

pathogenic activity commonly clusters within 15°C-20°C and 80%-100% relative humidity, emphasizing that humidity control influences a broad disease complex rather than only one pathogen.

## 4 Influence of Humidity Control Strategies on Disease Prevention and Crop Health

### 4.1 Ventilation and airflow regulation for disease suppression

Ventilation is the most direct humidity-control strategy for suppressing cucumber diseases in protected cultivation because it reduces leaf-surface moisture and shortens periods of pathogen-favorable saturation. Greenhouse evidence shows that relative humidity above 90% promotes cucumber downy mildew, whereas keeping humidity below 89% protects plants, and ventilating greenhouses during early infection can reduce infection percentage by 95.8% and disease severity by 70% (Khudhair and Aljarah, 2023). This aligns with broader greenhouse epidemiology showing that cucumber is especially vulnerable to fungi favored by high relative humidity, and that adaptive climate regulation is a central preventive strategy rather than a secondary management step (Fanourakis et al., 2026). Airflow design matters as much as simply opening vents, because ventilation configuration influences both cooling and pathogen dispersal pathways. CFD-based greenhouse simulations showed that ventilation mode determined how *Corynespora cassiicola* spores moved through cucumber houses, and a hybrid ventilation strategy alternating full and bottom openings balanced cooling with pathogen containment by blocking aerial spread routes. At the production scale, adding mechanical ventilation and internal air circulation to a traditional high tunnel improved heat and humidity uniformity, and the ventilated house achieved markedly better cucumber growth and a 126% higher total yield than natural ventilation alone.

The disease-suppression effect of ventilation also appears under different greenhouse designs and climates. In a semi-closed greenhouse, relative humidity was maintained below 95% with nighttime air circulation, and fungal diseases were largely absent, particularly downy mildew, while slight positive pressure also helped block airborne pathogens and pests. Similarly, in Mediterranean greenhouses, combining a double-roof system with increased natural ventilation consistently lowered disease severity for cucumber powdery mildew, downy mildew, and gummy stem blight compared with the control sector. Ventilation can also reduce dependence on chemical control while improving production outcomes. A greenhouse with three ventilation openings produced 3000 kg of cucumber versus 1800 kg in a regular house, and the same study concluded that ventilation at disease onset functioned as a natural control strategy for downy mildew. This fits evidence from Japanese greenhouse cucumber production, where humid closed-house cultivation is used to promote growth before noon, but the same practice also promotes plant diseases, illustrating the tradeoff between moisture retention for vigor and disease suppression through airflow.

### 4.2 Irrigation management and humidity regulation

Irrigation management affects disease prevention partly by regulating how much water enters both the root zone and the greenhouse air. In greenhouse cucumber, full irrigation without disease produced the best gas-exchange performance, while downy mildew infection reduced photosynthesis, transpiration, and stomatal conductance, and additional irrigation deficits further depressed growth and leaf area (Wang et al., 2024). A similar interaction was reported for powdery mildew, where nutrient-solution deficits combined with disease sharply reduced plant height, stem diameter, and leaf area, indicating that water stress and pathogen stress reinforce each other rather than acting independently. Well-calibrated irrigation can therefore support crop health by avoiding both excessive humidity generation and plant weakening from water deficit. A cucumber transpiration model developed for semi-closed greenhouses was proposed as a tool to optimize irrigation and greenhouse relative humidity control, because reducing overestimated transpiration and irrigation lowers unnecessary water input into the air. Complementing this, optimization experiments across air temperatures found that the best irrigation amount for integrated cucumber growth typically stayed close to crop evapotranspiration demand, with optimal ranges shifting from 87%-91% ET<sub>c</sub> at cooler temperatures to 107%-114% ET<sub>c</sub> at the hottest range.

Irrigation strategy also interacts with greenhouse structure and cooling regime. In hot arid regions, a naturally ventilated polyhouse combined with normal irrigation at 100% ET gave the most reliable commercial performance, whereas even moderate deficit irrigation caused significant yield losses across structures. Under