



Research article

Dynamics of coastal weather effects on Moler disease in Indonesia shallot production

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Abstract

Importance of the work: Coastal microclimatic factors influence pathogen dynamics; however, their impact on shallot diseases, such as Moler disease, remains poorly understood.

Objectives: To investigate multivariate relationships between coastal weather parameters and Moler disease development in shallot production systems.

Materials and Methods: Field surveys were conducted across 15 sites in Parangtritis, Yogyakarta, Indonesia, during the late rainy and dry seasons. Disease incidence and infection rates were assessed weekly alongside six weather parameters monitored via an automatic weather station. Principal component analysis (PCA) was used to analyze weather-disease relationships.

Results: Disease incidence was significantly higher during late rainy season (28.50%) compared to dry season (12.03%, $p = 0.03$), with infection rates of 0.14 units/d and 0.09 units/d ($p < 0.001$). The PCA revealed 84.62% of the weather-diseases relationship variance was explained by the two principal components. Radiation-precipitation variables had strong positive associations with infection rates, while relative humidity had an unexpected negative correlation (Pearson's correlation coefficient $r = -0.55$). Temperature had a secondary influence through weak through positive F2 loadings (25.54%, $r = 0.25$).

Main finding: Coastal weather-disease interactions deviated from inland patterns, particularly in humidity-disease relationships, necessitating maritime-specific disease prediction models for effective management.

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Introduction

The increasing prevalence of Moler disease, caused by the soil-borne pathogen *Fusarium oxysporum* f. sp. *cepae*, represents a critical threat to shallots globally (Haapalainen et al., 2016; Rout et al., 2016; Kálmán et al., 2020; Degani et al., 2024). Indonesia's coastal regions contains strategic development zones for priority horticultural commodities, such as shallots (Ekowari et al., 2023; Lailandra et al., 2024; Prastiwi et al., 2024). Disease severity reaching 60% causes 50% bulb damage in these cultivation zones, affecting food security and agricultural economics (Hadiwiyono et al., 2020; Supyani et al., 2021a).

Environmental conditions play a pivotal role in disease epidemiology, as high pathogen populations and virulence may not successfully infect susceptible hosts under non-conducive conditions (Freeman et al., 2018; Hawley et al., 2024). Typically, the optimal conditions for disease development deviate from host growth optima, occurring either below or above the optimal host physiological parameters, although some cases have been reported of overlapping environmental requirements (Agrios, 2005; Velásquez et al., 2018). Notably, an environmental shift toward disease-conducive conditions is responsible for 44% of the emergence of disease expression (Anderson et al., 2004).

Coastal agricultural zones have unique microclimatic patterns driven by complex air-sea thermodynamic interactions as these regions are characterized by distinct diurnal temperature variations, modified precipitation mechanisms and specialized moisture transport processes that fundamentally differ from those in inland environments (Yamanaka et al., 2018; Zhao et al., 2020; Das et al., 2022; Ruan et al., 2024).

Current epidemiological models for *Fusarium oxysporum* sp. progression are primarily derived from research conducted using inland agricultural systems, in which high relative humidity and temperature are the principal drivers of pathogen development (Ali et al., 2022; Liu et al., 2023; Gupta et al., 2024). However, conventional frameworks may not adequately capture disease dynamics in coastal environments. Furthermore, the complex interplay between sea breeze circulation, enhanced radiation attenuation and modified precipitation mechanisms in coastal zones potentially create unique pathogen-environment relationships that challenge established disease prediction paradigms (Ziv and Saaroni, 2011; Haider et al., 2017). Therefore, the current study aimed to fill this critical gap by examining the impact of coastal weather dynamics on Moler disease development in shallot production systems.

The current study was based on the hypothesis that coastal weather patterns create distinct seasonal windows of disease susceptibility through mechanisms that differ from those observed in inland models. Through a systematic field investigation of Indonesia's coastal region, the current study aimed: 1) to characterize the temporal dynamics of key meteorological parameters in a coastal cultivation zone; 2) to quantify seasonal variations in disease incidence and infection rates; and (3) to elucidate the multivariate relationships between coastal weather variables and disease development. This research addresses a critical knowledge gap in understanding maritime agricultural pathosystems.

Materials and Methods

Study Site

The study was conducted in Parangtritis, Kretek District (8°00'21" S, 110°18'34" E), within the coastal area of Bantul Regency, Yogyakarta, Indonesia, which is a known center for shallot cultivation. The study area experiences two distinct planting seasons: the late rainy season (March–May) and the dry season (June–August), during which shallot cultivation is actively practiced.

Weather data collection

Meteorological data were collected over the continuous period March 2024–September 2024 using an automatic weather station at the PGSP (Parangtritis Geomaritime Science Park) station in Parangtritis, Kretek District (8°00'32" S, 110°18'07" E). Throughout both planting seasons, the station continuously monitored air temperature, relative humidity, solar radiation, ultraviolet (UV) index, rain rate and total rainfall. The proximity of the weather station to the cultivation areas ensured that the collected data accurately represented the environmental conditions experienced by crops.

Disease assessment

Field surveys were conducted using a purposive sampling approach across 15 sites distributed throughout the study area. Disease monitoring occurred weekly throughout both planting seasons, focusing on the visual symptoms of Moler disease in each subplot. Disease incidence was calculated as the percentage of infected plants relative to the total number of observed plants using Equation 1:

$$\text{Disease incidence (\%)} = \frac{\text{Total number of infected plants}}{\text{Total number of observed plants}} \times 100 \quad (1)$$

The infection rate was determined using Equation 2:

$$r = (2.3/t)(\log(1/(1-X_t)))-(\log(1/(1-X_0))) \quad (2)$$

where r is the disease infection rate, t is the time interval between observations in weeks, X_0 is the disease proportion at initial observation and X_t is the disease proportion at time t .

Statistical analysis

Temporal patterns of meteorological variables were analyzed using scatter plots across growing seasons. The statistical parameters used were: the coefficient of variation to quantify data variability; a t test ($\alpha = 0.05$) for seasonal comparisons; and Pearson's correlation coefficient (r) for weather-disease relationships. Analysis was carried out using R Studio (version 4.4.0) for Windows, an integrated development environment for R, a programming language for statistical computing and graphics. (R Core Team, 2024). Principal component analysis (PCA) was conducted using the XLSTAT (2024.1) software (Lumivero, New York, USA) to reduce the dimensionality of the weather data and to elucidate the multivariate relationships between weather variables and diseases infection rates.

Results

Coastal weather fluctuations

The analysis of the coastal meteorological data revealed clear seasonal transitions from the late rainy to dry periods. As shown in Figure 1a, solar radiation peaked (930–980 W/m²) during March–April in the late rainy season, declining to 750 W/m² by May. Throughout the dry period (June–September), values oscillated in the range 720–880 W/m². Figure 1b shows that the UV index closely followed the solar radiation pattern, in the ranges 6.9–9.0 during the rainy season and 6.5–8.0 during the dry season.

There were for inverse seasonal relationships for temperature and relative humidity throughout the observation period. Figure 1c shows there were elevated temperature values (28.5–30.3°C) during the late rainy season, followed by lower values (26.9–29.5°C) during the dry season. Conversely, as depicted

in Figure 1d, relative humidity increased from approximately 70% to 78% during the late rainy season and thereafter maintained elevated levels (73–83%) during the dry season.

Precipitation metrics had the most pronounced inter-seasonal differentiation. Figure 1e shows that peak rainfall rates reached 30–35 mm/hr during the late rainy season, compared to 15–17 mm/hr in the dry season. Similarly, there were marked seasonal variations in cumulative rainfall, as shown in Fig. 1F, with 59 mm during the late rainy season versus 20–30 mm in the dry season.

Generally, the observed patterns were aligned with typical tropical coastal weather characteristics. These findings provided crucial insights into local weather dynamics and their potential implications in coastal management strategies.

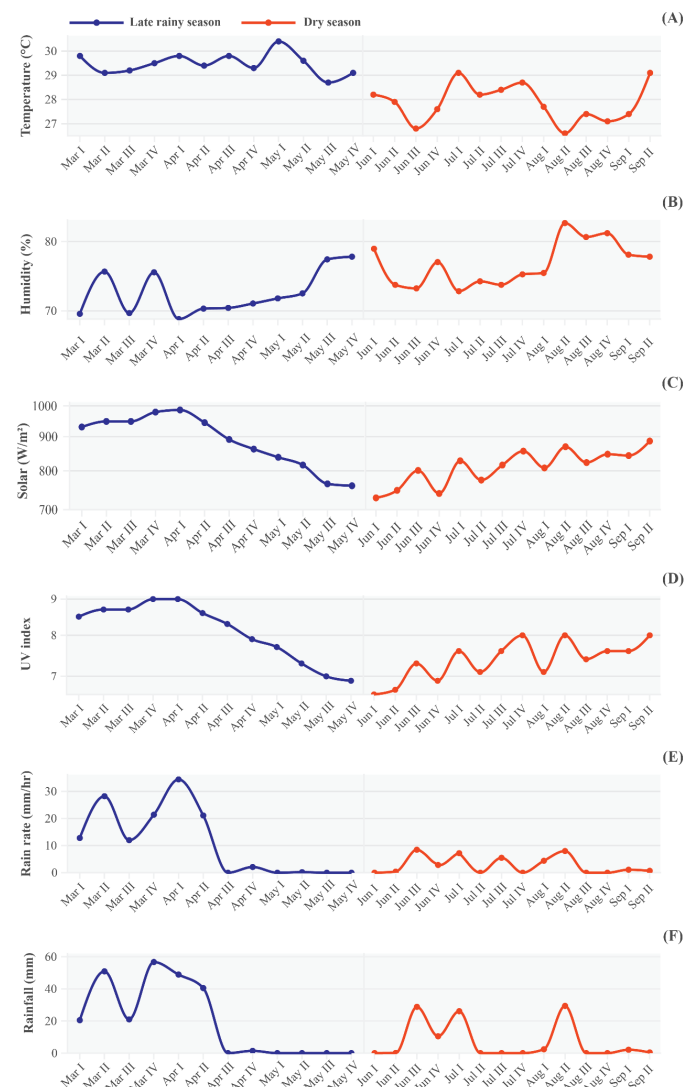


Fig. 1 Fluctuations in weather variables in coastal areas during observation period: (A) solar radiation; (B) ultraviolet (UV) index; (C) air temperature; (D) relative humidity; (E) rain rate; (F) total rainfall.

Seasonal patterns of disease development

Disease development followed distinct seasonal patterns, as illustrated in Fig. 2. The late rainy season had an exponential increase from week 4 to week 7, reaching an average incidence of 28.50% with a coefficient of variation (CV) of 40.3%. Statistical analysis, as presented in Table 1, confirmed significantly higher disease incidence during the late rainy season compared to the dry season ($p = 0.03$). Similarly, infection rates were significantly elevated in the late rainy season (0.14 units/d, CV = 39.6%) compared to the dry season (0.09 units/d, CV = 34.0%) ($p < 0.001$). These findings indicate that the environmental conditions during the late rainy season were conducive to disease development.

Correlation between weather and disease infection rate

The correlation analysis revealed varying relationships between weather variables and disease infection rates, as depicted in Fig. 3. The precipitation (rain rate and rainfall) variables were moderately positively correlated with the infection rate ($r = 0.55$ and $r = 0.52$, respectively). Similarly, the radiation (solar radiation and UV index) variables were moderately positively correlated with the infection rate ($r = 0.49$ and $r = 0.42$, respectively), while humidity had a moderate negative correlation ($r = -0.55$). These patterns suggested precipitation and humidity were primary drivers of

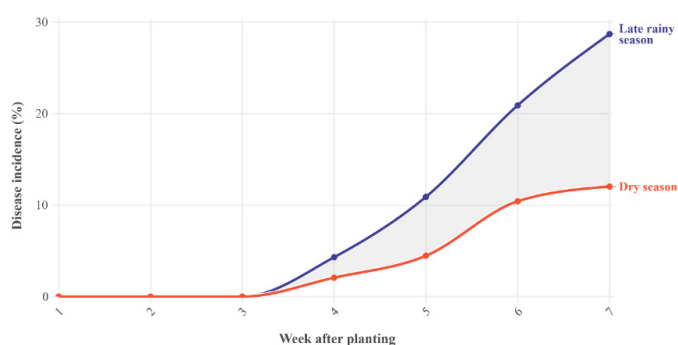


Fig. 2 Temporal progression of disease incidence over weeks after planting during observation period, where the shaded area between the two curves represents the difference in disease progression between late rainy season and dry season

Table 1 Comparison of disease variables between late rainy and dry seasons.

Disease variable	Season	Average	Coefficient of variation	p -value
Disease incidence (%)	Late rainy	28.50	40.3%	0.03
	Dry	12.03	30.8%	
Infection rate (units/d)	Late rainy	0.14	39.6%	0.00
	Dry	0.09	34.0%	

disease development, with radiation variables as secondary influencing factors.

Multivariate analysis of weather-disease infection rate relationship

The PCA revealed distinct weather-disease relationships, as illustrated in Fig. 4, with the F1 and F2 components explaining 84.62% of total variance (59.08% and 24.54%, respectively). The F1 axis represents thermal-moisture gradients, where temperature had strong positive correlations in the positive quadrant, while relative humidity projected a negative association.

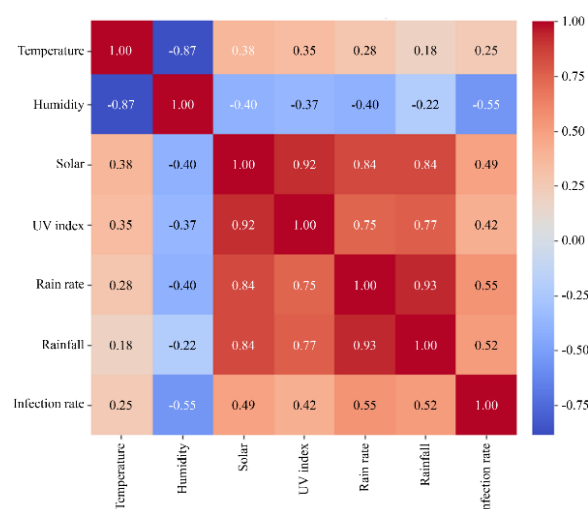


Fig. 3 Correlation matrix heatmap depicting relationship between weather variables and disease infection rate, where values close to +1 and -1 indicate strong positive and negative correlations, respectively, while values close to 0 indicate weak correlations

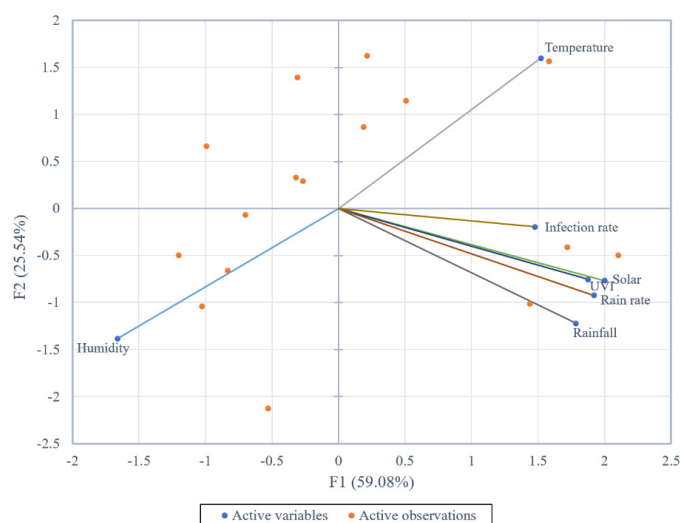


Fig. 4 Principal component analysis biplot axes F1 and F2 = 84.62% displaying relationship between weather variables and disease infection rate, where UVI is abbreviation for UV index

The precipitation and radiation variables were clustered positively in F1, with moderate-to-strong correlations. The infection rate vector's intermediate position between the thermal and precipitation clusters indicated complex weather-disease interactions.

The F2 axis separates thermal variables (positive loadings) from precipitation variables (negative loadings). Over the study period, there was considerable variation across both main components, showing that the weather changed greatly over time. Furthermore, the high cumulative variance explained by F1 and F2 (84.62%) effectively captured weather-disease relationships, particularly highlighting the opposing effect of coastal humidity on disease development.

Discussion

This study provided comprehensive insights into the intricate relationship between coastal weather dynamics and Moler's disease development in shallot cultivation systems. Based on the findings, the influence on disease progression was identified of distinct meteorological characteristics of coastal agricultural environments, while highlighting the need for adapted model approaches in these unique agricultural zones.

A detailed analysis of the meteorological patterns in Parangtritis revealed complex temporal patterns that fundamentally reflected the unique characteristics of the coastal environment. Observed air temperatures were higher during the late rainy season (28.7–30.3°C) than during the dry season (26.6–29.1°C). Notably, this pattern diverged from tropical inland conditions (>100 km from the coastline) as documented by Mori et al. (2018) and Ananta et al. (2024), primarily due to fundamental land-sea thermodynamic interactions.

Coastal-terrestrial thermal gradients generate specific circulation mechanisms whereby terrestrial thermal amplitudes facilitate the advection of moisture-rich maritime air masses toward continental zones (Carter et al., 2012; Soderholm et al., 2017; Parfitt, 2024). Consequently, this ocean-atmosphere coupling develops a moderate climate characterized by cooler dry conditions and wet conditions that are not too cold (Moser et al., 2016; Toros et al., 2019; Nissanka et al., 2023). The moderate climate regime at the study site was further evidenced by elevated relative humidity (73–83%) during the dry season. This finding aligned with other studies (Virmani et al., 2005; Erlick et al., 2006; Ziv and Saaroni, 2011).

Based on the current results, there were temporal variations in radiation parameters, characterized by lower fluctuations in solar radiation (720–880 W/m²) and the UV index (6.5–80) during the dry season. These variations exemplified the modulation of the radiation transmission process by the atmospheric moisture content in coastal areas. Enhanced cloud development during this period results in pronounced radiation attenuation through reflection and diffuse scattering mechanisms (Grabner and Kvicera, 2014; Cheng et al., 2016; Supyani et al., 2021b). These unique coastal meteorological dynamics generate favorable conditions for the development of shallot pathogens.

Moler disease development during shallot production exhibits a distinct seasonal pattern in the coastal systems. Disease incidence was significantly higher during the late rainy season (28.50%) than during the dry season (12.03%) ($p = 0.03$). Similarly, infection rates were significantly elevated in the late rainy season (0.14 units/d versus 0.09 units/d, $p = 0.00$). These patterns suggest that coastal weather conditions during the late rainy season create an environment conducive to pathogen establishment and disease progression. This temporal pattern aligned with the results of other studies on Moler's disease dynamics (Supyani et al., 2021a; Hidayah et al., 2023; Widono et al., 2023).

The results of the multivariate analysis revealed complex interactions between weather variables, creating unique disease-favorable periods in the coastal zone. The PCA biplot (Fig 4) revealed that the infection rate vector had stronger positive associations with the radiation (solar radiation-UV index) and precipitation (rain rate-rainfall) clusters through their proximate angular position and significant loading value on F1 (59.08%). These findings enriched those of Rodríguez Zafra et al. (2016), Salvacion et al. (2019) and Wahyuni et al. (2023), who reported that precipitation variables do not stand alone but work in synergy with radiation variables in disease development. Radiation may influence disease progression indirectly by affecting host susceptibility, whereas precipitation enhances pathogen spore dispersal via rain splashes and mycelial growth through increased soil moisture (Nguyen et al., 2009; Penet et al., 2014; Dita et al., 2018; Shoaib et al., 2024).

Temperature had weak positive loadings on F2 (25.54%), suggesting a secondary but regulated influence on disease progression. *Fusarium oxysporum* sp. pathogens require specific thermal thresholds rather than showing linear responses to temperature increases (Jelínek et al., 2019). The optimal temperature range for epidemic development (25–30 °C), as reported by Attri et al. (2018) and Liu et al. (2023), corresponded to the air temperature range observed in the current study area (26.6–30.3 °C).

Based on the current results, there was an inverse relationship between the humidity and thermal variables, which was strongly projected in the negative F1 direction of the PCA biplot (Fig. 4). The correlation analysis indicated a moderate negative association between humidity and disease infection rate ($r = -0.55$), presenting an intriguing deviation from established patterns. This finding contrasted with those of Quintana et al. (2017), Liu et al. (2023) and Khanna et al. (2022), who reported positive correlations between humidity and *Fusarium oxysporum* sp. infection rates in inland agricultural systems. This suggested that coastal humidity dynamics may influence disease development through mechanisms distinct from those observed in inland environments.

The unique mechanism explaining the inverse relationship between the humidity-disease relationship in coastal areas could be attributed to several key factors. Coastal aerosols containing salt particles in the air from ocean spray alter the osmotic potential surrounding fungal propagules. This osmotic modification potentially inhibits *Fusarium* conidial development by disrupting the water potential gradient necessary for successful host colonization (Macteau et al., 2008; Palmero Llamas et al., 2008; Dossa et al., 2019). Additionally, elevated humidity in coastal zones functions as an effective radiation attenuation mechanism. Subsequently, this attenuation reduces solar radiation exposure at the crop level, which in turn modifies host susceptibility to pathogen infections (Li et al., 2015; Delgado-Vargas et al., 2023).

The link between humidity and disease growth in coastal areas requires further exploration. Long-term studies are essential to examine the stability of weather-disease relationships across multiple seasons. This approach would align with the work of Jonas et al. (2015), Naseri and Sasani (2020), who investigated weather variables and their lagged effects on crop-disease systems. Furthermore, the current findings indicated that conventional disease models would require substantial adjustments for use in coastal regions. This aligned with the work of Haider et al. (2018), who highlighted the importance of considering microclimatic conditions in coastal areas when modeling disease development. Developing coastal-specific disease prediction tools is crucial to improving management strategies in these unique agricultural environments. To achieve this, installing weather stations in each shallot production center across coastal regions would provide precise microclimatic data for effective modeling where standard models fail.

Understanding these weather-disease relationships is becoming increasingly critical as coastal agricultural systems

face growing challenges from climate change. The distinct seasonal patterns and complex environmental interactions documented in the current study should provide a foundation for developing targeted management strategies that account for the unique characteristics of the coastal cultivation zones. Future research should focus on validating these relationships across different coastal regions and developing integrated management approaches that adapt to changing climatic conditions.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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