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Influence of Humidity Control on Disease Occurrence in Cucumber Production

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Abstract Humidity management is a critical environmental factor influencing disease occurrence, crop health, and productivity in cucumber (*Cucumis sativus* L.) production systems. Excessive humidity, prolonged leaf wetness, and unstable microclimatic conditions create favorable environments for pathogen survival, spore germination, and infection, resulting in severe losses caused by fungal and bacterial diseases. With the rapid development of protected cultivation and precision agriculture technologies, humidity regulation has become an important strategy for sustainable disease prevention and improved crop performance. This review systematically summarizes the mechanisms underlying humidity-mediated disease development in cucumber production, focusing on the interactions among environmental humidity, plant physiological responses, and pathogen infection processes. The effects of humidity conditions on major cucumber diseases, including powdery mildew, downy mildew, gray mold, and bacterial diseases, are discussed from ecological and physiological perspectives. Furthermore, current humidity control approaches, such as ventilation management, irrigation optimization, dehumidification technologies, and integrated greenhouse climate regulation, are evaluated for their effectiveness in reducing disease risks. Advances in computational modeling, machine learning-based disease prediction, and sensor-driven environmental control systems are also highlighted as emerging tools for real-time disease forecasting and precision management. A case study framework is presented to demonstrate how humidity monitoring, disease assessment, and predictive modeling can be integrated to optimize greenhouse cucumber production. Despite significant progress, challenges remain in accurately defining humidity thresholds across cultivars and production environments, improving model interpretability, and integrating multi-factor environmental regulation strategies. Future research combining artificial intelligence, digital agriculture, and plant-microbe interaction studies will provide new opportunities for developing sustainable and intelligent disease management systems in cucumber production.

Keywords Humidity control; Cucumber production; Disease occurrence; Greenhouse microclimate management; Precision agriculture

1 Introduction

Cucumber is a major greenhouse vegetable crop, and its productivity depends heavily on precise microclimate regulation in protected cultivation systems. Greenhouse production enables high yields through environmental control, but the same stable environment can also favor pathogen establishment when humidity, temperature, and ventilation are not well managed (Fanourakis et al., 2026). This dual role makes humidity management especially important in cucumber production, where crop performance is shaped not only by resource-use efficiency and yield optimization but also by the need to suppress disease-conducive conditions. Long-term greenhouse observations further show that cucumber yield is significantly associated with environmental variables including relative humidity, with average nighttime humidity emerging as a meaningful correlate of production outcomes in semi-closed systems. Humidity control is therefore not a secondary engineering detail, but a central production factor linking plant growth, fruit yield, and crop health. In practical terms, managing humidity affects leaf wetness duration, canopy moisture, and air exchange, all of which influence whether greenhouse cucumber systems operate near optimal physiological conditions or drift toward environments that increase production risk.

The importance of humidity management becomes even clearer when considering disease epidemiology in cucumber crops. Across greenhouse vegetables, warm and humid conditions consistently promote fungal and

bacterial pathogens, and cucumber is particularly characterized by foliar fungal diseases favored by high relative humidity (Fanourakis et al., 2026). In cucumber specifically, downy mildew remains one of the most destructive diseases, and its development is tightly linked to moisture availability. Experimental work has shown that *Pseudoperonospora cubensis* forms abundant sporangia when infected tissues are wetted or exposed to 100% relative humidity, whereas only a few sporangia are produced at 90% relative humidity. These findings indicate that relatively small differences in humidity can determine whether pathogen reproduction is strongly amplified or constrained. More broadly, humidity interacts with temperature to regulate infection timing, sporulation intensity, and epidemic development, which explains why disease outbreaks in cucumber houses often occur rapidly once favorable microclimatic thresholds are reached. Because greenhouse cultivation often involves dense canopies and restricted air movement, unmanaged humidity can quickly create persistent infection windows that are difficult to reverse after symptoms appear.

Research over the last decade has strengthened the case for humidity-based disease prevention by identifying actionable thresholds and revealing similar moisture dependence across multiple cucumber pathogens. In greenhouse trials on cucumber downy mildew, relative humidity above 90% favored disease development, whereas keeping humidity below 89% protected plants from infection; under early infection, ventilation-based humidity reduction decreased infection percentage by 95.8% and disease severity by 70% (Khudhair and Aljarah, 2023). Comparable patterns have also been reported for cucumber target leaf spot caused by *Corynespora cassiicola*, for which moisture had a stronger effect than temperature on sporulation on living plants, maximum spore production occurred at 100% relative humidity, and only a few spores formed at 75% relative humidity (Zhao et al., 2022). Together, these studies suggest that humidity regulation is not relevant to a single disease only, but is a broader mechanism for suppressing inoculum production and secondary spread in cucumber production systems. At the same time, reliance on fungicides alone is increasingly problematic because repeated use raises concerns about residues, environmental contamination, and resistance development, which further motivates non-chemical strategies centered on environmental control (Abdelfatah et al., 2025).

Against this background, current research is moving from descriptive observation toward predictive and automated humidity management. Forecasting models for cucumber downy mildew have already been proposed to reduce epidemic risk by combining records of pathogen presence with temperature and relative humidity in greenhouse and field settings, highlighting the value of climate-informed decision support. At the production level, modern protected cultivation is also beginning to use sensor-based and AI-assisted control systems, with remotely managed greenhouse compartments showing that artificial intelligence can perform well in cucumber climate regulation, and IoT-based microclimate systems maintaining more favorable humidity conditions while increasing yield by 41.6% per vine under protected cultivation. Therefore, the objective of this paper is to examine how humidity control influences disease occurrence in cucumber production by integrating evidence on microclimate regulation, humidity-pathogen interactions, and emerging predictive control strategies. Particular attention is given to the role of relative humidity in shaping disease-conducive environments, to the potential of ventilation and automated monitoring as preventive tools, and to the broader significance of humidity management for sustainable cucumber health and quality control.

2 Humidity Characteristics and Microclimatic Regulation in Cucumber Production Systems

2.1 Sources and dynamics of humidity variation in cultivation environments

Humidity variation in cucumber production systems arises from the interaction of greenhouse enclosure, crop transpiration, soil or substrate evaporation, and external weather forcing. Protected cultivation stabilizes the environment for year-round production, but that same enclosed microclimate can also retain moisture and increase the probability of pathogen-favorable conditions (Fanourakis et al., 2026). In cucumber houses specifically, total radiation, air temperature, and humidity show strong seasonal variation, and average nighttime relative humidity is significantly associated with yield, indicating that humidity is not static but part of a continuously shifting greenhouse climate system. The temporal pattern of humidity is especially important because many cucumber diseases respond to short periods of high moisture rather than daily averages alone. For downy mildew, infection

and sporulation depend on temperature and moisture together, and lesions produce abundant sporangia when leaves are wetted or exposed to 100% relative humidity, but only a few at 90% relative humidity. Field-oriented greenhouse observations similarly show that downy mildew initiation is favored by relative humidity above 90% for several hours, with disease increasing under humid, cooler conditions and declining in dry-hot periods (Khudhair and Aljarah, 2023).

Humidity dynamics also differ among disease types because the relevant moisture source may be aerial or soil-based. Greenhouse reviews indicate that cucumber disease pressure is dominated by phytopathogenic fungi favored by high relative humidity as well as soilborne pathogens, showing that both canopy moisture and root-zone wetness contribute to disease risk (Fanourakis et al., 2026). This distinction is supported by *Fusarium* wilt experiments, where soil moisture played an important role in disease initiation and development, with maximum incidence observed at 45% soil moisture and no disease at 15% soil moisture. Crop architecture and air exchange further shape local humidity accumulation within cucumber houses. Greenhouses with elevated humidity and restricted airflow create optimal conditions for diverse fungal pathogens, including mixed infections involving *Fusarium*, *Botrytis*, *Alternaria*, and *Cladosporium*, which suggests that poor ventilation can intensify both single-pathogen and multi-pathogen problems. Broader greenhouse monitoring likewise shows that cucumber diseases under covered production are strongly influenced by temperature and humidity, with many pathogens remaining active within roughly 15°C-20°C and 80%-100% relative humidity.

2.2 Effects of humidity on cucumber growth and physiological processes

Humidity affects cucumber growth not only through disease pressure but also through direct regulation of photosynthesis, water relations, and biomass accumulation. Under greenhouse conditions, environmental management is important for improving resource-use efficiency and yield, and long-term modeling shows that nighttime relative humidity has a significant relationship with cucumber production. However, high humidity becomes physiologically harmful when combined with low temperature, as young cucumber plants exposed to low temperature plus 95% humidity showed reduced shoot and root biomass, lower photosynthetic rate and chlorophyll fluorescence, and greater oxidative stress (Amin et al., 2024). Recent physiological work indicates that the effect of high humidity depends on the broader stress context and developmental stage. In cucumber seedlings, combined low temperature and high relative humidity reduced chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids, while also impairing chlorophyll biosynthesis and increasing oxidative damage. At the same time, older plants at the six-leaf stage showed greater tolerance than plants at the two- and four-leaf stages, suggesting that humidity-related stress sensitivity is developmentally regulated rather than uniform across crop stages (Amin et al., 2024).

Humidity also shapes disease severity in ways that feed back onto cucumber growth and yield. Downy mildew can spread rapidly under favorable heat and humidity and may cause severe productivity and quality losses, making humidity control relevant to both plant health and harvest performance (Abdelfatah et al., 2025). Seasonal surveys likewise found that increased relative humidity combined with low or moderate temperature increased downy mildew severity, and these disease changes were accompanied by differences in fresh weight, dry weight, fruit number, and yield. Not all cucumber pathogens respond to humidity in the same way, but moisture remains a core physiological and epidemiological driver. For target leaf spot caused by *Corynespora cassicola*, maximum spore production occurred at 100% relative humidity, and moisture explained a large share of spore-size variation, which matters because larger spores were more virulent (Zhao et al., 2022). By contrast, powdery mildew showed best development under intermediate humidity ranges of 50-70%, whereas very low relative humidity suppressed germination and very high relative humidity favored germination but limited continued lesion growth, underscoring that humidity management must consider pathogen-specific responses rather than assuming a single threshold for all diseases (Saad and Khalifa, 2021).

2.3 Environmental monitoring and humidity control technologies

Because humidity fluctuates rapidly and disease responses can be threshold-based, effective cucumber production increasingly depends on continuous monitoring and active control technologies. Climate-informed decision

systems are emerging in greenhouse horticulture, and reviews emphasize that adaptive climate regulation combined with environmental sensing offers a preventive pathway for pest and disease management (Fanourakis et al., 2026). Forecasting studies on cucumber downy mildew further show that recording temperature and relative humidity can support epidemic prediction and reduce disease risk, input costs, and fungicide residues when linked to timely intervention. Ventilation remains one of the most direct humidity-control methods in cucumber houses. In greenhouse trials, relative humidity above 90% promoted downy mildew, whereas keeping humidity below 89% was protective, and adding ventilation openings reduced infection percentage by 95.8% and disease severity by 70% under early infection conditions (Khudhair and Aljarah, 2023). This practical effect is consistent with the broader principle that microclimatic stability determines infection probability and host susceptibility, so active air exchange can disrupt disease-conducive moisture regimes before epidemics intensify (Fanourakis et al., 2026).

More advanced systems combine sensors with automated actuators to maintain target humidity conditions. In small- and medium-scale protected houses, IoT-based systems used digital temperature and humidity sensors together with foggers and exhaust fans to control relative humidity, maintained more favorable daytime humidity conditions, and increased cucumber yield by 41.6% per vine compared with conventional management. At the high-technology end, AI-controlled greenhouse compartments for cucumber production integrated ventilation, screens, heating, fogging, CO₂ supply, irrigation, and continuous sensing, and overall AI performed well in greenhouse climate control. Humidity management technologies can also be integrated with environmentally safer disease suppression methods. For diseases strongly affected by humidity such as cucumber downy mildew, thermal fogging with chlorine dioxide achieved 80.9% control efficacy and outperformed conventional diluted spray approaches, suggesting that delivery methods interacting with greenhouse moisture conditions can materially change control success (Kim et al., 2021). Older greenhouse disease-control work likewise showed that successful biological control depends on abiotic conditions such as vapor pressure deficit and humidity, indicating that future cucumber protection systems will work best when humidity regulation, monitoring, and biological or low-residue interventions are designed together rather than separately.

3 Mechanisms Linking Humidity Conditions to Cucumber Disease Occurrence

3.1 Effects of humidity on pathogen survival and infection processes

Humidity influences cucumber disease occurrence first by controlling whether propagules can survive, germinate, and complete infection on plant surfaces. In *Pseudoperonospora cubensis*, abundant sporangia are produced when infected tissue is wetted or held at 100% relative humidity, whereas only a few sporangia form at 90% relative humidity, showing that small increases near saturation can sharply increase inoculum pressure. Infection also depends on the interaction between moisture duration and temperature, with minimum wetness requirements dropping to about 1 h at 20°C-25°C but becoming much longer at cooler or hotter temperatures, which explains why short humid periods can still trigger outbreaks under favorable thermal conditions. Humidity also affects the later stages of pathogen release and dispersal rather than only germination. For cucumber target leaf spot, alternating wet and dry conditions coupled with wind were necessary for spore discharge and spread to neighboring plants, while constant high or low humidity without wind did not produce infection in healthy plants. A similar principle has been shown for angular leaf spot, where high relative humidity increased the release amount, survival time, and infectivity of *Pseudomonas amygdali* pv. *lachrymans* aerosols, with the highest survival recorded at 18°C and 95% relative humidity (Chai et al., 2023).

Not all cucumber pathogens respond to humidity in the same way, but most show humidity-sensitive windows for successful infection. Powdery mildew conidia germinated poorly at 20-40% relative humidity, developed best at intermediate humidity of 50%-70%, and showed limited continued lesion growth under prolonged 80%-90% relative humidity, indicating a nonlinear moisture response rather than a simple “more humidity, more disease” pattern (Saad and Khalifa, 2021). By contrast, *Didymella bryoniae* infection under experimental conditions depended strongly on surface wetness duration, which was a more important determinant of infection than temperature once leaves and petioles were exposed to saturated humidity. Humidity effects also extend belowground, where soil water status governs survival and infection by vascular wilt pathogens. In cucumber

Fusarium wilt, disease incidence was highest at 45% soil moisture and absent at 15% soil moisture, indicating that pathogen activity and host invasion require an intermediate-to-high soil moisture range rather than dry substrates (Figure 1). Fruit pathogens show a similarly broad but humidity-responsive capacity for infection, because *Phytophthora capsici* formed lesions across all tested relative humidities, yet water-soaking and pathogen growth increased as humidity increased, demonstrating that elevated atmospheric moisture can intensify symptom expansion even when infection is already possible.

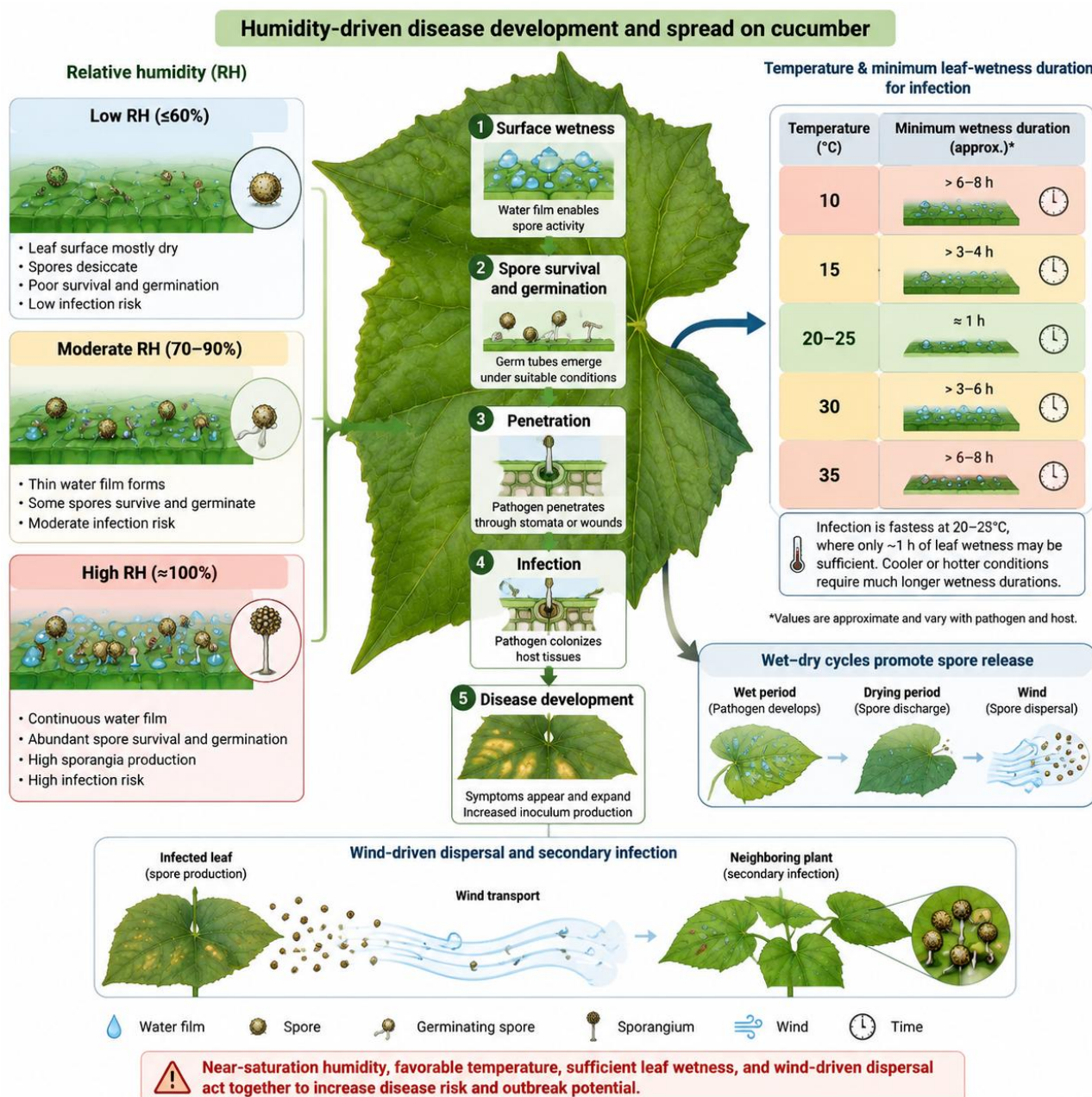


Figure 1 Conceptual framework illustrating the effects of relative humidity, leaf wetness duration, temperature, and wind-driven dispersal on cucumber pathogen survival, germination, infection, and disease development

3.2 Humidity-mediated changes in plant-pathogen interactions

Humidity conditions modify plant-pathogen interactions not only by favoring the pathogen, but also by changing cucumber physiology and defense capacity. Under low temperature plus 95% humidity, young cucumber plants showed reduced photosynthesis, chlorophyll content, and biomass together with increased oxidative stress markers, indicating that humid stress environments can weaken host performance at the same time that they favor disease development. Later work similarly showed that low temperature and high relative humidity reduced

chlorophyll pigments and precursor levels while increasing oxidative damage, which provides a physiological basis for greater vulnerability under prolonged humid stress (Amin et al., 2024). These humidity-driven physiological changes are not uniform across development, which means disease susceptibility can shift with plant stage. Seedlings at earlier leaf stages were more sensitive to high-temperature high-humidity stress, with larger reductions in biomass, net photosynthesis, and photosynthetic electron transfer than older seedlings, while four-leaf plants showed the greatest tolerance (Wang et al., 2024). Comparable stage dependence was observed under low-temperature high-humidity stress, where six-leaf plants were more tolerant than two- and four-leaf plants, suggesting that humidity-mediated disease risk partly reflects the developmental capacity of the host to maintain antioxidant and hormonal balance.

Humidity-mediated disease outcomes also depend on how effectively cucumber defense pathways are activated after pathogen challenge. In downy mildew resistance, increased lignin and hydrogen peroxide accumulation were associated with reduced germination and extension of *P. cubensis*, and transcriptome profiling identified defense functions involving pathogen recognition, signal transduction, reactive oxygen species, and transcriptional regulation (Gao et al., 2021). In gray mold, the resistant cucumber genotype showed shorter hyphae and lower spore germination than the susceptible mutant, together with stronger activation of redox, jasmonic acid, and ethylene signaling pathways, indicating that host biochemical responsiveness can counteract pathogen establishment even under favorable greenhouse humidity (Yang et al., 2020). At the greenhouse scale, humidity therefore acts as a regulator of both infection probability and host susceptibility. Greenhouse syntheses indicate that microclimatic stability determines infection probability and host vulnerability, while warm humid conditions generally promote fungal and bacterial pathogens in cucumber systems (Fanourakis et al., 2026). This interaction becomes agronomically important because greenhouse environments with elevated humidity and restricted airflow support mixed infections by *Fusarium*, *Botrytis*, *Alternaria*, and *Cladosporium*, so humidity stress can coincide with exposure to multiple pathogens rather than a single disease agent.

3.3 Major cucumber diseases associated with humidity conditions

Among humidity-associated cucumber diseases, downy mildew remains the clearest example of a pathogen tightly governed by moist air and leaf wetness. Greenhouse observations found that relative humidity above 90% was sufficient to trigger downy mildew development, whereas keeping humidity below 89% protected plants and sharply reduced infection and severity under early epidemic conditions (Khudhair and Aljarah, 2023). This strong moisture dependence is consistent with the infection biology of *P. cubensis*, whose sporangia germinate in free water and penetrate through stomata after zoospore release, making saturated leaf-surface conditions central to epidemic onset. Field and survey data also show that downy mildew severity rises under cooler, more humid conditions. Increased relative humidity together with low or moderate temperature increased disease severity in Egyptian production environments, and disease initiation elsewhere has been linked to high night relative humidity above 93% combined with prolonged night leaf wetness. The importance of downy mildew in cucumber production is amplified by its economic impact, because it is among the most destructive foliar diseases of cucurbits and has caused annual yield losses of up to 80% in European greenhouse and field production.

Other major cucumber diseases also show strong but distinct humidity relationships. Target leaf spot caused by *Corynespora cassiicola* produced the most spores at 100% relative humidity, and moisture explained most of the variation in spore size, which mattered because larger spores were more virulent than small spores (Zhao et al., 2022). Gray mold caused by *Botrytis cinerea* is similarly favored by greenhouse conditions of high humidity and 20°C-30°C, helping explain its persistence in continuously cropped protected systems (Yang et al., 2020). Humidity associations extend to powdery mildew, *Fusarium* wilt, and fruit rots, showing that cucumber disease risk spans both foliar and root or fruit pathogens. Powdery mildew is one of the major fungal diseases of cucumber and can recur annually, while its epidemic development is optimized at intermediate humidity rather than saturation, distinguishing it from downy mildew and target leaf spot (Saad and Khalifa, 2021). *Fusarium* wilt becomes more severe in warm, moist soil, and greenhouse disease monitoring has further shown that cucumber

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_c at cooler temperatures to 107%-114% ET_c 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

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

greenhouse disease management (Lee and Yun, 2023). A central variable in these models is leaf wetness duration, because humidity affects disease not only through bulk air moisture but through condensation and persistence of wet surfaces. Early warning work for cucumber downy mildew treated leaf wetness duration as a key variable and combined leaf-wetness sensing with a relative-humidity threshold approach to create a practical estimation method when direct monitoring was difficult. Later greenhouse studies confirmed that leaf wetness duration is an important disease-model input related to infection and pathogen development, and showed that a back-propagation neural network estimated it more accurately than a simple relative-humidity model, reaching accuracies of 0.90 and 0.92 in two greenhouses (Liu et al., 2020).

Recent modeling has also moved from point estimates toward spatially explicit representations of humidity-related infection conditions inside greenhouses. A CFD transient model showed that canopy condensation caused by high humidity is a major cause of leaf wetness duration formation and could estimate the temporal and spatial distribution of wetness across cucumber canopies with good agreement to observations. Spatial heterogeneity studies likewise found that leaf wetness duration varied systematically within solar greenhouses, with longer wetness in the south and east zones and on rainy days, patterns that are closely related to the occurrence of high-humidity cucumber diseases (Liu et al., 2020). Another advance is the coupling of climate prediction with disease-process models so that warning systems can anticipate risk before unfavorable humidity conditions fully develop. A model-based methodology combined a mechanistic greenhouse climate model with a disease model, first predicting indoor climate 72 hours ahead and then using that forecast to detect downy mildew occurrence in advance. This integration is strengthened by machine-learning humidity forecasting, where a stacking ensemble for greenhouse indoor humidity achieved an R^2 of 0.96515 and high predictive precision, showing that accurate humidity prediction itself is now feasible enough to support downstream disease-risk models (Melal et al., 2024).

5.2 Machine learning prediction of disease risk

Machine learning has improved cucumber disease-risk prediction by exploiting the sequential structure of greenhouse environmental data rather than relying only on static thresholds. In cucumber downy mildew, an LSTM neural network was built from IoT-acquired time-series data on temperature, relative humidity, soil temperature, and solar radiation, and the resulting disease prediction model achieved 90% accuracy, 94% precision, 89% recall, and an AUC of 90.15%. The advantage of this approach is that classic machine-learning methods often handle long-term sequence dependence poorly, whereas LSTM better captures previous environmental feature information that is closely tied to disease onset (Liu et al., 2022). Prediction performance has improved further when environmental data are fused with direct disease indicators. A CNN-LSTM model for cucumber downy mildew integrated greenhouse and outdoor environmental records with airborne spore counts and observed diseased leaf area, reaching an R^2 of 0.9127 with low mean absolute and root mean square errors. The same study argued that future real-time prediction should integrate online spore detection with environmental big data, indicating that disease forecasting is moving toward multimodal monitoring rather than climate-only inference (Wang et al., 2024).

Broader deep-learning evidence suggests that humidity-based risk prediction can generalize beyond a single crop or pathogen when sufficient environmental data are available. A recent sequential deep-learning framework used previous growth-environment information, including air temperature, relative humidity, dew point, and CO_2 concentration, to predict crop disease risk and achieved an average AUROC of 0.917 across multiple crops and facilities. This wider applicability is plausible because environmental data are comparatively easy to collect in facility farms, and the authors argue that such data-driven learning frameworks could be used broadly for disease and pest prevention in controlled agriculture (Lee and Yun, 2023). At the same time, current machine-learning prediction still depends on stable management conditions and high-quality sensor streams. In the cucumber LSTM study, abrupt human-driven changes in greenhouse climate could disrupt data acquisition and degrade prediction accuracy, so venting schedules and field operations had to remain orderly for reliable modeling (Liu et al., 2022). Related greenhouse IoT reviews similarly note that high-detail monitoring in space and time is what enables more

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 (Benyezze 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.

6.2 Effects of different humidity regimes on disease development

Different humidity regimes produce clear differences in cucumber disease development, but the response depends on the pathogen and its interaction with temperature and leaf wetness. For cucumber downy mildew, sporangial germination and infection are favored by very high humidity, with infection commonly requiring relative humidity above 90% for several hours, and greenhouse observations showed that maintaining humidity below about 89% sharply reduced disease incidence and severity (Khudhair and Aljarah, 2023). Controlled-environment work supports this threshold behavior: downy mildew lesions produced abundant sporangia under leaf wetness or 100% RH, but only a few at 90% RH, and the minimum wetness duration needed for infection varied strongly with temperature.

Other cucumber pathogens show related but not identical humidity responses, which means that humidity targets should be set for multi-disease suppression rather than a single disease alone. For target leaf spot, maximum spore production occurred at 100% RH and moisture explained most of the variation in spore size, while larger spores were more virulent, indicating that saturated air not only increases inoculum quantity but can also increase its aggressiveness (Zhao et al., 2022). For powdery mildew, by contrast, intermediate RH of 50%-70% optimized disease development, while low RH of 20%-40% reduced lesion growth and short daily exposure to 35°C suppressed disease development by 70%-92%, showing that not all foliar pathogens peak under the same humidity regime (Figure 2) (Saad and Khalifa, 2021).

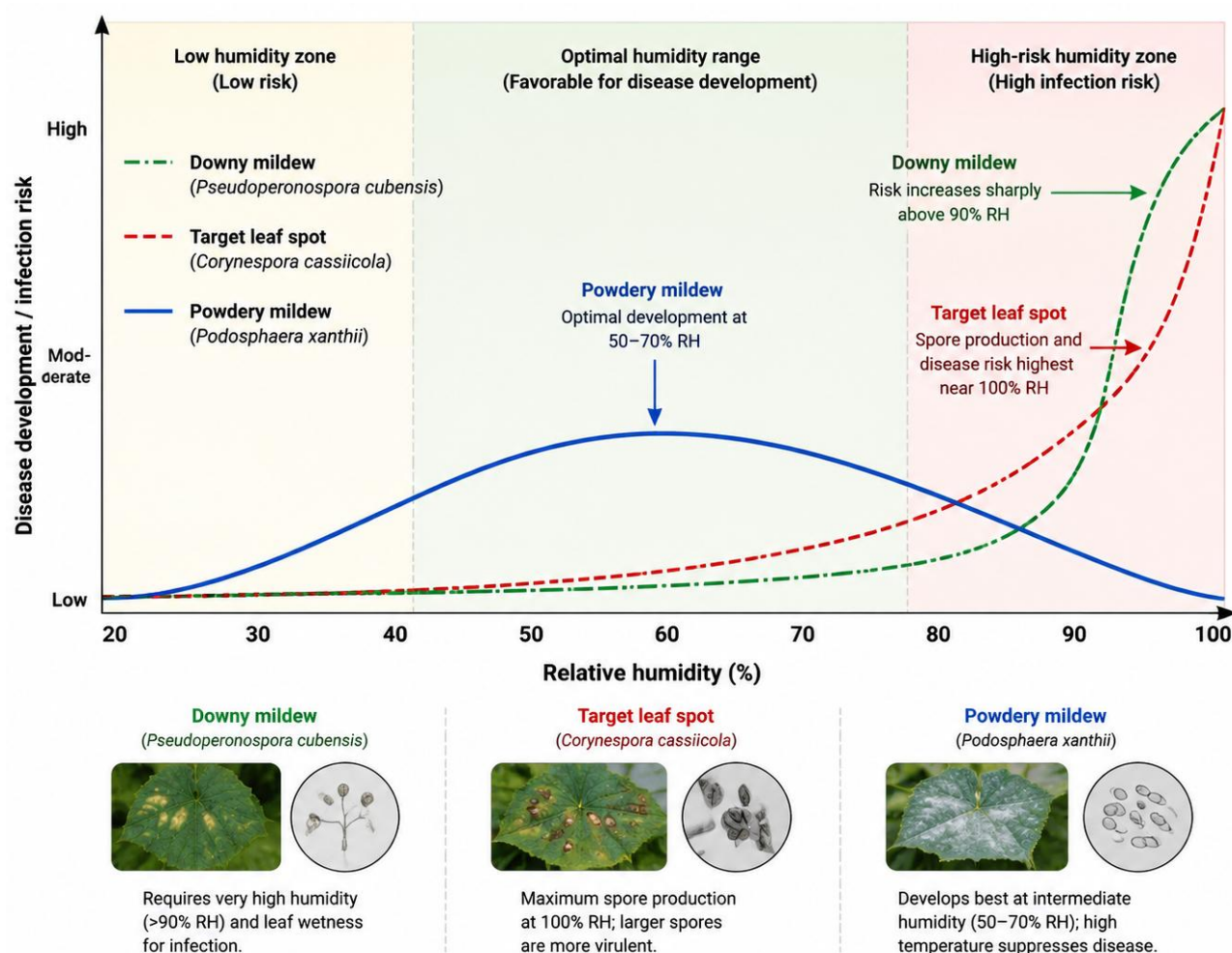


Figure 2 Conceptual humidity-response patterns of major cucumber foliar diseases. Different pathogens exhibit distinct humidity-sensitive infection windows, with downy mildew and target leaf spot showing increased disease risk under near-saturated humidity, whereas powdery mildew develops optimally under intermediate relative humidity conditions

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).

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

disease-control measure in cucumber production. It is the environmental backbone of a broader precision and smart-management strategy that can reduce disease, improve yield, and support more sustainable greenhouse production.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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