

### 6.3 Development of optimized humidity management strategies

Optimized humidity management in greenhouse cucumber production should prioritize ventilation-led control while integrating forecasting and disease thresholds. In a greenhouse case study on downy mildew, adding three ventilation openings reduced infection percentage and disease severity by 95.8% and 70%, respectively, and increased total fruit production relative to the regular greenhouse, indicating that relatively simple structural ventilation can serve as an effective non-chemical suppression strategy (Khudayer1 and Ahmed, 2025). Broader greenhouse engineering evidence supports this approach: ventilation is the most common dehumidification method because of its simple infrastructure, and the central operational goal is to prevent condensation on plant surfaces while keeping operating costs acceptable for growers.

A more advanced strategy is to combine temperature-relative humidity control with predictive analytics so that dehumidification is activated before long humid periods produce persistent leaf wetness or disease onset. Dehumidification modeling recommends integrated T-RH control rather than humidity control alone, and in cold regions suggests ventilation as the main control method, supplemented by mechanical dehumidification when ambient humidity is high or heating costs are limiting. On the disease side, greenhouse prediction studies show that environmental time-series data can forecast downy mildew occurrence with strong performance, and coupled climate-disease models have matched first field observation after early warnings, supporting a management framework in which ventilation, dehumidification, and monitoring are triggered by forecasted risk rather than calendar schedules (Liu et al., 2022).

## 7 Challenges and Future Perspectives

### 7.1 Limitations in current humidity-based disease management

Humidity control remains necessary in greenhouse cucumber disease suppression, but it is not sufficient because disease risk is shaped by a broader microclimatic system that includes temperature, vapor pressure deficit, light, host susceptibility, and pathogen-specific biology (Khudhair and Aljarah, 2023). This matters in cucumber because high relative humidity strongly favors fungal diseases such as downy mildew, yet humidity thresholds alone do not capture the full epidemiological variability across greenhouse conditions (Fanourakis et al., 2026).

A second limitation is that humidity-based management is often operationally fragile because greenhouse climate can shift abruptly under routine human actions or external weather changes, which reduces the stability of environmental measurements and weakens disease prediction reliability (Liu et al., 2022). Even where ventilation lowers downy mildew infection substantially, successful control still depends on timely implementation and coordinated regulation of temperature and humidity rather than ventilation as an isolated intervention (Khudhair and Aljarah, 2023).

### 7.2 Integration of artificial intelligence and precision agriculture

The next step is to embed humidity management within AI-enabled forecasting systems that combine sensor networks, time-series learning, and greenhouse decision support. In cucumber downy mildew, long short-term memory models have shown strong performance for forecasting greenhouse environmental variables and subsequent disease occurrence, which supports earlier intervention than symptom-based control (Liu et al., 2022). More broadly, AI, IoT, and machine learning are increasingly positioned as core tools for proactive disease forecasting and precision crop management under variable environmental conditions (Delfani et al., 2024).

The main constraint is not proof of concept but deployment quality. Current systems still face problems with data availability, validation, transparency, and real-world usability, while greenhouse sensors can suffer from communication interference, environmental noise, and mismatch between training conditions and commercial conditions (Delfani et al., 2024). Even so, the trajectory is promising because machine-learning models can predict greenhouse humidity with high accuracy, and future cucumber systems can extend from binary outbreak alerts toward severity prediction and dynamic visual decision platforms (Liu et al., 2022; Melal et al., 2024).