

Microclimate-Pathogen Interactions: Critical Drivers of Crop Disease Dynamics

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Abstract

Microclimatic factors significantly influence the development and spread of plant diseases. Variations in temperature, rainfall, humidity, light, wind and leaf wetness create microhabitats that affect pathogen infection, reproduction and dispersal. Factors such as canopy structure, plant spacing and management practices further modify these conditions, shaping disease intensity and distribution. A thorough understanding of microclimate-pathogen interactions is crucial for improving disease forecasting models and developing sustainable management approaches that minimize crop losses and promote plant health under variable environmental conditions.

Keywords: Microclimate, Plant disease, Pathogen-host interactions, Canopy microenvironment, Disease management, Epidemics

Introduction

Microclimate refers to the set of climatic conditions that exist within a small, localized area such as inside a crop canopy, at the soil surface or beneath plant foliage which may differ notably from the broader regional climate. Important microclimatic variables include temperature, humidity, light intensity, wind and moisture, all of which exert strong influences on plant growth, pathogen activity and pest behaviour. Within plant canopies, these microclimatic variations can create zones of elevated humidity or restricted airflow, which affect transpiration rates, leaf wetness and plant vulnerability to diseases. Structural characteristics such as canopy architecture, planting density and spatial arrangement further shape these conditions by influencing light penetration, ventilation and moisture retention.

Plant disease development is driven by the interplay between a susceptible host, a virulent pathogen and the surrounding microclimate. Shifts in microclimate directly or indirectly affect both the host and pathogen, often determining the emergence and intensity of diseases.

Among the key microclimatic factors, temperature, relative humidity, leaf wetness duration and canopy structure play dominant roles. Optimal temperature favours pathogen germination, infection and survival, while high humidity and prolonged leaf wetness enhance fungal and bacterial proliferation. Dense canopies trap moisture, promoting foliar diseases like rusts and mildews, whereas good airflow reduces humidity and infection risk. Wind, rainfall and solar radiation also influence spore dispersal and canopy drying dynamics. The impact of the weather on disease occurrence or development is not same for all the crops or diseases. It is also important to note that the weather is highly variable. Hence, better understanding about the different weather variables and its interaction with disease is vital in forewarning the disease occurrence and spread.

Drivers of plant disease occurrence and spread

Environmental conditions play a crucial role in influencing plant disease development. Temperature, humidity, rainfall and soil moisture, along with pathogen traits such as virulence, inoculum potential and dispersal ability, host-related factors including resistance, age and overall health and management practices like crop rotation, irrigation and fertilization collectively influence the occurrence and severity of plant diseases. The interaction among these factors determines the disease occurrence, severity and spread. The following are some of the microclimatic variables and its interaction with the diseases.

Temperature

Temperature is a major determinant of plant growth, physiological activity and disease development. It influences key stages of pathogen life cycles, including infection, incubation, sporulation and dispersal, while also affecting host resistance. Each host-pathogen system operates within an optimal temperature range that promotes infection and disease progression, whereas conditions outside this range restrict pathogen metabolism, survival and transmission. Elevated temperatures can accelerate plant metabolism and growth but may also suppress defense-related proteins, increasing susceptibility. Conversely, moderate warming can enhance protective mechanisms such as systemic acquired resistance and heat-shock protein expression.

Temperature variations within the canopy, shaped by radiation, transpiration and plant structure, create localized environments that strongly influence pathogen activity and epidemic behaviour. Most fungal and viral pathogens show optimal infection between 25-30°C (Table 1), whereas, bacterial pathogens show optimal infection between 25-35 °C (Table 2). Cooler, humid canopy zones often serve as microrefugia, which are small, localized zones that maintain favourable microclimatic conditions enabling pathogens to persist despite broader environmental shifts such as climate warming or habitat modification. Understanding these temperature-dependent interactions is essential for improving climate-resilient crop management strategies.

Relative humidity

Relative humidity (RH) within the crop canopy is a key microclimatic factor influencing the infection cycle and epidemic dynamics of many plant pathogens. Canopy microclimate, determined by leaf density, plant architecture and airflow, often maintains higher RH and prolonged leaf wetness compared to ambient conditions. These environments favour spore germination, infection initiation and sporulation in numerous fungal and bacterial pathogens. Diseases such as rice blast, downy mildew and leaf spot develop most rapidly under sustained RH above 90% coupled with optimal temperatures, while low RH reduces pathogen survival and infection efficiency. Extended humidity periods decrease the vapour pressure deficit, maintaining water films on leaf surfaces essential for spore adhesion, germ-tube emergence and appressorium formation. In bacterial pathogens, high RH fosters virulence by supporting water-saturated microenvironments within leaf tissues that enhance bacterial proliferation and dissemination. Some bacterial effectors also exhibit optimal activity at high humidity, suppressing plant defenses such as stomatal closure and immune responses.

Elevated canopy humidity not only promotes primary infection but also enhances pathogen reproduction and secondary spread, thereby accelerating disease epidemics. Dense, shaded and poorly ventilated canopies tend to retain moisture, forming microhabitats favourable for pathogen persistence and sporulation. In contrast, open or well-ventilated canopies, where leaf surfaces dry rapidly, restrict disease development and transmission. The optimal RH range for most plant pathogens generally lies between 80% and 95%, though this varies with pathogen species and host type. Integrated management practices such as wider plant spacing,

strategic pruning and optimised irrigation help lower canopy RH and reduce infection risk. Thus, precise monitoring and regulation of canopy humidity are vital for the implementation of sustainable crop protection strategies.

Light

Light availability within the plant canopy significantly influences host-pathogen interactions and the microclimatic conditions that govern disease development. Through photoreceptors such as phytochromes and cryptochromes, light regulates defense signalling pathways involving salicylic acid (SA) and jasmonic acid (JA). Low red to far-red light ratios reduce the synthesis of defense-related secondary metabolites, weakening plant resistance, while red light can suppress certain diseases, such as powdery mildew, by inhibiting spore germination. In dense canopies, reduced light penetration creates shaded, cooler and more humid environments that maintain leaf wetness and delay surface drying, thereby enhancing pathogen establishment and survival. Limited light exposure also suppresses light-dependent defense mechanisms, including the production of phytoalexins, phenolic compounds, and reactive oxygen species, increasing plant susceptibility to fungal, bacterial and oomycete infections.

Light further influences pathogen physiology and survival. Many fungal and oomycete spores are sensitive to ultraviolet (UV) radiation, which damages DNA and inhibits germination; shaded conditions protect these propagules, supporting sporulation and epidemic spread. Pathogens such as *Agrobacterium tumefaciens* exhibit reduced motility and virulence under light exposure, while fungal photoreceptors regulate sporulation timing in response to environmental cues. Light interacts with temperature and humidity to form microclimatic niches favourable for infection, particularly in the shaded lower canopy. Consequently, agronomic practices that improve canopy light distribution such as pruning, wider spacing and cultivating open leaf architectures, can reduce pathogen survival, shorten infection windows and mitigate disease development.

Leaf wetness duration (LWD)

Leaf wetness duration (LWD) is a key microclimatic variable that plays a crucial role in the initiation and development of infections and epidemics caused by foliar pathogens. The presence of a thin layer of moisture or dew on leaf surfaces is essential for vital pathogen processes, including spore germination, appressorium formation and penetration into host tissues. Moist leaf surfaces create favourable conditions for pathogen activities such as enzymatic breakdown of plant cells, penetration and sporulation, making LWD one of the most influential environmental determinants in plant disease epidemiology. The duration and timing of leaf wetness, typically recorded in hours, have a direct impact on both infection likelihood and intensity. Many pathogens require a minimum wetness period of approximately 2–8 hours to initiate infection, while extended wetness up to 24 hours can result in more severe disease outcomes. For example, *Xanthomonas arboricola* pv. *juglandis*, the pathogen responsible for walnut bacterial blight, needs several consecutive hours of leaf wetness for successful infection, with lesion formation accelerating after 12–15 hours under favourable temperature conditions. Similarly, fungal pathogens such as *Alternaria solani* (which causes early blight in tomato and potato) and *Botrytis cinerea* (gray mold) demonstrate optimal germination and infection under prolonged leaf wetness, highlighting the critical dependence of pathogen activity on surface moisture levels.

Other microclimatic factors, including canopy architecture, relative humidity and temperature, further shape the influence of LWD. Dense or poorly aerated canopies often prolong wetness periods by reducing air

circulation and light penetration, creating favourable microhabitats for pathogen establishment and secondary inoculum production. In contrast, open canopy structures that allow for faster drying shorten the duration of wetness and consequently lower the risk of disease. A thorough understanding of these interactions is vital for effective disease control. Management strategies such as adjusting canopy structure, optimizing irrigation practices and developing cultivars with rapid leaf drying capabilities can help reduce LWD and suppress pathogen proliferation. Furthermore, incorporating LWD data into disease forecasting models can enhance prediction accuracy, enabling the timely application of cultural, chemical or biological control measures.

Wind

Wind strongly influences canopy microclimate and plays a vital role in plant disease development. By regulating the exchange of heat, moisture and gases between the canopy and atmosphere, wind affects leaf temperature, humidity and transpiration factors crucial to pathogen survival. Moderate airflow promotes leaf drying and suppresses moisture-dependent pathogens, while limited ventilation in dense canopies sustains high humidity favourable for infection. Mechanical damage caused by wind can also provide entry points for pathogens, linking air movement and canopy structure directly to disease incidence and severity.

In addition to altering microclimate, wind acts as a major agent of pathogen dispersal. It carries fungal spores, bacterial cells and virus vectors across short and long distances, often in combination with rain or dew that release and lift spores into the air. Stronger winds increase the quantity and range of inoculum spread, heightening epidemic risk. Airborne pathogens such as rust fungi and *Venturia inaequalis* rely on prevailing winds for long-distance transport, while canopy structure influences whether spores are retained locally or dispersed widely. Understanding these wind-pathogen-canopy interactions is essential for predicting disease outbreaks and improving management through better ventilation and reduced humidity.

Table 1. Optimum weather ranges for major fungal phytopathogens

Disease	Host	Causal organism	Temperature (°C)	Relative humidity (%)	Leaf wetness duration (Hours)	Wind (m/s)
Blast	Rice	<i>Pyricularia oryzae</i>	25-30	85-100	8-12	0.5
Sheath Blight	Rice	<i>Rhizoctonia solani</i>	28-32	90-100	10-14	0.5-2.0
Brown Spot	Rice	<i>Bipolaris oryzae</i>	25-30	85-95	8-12	1-1.5
Charcoal Rot	Sorghum, Soybean, Maize	<i>Macrophomina phaseolina</i>	30-35	60-70	Negligible	Negligible
Crown Rust	Oat	<i>Puccinia coronata</i>	15-25	70-85	6-10	1-4
Head Scab (Fusarium Head Blight)	Wheat, Barley	<i>Fusarium graminearum</i>	25-28	90-100	12-16	1-5
Loose Smut	Wheat, Barley	<i>Ustilago nuda, U. tritici</i>	18-24	60-85	4-6	4.5-9.5
Black Stem Rust	Wheat	<i>Puccinia graminis tritici</i>	15-30	70-80	6-8	1-4
Stem Rot	Groundnut	<i>Sclerotium rolfsii</i>	25-35	80-95	8-12	Negligible
Collar Rot	Groundnut	<i>Aspergillus niger</i>	30-34	80-95	8-12	Negligible

Wilt	Pigeonpea, Cotton, Tomato	<i>Fusarium oxysporum</i> f. sp. <i>udum</i> , <i>vasinfectum</i> , <i>lycopersici</i>	25-30	70-85	Negligible	Negligible
Rust	Coffee	<i>Hemileia vastatrix</i>	15-28	85-100	6-10	0.5-1.5
Anthraco nose	Chilli, Mango, Beans	<i>Colletotrichum gloeosporioides</i> , <i>C. lindemuthianum</i>	25-30	90-100	8-12	1-3
Ergot	Pearl Millet, Rye	<i>Claviceps fusiformis</i> , <i>C. purpurea</i>	20-28	85-100	6-12	1-3
Powdery Mildew	Pea, Wheat, Cucurbits	<i>Erysiphe polygoni</i> , <i>E. cichoracearum</i>	20-25	60-80	<6	0.5-1.5
Fruit Rot	Tomato, Chilli	<i>Phytophthora infestans</i> and <i>Alternaria alternata</i>	20-25	90-100	8-12	0.5-3.6
Downy Mildew	Grapes, Cucurbits	<i>Plasmopara</i> <i>la</i> , <i>Pseudoperonospora cubensis</i>	18-24	90-100	6-10	0.5-1.5
Wilt	Banana	<i>Fusarium oxysporum</i> f. sp. <i>cubense</i>	25-30	75-85	Negligible	Negligible
Tikka leaf spot	Groundnut	<i>Cercospora arachidicola</i> and <i>C. personata</i>	26-31	85-95	8-12	1-3

Table 2. Optimum weather ranges for major bacterial phytopathogens

Disease	Host	Causal organism	Temperature (°C)	Relative humidity (%)	Leaf wetness duration (Hours)	Wind (m/s)
Black rot	Cruciferous crops	<i>Xanthomonas campestris</i>	25-30	>85	6-12	1-3
Bacterial blight, speck	Beans, peas and tomato	<i>Pseudomonas syringae</i>	15-25	>90	8-24	1-3
Bacterial wilt	Potato, tomato and brinjal	<i>Ralstonia solanacearum</i>	28-32	>80	>10	<2
Fire blight	Pear, apple	<i>Erwinia amylovora</i>	18-30	>85	4-8	1-3
Crown gall	Many dicots	<i>Agrobacterium tumefaciens</i>	20-28	85-90	12-48	1-3
Citrus canker	Citrus	<i>Xanthomonas axonopodis</i>	25-30	>85	8-12	1-3
Bacterial canker	Tomato, potato	<i>Clavibacter michiganensis</i>	25-30	>85	8-10	1-3
Soft rot	Potato, vegetables	<i>Pectobacterium</i> spp.	25-35	>90	8-24	1-3
Bacterial leaf blight	Rice	<i>Xanthomonas oryzae</i>	25-30	>85	8-12	1-3
Bacterial leaf streak	Rice	<i>Xanthomonas oryzae</i> pv. <i>oryzicola</i>	25-34	70-80	12-24	1-3

Conclusion

Microclimatic factors play a decisive role in determining the dynamics of crop diseases by shaping the environment in which host-pathogen interactions occur. Variations in temperature, humidity, light intensity, wind movement and leaf wetness within the canopy can markedly influence pathogen survival, infection efficiency and epidemic development. Managing these microenvironmental conditions through appropriate cultural and agronomic practices can effectively suppress disease development while supporting healthy crop growth. A clear understanding of microclimate-pathogen relationships thus provides a foundation for accurate disease forecasting and the formulation of sustainable, site-specific plant protection strategies under changing climatic conditions.

References

- Abebe, A., & Gobena, A. (2019). Review on effect of light on disease development and management of horticultural crops under protected cultivations. *Int. J. For. Hortic.*, 5(3), 5–18. <https://doi.org/10.20431/2454-9487.0503002>
- Agrios, G. N. (2005). *Plant pathology (5th ed.)*. Elsevier Academic Press.
- Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., & Daszak, P. (2004). Emerging infectious diseases of plants: Pathogen pollution, climate change and agrotechnology drivers. *Trends Ecol. Evol.*, 19, 535–544.
- Bock, C. H., Graham, J. H., Gottwald, T. R., Cook, A. Z., & Parker, P. E. (2010). Wind speed effects on the quantity of *Xanthomonas citri* dispersed from citrus canopies. *Plant Dis.*, 94, 725–736.
- Carisse, O., et al. (2020). Influence of leaf wetness duration and temperature on infection of strawberry by *Diplocarpon earlianum*. *Plant Dis.*, 104(2), 365–373. <https://doi.org/10.1094/PDIS-02-20-0262>
- Carroll, J. E., et al. (2003). Effects of humidity on the development of grapevine powdery mildew. *Phytopathology*, 93(10), 1137–1144.
- Chen, D. V., et al. (2024). High temperatures reduce growth, infection, and transmission of some plant pathogens. *Ecology*, 105(3), e4373.
- Dita, M., Barquero, M., Heck, D., Mizubuti, E. S. G., & Staver, C. P. (2018). Fusarium wilt of banana: Current knowledge on epidemiology and research needs toward sustainable disease management. *Front. Plant Sci.*, 9, 1468. <https://doi.org/10.3389/fpls.2018.01468>
- Dobrowski, S. Z. (2011). A climatic basis for microrefugia: The influence of terrain on climate. *Glob. Change Biol.*, 17, 1022–1035.
- García-Bastidas, F., et al. (2024). The past, present and future of Fusarium wilt of banana (*Fusarium oxysporum* f. sp. *cubense*). *Burleigh Dodds Sci. Publ.* <https://doi.org/10.19103/AS.2023.0102.02>
- Garrett, K. A., et al. (2011). Complexity in climate-change impacts mediated by plant disease. *Plant Pathol.*, 60(1), 15–30.

- Gates, D. M. (1980). *Biophysical ecology*. New York: Springer-Verlag.
- Geiger, R. (1966). *The climate near the ground*. Cambridge, MA: Harvard Univ. Press.
- Gu, X., et al. (2024). Evaluation of plant canopy microclimates with realistic airflow models. *Agric. For. Meteorol.*, 345, 109879.
- Haile, F. J. (2001). The influence of cultivar and plant architecture on yield loss. In R. K. D. Peterson & L. G. Higley (Eds.), *Biotic stress and yield loss* (pp. 99–116). Boca Raton: CRC Press.
- Hu, X., Wang, H., & Zhang, L. (2023). Dynamics of *Puccinia striiformis* f. sp. *tritici* urediniospores in the atmosphere: Implications for long-distance dispersal. *Plant Dis.*, 107(2), 237–245. <https://doi.org/10.1094/PDIS-02-23-0237>
- Hunjan, M. S., & Lore, J. S. (2020). Climate change: Impact on plant pathogens, diseases, and their management. In K. Jabran, S. Florentine, & B. Chauhan (Eds.), *Crop protection under changing climate* (pp. 57–82). Cham: Springer: https://doi.org/10.1007/978-3-030-46111-9_4
- IRRI Rice Knowledge Bank. (2017). Bacterial leaf streak. <https://knowledgebank.irri.org/training/factsheets/pest-management/diseases/item/bacterial-leaf-streak>
- Jambhulkar, P. P., Jambhulkar, N., Meghwal, M., & Ameta, G. S. (2016). Altering conidial dispersal of *Alternaria solani* by modifying microclimate in tomato crop canopy. *Plant Pathol. J.*, 32(6), 508–518. <https://doi.org/10.5423/PPJ.OA.06.2015.0101>
- Kaur, S., & Sandhu, S. (2017). Effect of weather parameters on the development of yellow rust of wheat under Punjab conditions. *Int. J. Curr. Microbiol. Appl. Sci.*, 6(7), 546–554.
- Keppel, G., et al. (2012). Refugia: Identifying and understanding safe havens for biodiversity under climate change. *Glob. Ecol. Biogeogr.*, 21, 393–404.
- Kodati, S., et al. (2023). Effect of temperature, leaf wetness period, and cultivar on infection of walnut by *Xanthomonas arboricola* pv. *juglandis*. *Plant Dis.*, 107(5), 1204–1211. <https://doi.org/10.1094/PDIS-05-22-1022>
- Kushwaha, P., Kumari, P., Shrivastava, S., Bharti, D., Saini, K., & Kumar, A. (2024). Climate change and its impact on plant disease: A comprehensive analysis. In *Proc. Natl. Conf. Modern Agric.: Innovation and Sustainability for a Resilient Future* (pp. 1–10).
- Kweku, D., Bismark, O., Maxwell, A., Desmond, K., Danso, K., Oti-Mensah, E., Quachie, A., & Adormaa, B. (2019). Greenhouse effect: Greenhouse gases and their impact on global warming. *J. Sci. Res. Rep.*, 17, 1–9. <https://doi.org/10.9734/jsrr/2017/39630>
- Lahlali, R., et al. (2024). Effects of climate change on plant pathogens and host–pathogen dynamics. *Curr. Res. Microb. Sci.*, 5, 100143.