems and IoT-fuzzy control platforms suggest that smart disease prevention can be made technically feasible for smaller greenhouse operations rather than only high-capital facilities. Humidity regulation, then, is not just a