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The Nocturnal Disease Window: Deciphering the Role of Night-Time Microclimate in Fungal Disease Development

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Abstract

Night-time weather conditions play a significant role in plant disease development by regulating pathogen reproduction, inoculum dynamics and host susceptibility. Unlike conventional weather observations, which may not adequately represent conditions within crop canopies, nocturnal microclimates are characterised by variations in temperature, relative humidity, dew formation and leaf-wetness duration that directly influence pathogen activity. These weather factors govern fungal sporulation, spore maturation, liberation, dispersal and infection, with distinct responses observed among important foliar pathogens, including *Alternaria*, *Botrytis*, *Magnaporthe*, *Colletotrichum* and *Phytophthora*. Plant circadian rhythms further contribute to disease development by regulating defence signalling and time-dependent susceptibility to pathogen infection. The variation in weather requirements among pathogens highlights the existence of distinct nocturnal disease windows, during which specific combinations of temperature, moisture and humidity favour different stages of disease development. Integrating canopy-level microclimate monitoring, automated sensors, remote sensing and machine learning into disease forecasting systems could enhance the precision of disease-risk assessment and outbreak prediction.

Introduction

Plant disease development is primarily determined by the complex interactions among three essential components: a susceptible host, a virulent pathogen and a conducive environment, collectively illustrated by the classical disease triangle. Of these components, environmental conditions, particularly weather parameters, have a major influence on pathogen survival, sporulation, spore germination, host penetration and subsequent disease establishment. However, meteorological data obtained from conventional weather stations may not always reflect the actual weather conditions prevailing within crop canopies. This is because the crop canopy creates a distinct microclimate characterised by variations in temperature, relative humidity, air movement and surface moisture. Such microclimatic variations become particularly significant during night time, when the absence of solar radiation, progressive cooling of plant surfaces, rising relative humidity and reduced atmospheric turbulence favour dew formation

and extended leaf-wetness periods. Consequently, nocturnal weather conditions, through the combined effects of temperature, relative humidity, dew deposition, leaf wetness, rainfall and wind, influence pathogen activity, inoculum production, dispersal and infection (Figure 1). Among these factors, minimum temperature and the persistence of favourable temperature and moisture conditions are particularly important epidemiological determinants, as fungal spore germination and successful infection often require specific combinations of temperature and leaf-wetness duration. Similarly, rainfall and wind contribute to inoculum liberation, dispersal and deposition, while canopy structure and local weather conditions influence the retention and persistence of moisture on plant surfaces. These weather variables rarely act independently; instead, their combined and interdependent effects determine the suitability of conditions for different stages of fungal disease development. Thus, nocturnal canopy microclimate represents an important environmental component of plant disease epidemiology, influencing pathogen activity, spore germination and successful infection, and emphasising the significance of night-time weather dynamics in fungal disease development.

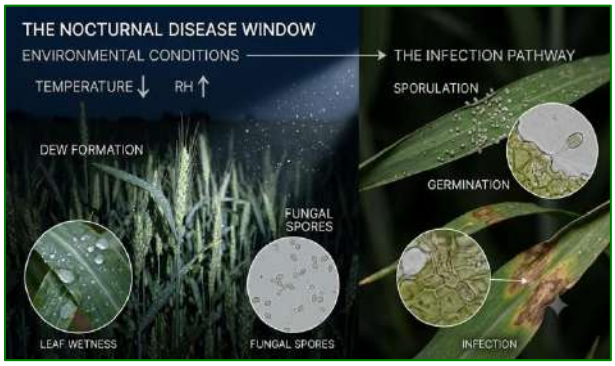


Figure 1: The nocturnal disease window

Nocturnal Regulation of Sporulation and Inoculum Production

Sporulation is a vital stage in the life cycle of fungal pathogens, serving as the link between vegetative mycelial development and the production of secondary inoculum that initiates subsequent infection cycles. Its initiation and progression are largely governed by weather conditions, particularly temperature, relative humidity, moisture availability and light, which influence the formation and development of reproductive structures such as conidiophores, sporangiophores and their associated spores. Temperature plays a fundamental role in regulating mycelial growth, reproductive differentiation, spore production and maturation, with each fungal pathogen exhibiting specific minimum, optimum and maximum temperature requirements for these processes. Notably, the temperature that favours maximum vegetative growth may differ from that required for optimal sporulation. Similarly, high relative humidity and the presence of surface moisture promote reproductive development in several foliar fungal pathogens by providing favourable hydration conditions for the formation of conidiophores or sporangiophores and subsequent spore production. For example, species of *Alternaria* show considerable variation in their sporulation requirements, with several species producing conidia across a temperature range of approximately 10-30°C. However, high relative humidity (90-100%) and the availability of free moisture generally favour conidial production, highlighting the importance of moisture-related environmental conditions in regulating fungal sporulation.

The influence of night-time weather conditions on inoculum production is further illustrated by

the diverse responses of fungal and fungus-like pathogens to changes in light intensity and humidity. In *Alternaria* species, elevated humidity and dew deposition favour conidial initiation, while alternating light and dark periods, together with exposure to specific light wavelengths, regulate conidiophore differentiation and subsequent conidial production. In *Botrytis cinerea*, conidium production exhibits a characteristic daily rhythm influenced by temperature and relative humidity. During the morning, rising temperatures and declining humidity cause mature conidiophores to dry and twist, thereby facilitating the release of conidia into surrounding air currents. A similar variation in environmental responses is observed in *Phytophthora infestans*, the causal agent of late blight, in which sporangium production is generally favoured by dark and humid conditions, whereas light can suppress sporulation. In contrast, certain *Phytophthora* species associated with underground plant tissues exhibit light-stimulated sporulation. These examples highlight the considerable differences among pathogens in their reproductive responses to environmental fluctuations and light-dark cycles. Therefore, although nocturnal conditions may provide favourable conditions for inoculum production in several pathogens, their effects on sporulation are not universal but depend on species-specific physiological characteristics, reproductive requirements and environmental adaptations.

Pathogen	Disease and Crop	Favourable nocturnal conditions
Magnaporthe oryzae	Blast – rice	18–24°C; RH >90%; prolonged leaf wetness
Botrytis cinerea	Grey mould – cucumber, strawberry, rose	9–21°C; prolonged nocturnal humidity; leaf wetness >7 h
Colletotrichum acutatum	Anthracnose – strawberry	23–27.7°C; continuous surface wetness
Alternaria solani and *A. alternata*	Early blight / leaf spot – potato and tomato	Dark, humid conditions; prolonged leaf wetness
Phytophthora infestans	Late blight – potato and tomato	18–22°C; RH >90%; free moisture

Nocturnal Microclimate and the Synchrony of Sporulation, Dispersal and Host Susceptibility

Nocturnal microclimatic conditions significantly influence secondary inoculum production and subsequent infection in several foliar pathogens. Dew formation, prolonged leaf wetness and high relative humidity favour reproductive development on infected or senescent plant tissues. In *Alternaria dauci*, the causal agent of carrot leaf blight, conidial production occurs predominantly at night, requiring 96-100% relative humidity or free moisture, with sporulation occurring between 8 and 28°C and declining considerably below 7-8°C. Similarly, in sweet basil downy mildew caused by the oomycete *Peronospora belbahrii*, sporulation requires at least 7.5 hours of high humidity (≥95%) during night time, while infection requires a minimum of four hours of free leaf moisture. Even brief interruptions in humidity can suppress spore production, highlighting the importance of continuous favourable conditions. Field experiments further demonstrated that

nocturnal air circulation through mechanical fanning reduced canopy humidity and dew deposition, lowering disease incidence from approximately 90-96% in non-fanned net houses to 0.5-1.7% in fanned net houses. These findings demonstrate that the duration and continuity of favourable night time conditions are critical in determining pathogen sporulation, inoculum availability and subsequent infection.

Host susceptibility to pathogen infection also exhibits time-dependent variations governed by the plant's endogenous circadian clock, which regulates defence signalling, hormone production and the expression of infection-responsive genes. In *Arabidopsis thaliana*, susceptibility to the necrotrophic fungus *Botrytis cinerea* varied with the time of inoculation, with greater susceptibility observed during night-time than around subjective dawn. This variation persisted under constant-light conditions, confirming the involvement of the internal circadian clock rather than an immediate response to external light conditions. Reduced susceptibility around subjective dawn was associated with more rapid activation of jasmonate-mediated defence responses. These findings indicate that the success of nocturnally initiated infections depends not only on favourable weather conditions but also on the circadian-regulated physiological state and defence capacity of the host plant at the time of pathogen attack.

The influence of nocturnal conditions on disease development also depends on the timing of spore production, release and subsequent host infection. In several foliar pathogens, reproductive development occurs during night-time, whereas the release and dispersal of mature spores are often concentrated around dawn or during the following daytime. Airborne inoculum studies have demonstrated considerable variation in spore-release patterns among pathogen species, influenced by foliage drying, atmospheric humidity and wind activity. However, spore liberation is not always restricted by darkness. In the apple scab pathogen *Venturia inaequalis*, infrared radiation stimulated ascospore discharge, with artificial infrared illumination increasing overnight spore release by up to 46% under field conditions. These observations highlight the influence of nocturnal weather conditions on pathogen reproduction and inoculum release, while emphasising the importance of synchronisation between pathogen reproductive activity, spore dispersal and host susceptibility in determining successful infection.

Pathogen-Specific Nocturnal Disease Windows

The influence of nocturnal microclimatic conditions varies among pathogens, determining whether favourable night-time environments predominantly support spore production, germination or infection. In rice blast caused by *Magnaporthe oryzae*, night temperatures of 18-24°C, high relative humidity and prolonged leaf wetness favour conidial production and subsequent infection. Similarly, grey mould caused by *Botrytis cinerea* is associated with night temperatures of 9-21°C persisting for more than 9.5 hours, along with extended foliage wetness, contributing to disease outbreaks in cucumber greenhouses. In *Colletotrichum acutatum*, studies on strawberry have identified 23.0-27.7°C as the optimum temperature range for conidial germination under continuous wetness. In contrast, *Alternaria solani* favours sporulation under high humidity, alternating wet

and dry conditions and darkness, although conidial release generally occurs during daytime. Likewise, *Phytophthora infestans*, the causal agent of potato and tomato late blight, predominantly produces sporangia under dark, humid conditions, with sporulation reported to be optimal at 18-22°C. These differences illustrate the pathogen-specific nature of nocturnal environmental requirements and their influence on different stages of disease development.

Nocturnal Microclimate in Disease Forecasting

Traditional plant disease forecasting models largely depend on meteorological variables, including temperature, relative humidity, rainfall and leaf-wetness duration, to assess the likelihood of disease occurrence and development. Nevertheless, integrating time-specific weather measurements, particularly those recorded during night time, may enhance the accuracy and reliability of disease-risk prediction. Parameters such as minimum nocturnal temperature and the duration of leaf wetness during night time can provide additional epidemiological information for identifying periods conducive to pathogen activity, spore germination and potential infection. Furthermore, continuous monitoring of these weather variables directly within the crop canopy can offer a more realistic representation of the conditions experienced by pathogens and host plants than conventional observations obtained from standard weather stations. This is particularly relevant in agricultural systems where variations in canopy structure, vegetation density and local environmental conditions create distinct microclimates that may substantially influence disease development. Therefore, incorporating nocturnal microclimatic observations into existing disease forecasting approaches could improve the identification of favourable infection periods and support more precise assessment of plant disease risk.

The use of automated weather stations, crop-canopy temperature and leaf-wetness sensors, along with remote-sensing technologies, provides new opportunities for continuous monitoring and spatially representative assessment of microclimatic conditions. The weather data generated through these technologies can be integrated into disease forecasting models to identify periods of elevated disease risk more accurately and determine the appropriate timing of disease management interventions. In addition, machine learning techniques offer the ability to process and analyse large datasets involving meteorological parameters, canopy-level microclimatic observations and disease incidence records, thereby identifying complex weather relationships and patterns associated with disease development. Integrating nocturnal microclimate monitoring with advanced sensor technologies, remote sensing and predictive modelling could therefore contribute significantly to the development of more accurate, location-specific and timely plant disease forecasting systems, ultimately supporting improved disease surveillance and management decisions.

Conclusion

Nocturnal microclimatic conditions represent an important yet often underexplored component of plant disease epidemiology, influencing pathogen reproduction, inoculum production, spore dispersal, germination and successful host

infection. The interactions among night-time temperature, relative humidity, dew formation, leaf-wetness duration and host circadian responses determine the suitability of nocturnal environments for different stages of disease development, with considerable variation in weather requirements among pathogen species. Understanding these pathogen-specific nocturnal disease windows provides valuable insights into the temporal dynamics of disease epidemics beyond conventional daytime weather observations. Integrating canopy-level microclimate monitoring with automated sensors, remote sensing and predictive modelling could further strengthen disease forecasting by identifying favourable infection periods with greater accuracy. Therefore, greater attention to night time environmental dynamics, alongside host–pathogen interactions, can contribute to more precise disease-risk assessment and the development of timely, location-specific and sustainable plant disease management strategies.

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