

Epidemiological Dynamics of Alternaria Diseases in Potato (*Solanum tuberosum* L.): Climate-Disease Interactions, Inoculation Timing and Economic Impacts in Eritrea

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Abstract

Alternaria diseases, caused by *Alternaria solani* (Early Blight) and *A. alternata* (Brown Spot), threaten potato production globally. This study quantified the epidemiological patterns of the diseases, climate-disease interactions, transmission dynamics, and economic impacts across three climatically different zones of Eritrea (Adi Keih, Asmara, and Halhale) during the 2025 growing season. A randomized complete block design with four treatments of different pathogen inoculation times, with three replications, was used. Disease assessments were conducted at five crop development stages. Apparent infection rate, area under disease progress curve (AUDPC), ANOVA, Pearson correlation, and linear regression were used for statistical analysis. Asmara exhibited high disease risk with Early Blight severity of 4.19 and Brown Spot severity of 3.13, with 100% incidence and the highest transmission rates (0.122/day for Early Blight, 0.108/day for Brown Spot). Moderate humidity (54.1%) combined with warmer temperature (19.2 °C) was found to be conducive. Across all places, the disease progressed rapidly between 30 and 45 days after planting. Negative correlations between transmission efficiency and yield were observed for both diseases. Yield losses reached 42% (13 t/ha) in high transmission environments, which is approximately Eritrean Nakfa (ERN) 130,000/ha (USD 8,667/ha) in economic losses. Inoculation timing did not affect AUDPC values, indicating that environmental factors outweigh pathogen incidence timing. Our findings indicate that moderate humidity (54-58%) coupled with warmer temperatures (19-20 °C) create ideal conditions for disease transmission, adding a scientific basis for understanding *Alternaria* epidemiology. The critical crop age period of 30-45 days after planting represents the highest vulnerability window requiring intensive monitoring. These findings, while based on a single growing season, provide a foundation for multi-year validation across broader geographic scales. Our study supports the development of site-specific, climate-informed, and economically optimized integrated disease management strategies that can help farmers achieve sustainable potato production in the face of changing climate conditions.

Keywords: AUDPC, *Alternaria*, climate-disease interactions, epidemiology, Halhale, pathogen transmission

1. Introduction

Plant disease epidemiology results from interactions among pathogen biology, host susceptibility, environmental conditions, and cultural practices (Madden et al., 2007; Singh et al., 2023). *Alternaria* diseases of potato, caused by *Alternaria solani* (Early Blight) and *A. alternata* (Brown Spot), are among the most damaging foliar diseases worldwide. Depending on pathogen pressure, severity, and climate, yield losses can range from 5% to 78% (Yuldashova et al., 2023). The primary drivers of epidemics are environmental factors conducive to spore germination, infection, and dispersal. Previous studies have shown that disease development accelerates at temperatures of 15-25 °C, with leaf wetness periods of up to 7 hours and elevated relative humidity (Meno et al., 2020, 2022). Highest spore concentrations typically occur between 20 and 25 °C (Escuredo et al., 2010). These relationships, however, vary markedly across geographical regions, and climate change is altering pathogen-host

dynamics, complicating epidemic forecasting and management (Kumar & Mukhopadhyay, 2025; Singh et al., 2023; Waheed et al., 2023).

Disease incidence and severity are further modulated by the timing of pathogen exposure relative to crop development stage, with different growth phases showing differential susceptibility (Pariaud et al., 2009). The Area Under the Disease Progress Curve (AUDPC) is the standard metric for quantifying cumulative disease intensity over time and is widely used for comparing treatments and environments (Jeger & Viljanen-Rollinson, 2001; Simko & Piepho, 2012).

Effective disease management requires precise timing of interventions. Fungicide applications against *Alternaria* are most successful when applied at epidemiologically critical periods, yet optimal thresholds can only be defined once the pathogen-host-environment interaction is clearly understood (Abuley et al., 2017; Camiletti et al., 2024; Leiminger & Hausladen, 2012). While several studies have examined fungicide timing, the relative contribution of initial inoculation timing versus prevailing environmental conditions to cumulative disease development remains unclear, especially in semi-arid highland climates.

This study addresses an important knowledge gap by developing an integrative framework that simultaneously examines epidemiological dynamics, climate-disease interactions, inoculation timing effects, and economic impacts under tropical highland conditions in Sub-Saharan Africa. This context is largely absent from the existing *Alternaria* literature, which has predominantly focused on temperate European and Asian potato systems. Specifically, this research quantifies climate-disease relationships, tracks disease progression across contrasting microclimates, measures transmission efficiency, evaluates inoculation timing effects, and assesses associated economic losses. By combining quantitative epidemiology with economic impact assessment in a single field-based study, and by explicitly testing whether pathogen inoculation timing modulates cumulative disease development under contrasting semi-arid highland microclimates, this study provides region-specific insights that can inform targeted integrated disease management strategies.

2. Materials and Methods

2.1 Experimental Site

The experiment was conducted at three potato growing areas of Eritrea. These areas represent different climatic variations, altitudinal gradients, and potato disease pressures. These are Adi Keih (15°56'N, 39°01'E; elevation 2329 meters above sea level (m.a.s.l.), 113 km south of the capital city, Asmara), Asmara (15°20'N, 38°55'E; 2213 m.a.s.l.), and Halhale (15°03'N, 39°14'E; 1917 m.a.s.l., 36 km southwest of Asmara). These areas are located in two main potato growing regions and are characterized by their different potato production potential, mainly seed production (Medhanie et al., 2024).

2.2 Experimental Design and Treatment

A randomized complete block design (RCBD) with three replications was implemented at each site. Each plot had a size of 3 × 4 meters, and an Electra potato variety was planted on a spacing of 70 × 30 cm. The following four treatments (three inoculation timing + control) were applied to establish disease epidemics with three inoculation times: Treatment 1 (during planting), Treatment 2 (one month after planting), Treatment 3 (two months after planting), and Treatment 4 (a water mock inoculation at every application of the other treatments as a control). To minimize the risk of cross-contamination between inoculation treatments and the mock-inoculated control plots, a minimum inter-plot spacing of 1.5 meters was maintained between adjacent plots within each block. Inoculations on the experimental plants in the field were performed in the late evening when wind speed was minimal, and no rain was forecast within 12 hours, to reduce the risk of spray drift and promote leaf surface colonization through overnight dew formation.

2.3 Spore Preparation and Pathogenicity Test

Pathogen cultures of *Alternaria solani* and *A. alternata* obtained from infected potato leaves observed symptomatically in the region were sporulated on Barley Sucrose Agar (BSA) (Ahmed et al., 2023). Two hundred grams of barley grains from the local market were washed and added to 500 ml of distilled water, and then boiled for 20 minutes. The barley grain extract was filtered using a cheesecloth. The extract was then mixed with 10 g of sucrose and 17 g of agar. The prepared media were transferred to a conical flask for sterilization, closed with a cotton-tight stopper, and autoclaved for 15 minutes at 121 °C and 1.5 kg/cm² pressure. The fungi were inoculated and left unsealed to allow aeration. To induce sporulation of the fungi, the medium was incubated for three days under alternating conditions of 12 hours of light and 12 hours of dark at a temperature of 15 °C in a growth chamber. The spore growth was then examined under a microscope after staining with 10% iodine and methylene blue. Microscopic species identity of the isolates was confirmed by following the

morphological characteristics described by Li et al. (2024), and Zheng et al. (2015), where *Alternaria solani* was identified by their obclavate to inverted cylindrical conidia with a prominent beak comprising 30-50% of total conidium length, and *Alternaria alternata* was distinguished by shorter, ovoid to obclavate conidia without prominent beaks. Conidial suspensions were then prepared by flooding the cultures with sterile distilled water containing 0.05% Tween-20, and concentrations were adjusted to 1×10^6 conidia/mL (Ivanović et al., 2022) using a Hemocytometer. Pathogenicity was confirmed via Koch's postulates; pathogens were reisolated from diseased samples, inoculated in the same medium in the laboratory, and the pathogen's presence was confirmed.

2.4 Disease Assessment

Disease onset and progression assessments were conducted twice per month from emergence until maximum disease severity of the potato plants. These observation days are the five critical ages of the plant (John, 2017) (Table 1). These are;

Table 1. Sampling time related to the age of the crop

Sampling time	Age of the crop (Days)	Potato development stage
1 st	15	Early establishment stage following emergence
2 nd	30	Active vegetative growth phase
3 rd	45	Tuber initiation stage
4 th	60	Tuber bulking phase
5 th	75	Crop maturation stage

Within each replicate plot, 10 plants were tagged and monitored for disease progression. Disease severity assessments were conducted using a 0-5 ordinal scale modified from established systems (Bektas, 2022; Li et al., 2024) as described in Table 2.

Table 2. Ordinal scale of severity evaluation of Alternaria disease of potato and diagrams (Modified after Duarte et al. (2013))

Score	0	1	2	3	4	5
% diseased	0	1-10%	11-25%	26-50%	51-75%	> 75%
Description	Free from infection	One, two, or a few necrotic spots on a few lower leaves	A few isolated spots on leaves	Many spots coalesced on leaves	Irregular, blighted leaves and sunken lesions with concentric rings	Whole plants are blighted, and leaves and fruits are starting to fall
Diagram						

2.5 Transmission Efficiency and AUDPC Analysis

The transmission efficiency of the pathogen was computed using the apparent infection rate (r) formula, an exponential model for polycyclic diseases (Dey et al., 2022; Van der Plank, 1963). This model assumes exponential disease increase during the log phase of the epidemic (typically 20-80% disease severity).

$$r = [\ln(x_2) - \ln(x_1)] / (t_2 - t_1) \quad (1)$$

where,

r = apparent infection rate (per day); x_1, x_2 = proportion of diseased tissue at times t_1 and t_2 ; t_1, t_2 = time points (days after planting).

Transmission rates classification was established based on the epidemiological significance of apparent infection rates in potato disease management into low ($r < 0.03$ per day, epidemic doubling time > 23 days), moderate

($0.03 \leq r < 0.10$ per day, doubling time 7-23 days), and high ($r \geq 0.10$ per day, doubling time < 7 days). While Van der Plank (1963) established the theoretical foundation for calculating apparent infection rates, specific threshold values vary depending on pathosystem characteristics and local conditions (Abuley et al., 2018).

Area Under Disease Progress Curve (AUDPC) was calculated using the trapezoidal integration method (Madden et al., 2007; Simko & Piepho, 2012).

$$AUDPC = \sum_{i=1}^{n-1} [(y_i + y_{i+1})/2] \times (t_{i+1} - t_i) \quad (2)$$

where,

y_i represents disease severity at assessment i ; t_i is time at assessment i ; and n is the total number of assessments.

2.6 Climate Monitoring and Data Collection

Meteorological data recording was done at each experimental site following agricultural weather station protocols during the growing season. Temperature ($^{\circ}\text{C}$) and relative humidity (%) were recorded using automated onsite HOBO MX2301A Data Loggers (Onset Computer Corporation, Bourne, MA, USA) installed at a 1.5m height. The rainfall data of the growing season was accessed from the MoA sub-regional office of Adi Keih and Asmara, and the Halhale meteorological office. Climate data were summarized as daily means and analysed for disease-favourable optimal range for *Alternaria* spp, which are a temperature of 15-25 $^{\circ}\text{C}$ and relative humidity of $> 60\%$. Cumulative favourable conditions were expressed as the number of days that fall under these conditions during the growing season, providing a quantitative measure of environmental disease pressure at each location.

2.7 Yield Loss Economic Assessment

Yield assessments were conducted at physiological maturity. Total yield per plot was recorded and converted to tons per hectare (t/ha).

Yield loss was calculated relative to the highest-yielding location:

$$\text{Yield Loss (\%)} = [(Y_{\max} - Y_{\min})/Y_{\max}] \times 100 \quad (3)$$

Economic impact was valued using average market prices in the Eritrean market. The unit cost was taken from the MoA planning office for a wholesale of the potato from the farm at 10,000 Eritrean Nakfa(ERN) per ton, which is equivalent to 667 USD (1 USD = 15 ERN).

$$\text{Economic Loss (\$/ha)} = (Y_{\max} - Y_{\min}) \times \text{Price} \quad (3)$$

2.8 Statistical Analysis

All the collected data were recorded and inspected in Microsoft Excel, and statistical analyses and plotting for visualization were conducted in R statistical software (R Core Team, 2023). The statistical significance threshold was set at $\alpha = 0.05$. Analysis of variance (ANOVA) was used to evaluate treatment timing effects on AUDPC values within each site, with treatment as a fixed effect and block as a random effect (Simko & Piepho, 2012). Pearson correlation coefficients quantified relationships between climate variables and disease parameters. Whereas linear regression analysis was used to understand the relationships between transmission rates and yield outcomes. Economic impact was assessed through yield loss calculations relative to the highest-yielding location.

3. Results

3.1 Site Climate Characterization and Disease Pressure

The climate assessment during the growing season revealed distinct environmental characteristics on the three experimental sites (Table 3, Figure 1). Adi Keih exhibited a cool-humid highland climate with a mean temperature of 17.2 $^{\circ}\text{C}$ and a relative humidity of 66.7%. Asmara represented a highland climate with a mean temperature of 19.2 $^{\circ}\text{C}$ and a relative humidity of 54.1%. Halhale, on the other hand, showed warmer climate characteristics (20.5 $^{\circ}\text{C}$ mean temperature and 57.9% relative humidity). Disease pressure analysis revealed that Adi Keih showed minimal disease with early blight severity of 0.21 and brown spot severity of 0.12. Asmara exhibited severe epidemics with early blight severity of 4.19 and brown spot severity of 3.13, having 100% incidence. Halhale demonstrated intermediate pressure with early blight severity of 2.75.

Table 3. Site climate characteristics and disease risk assessment

Site	Days	Temp (mean)	Humidity (mean)	Favourable Temp Days	Favourable Humidity Days	High Risk Days	Percent Favourable	Percent High Risk
Adi Keih	92	17.2	66.7	91	58	57	62.0	62.0
Asmara	92	19.2	54.1	92	40	40	43.5	43.5
Halhale	92	20.5	57.9	91	44	44	47.8	47.8

Climate Characteristics of the Three Experimental Sites

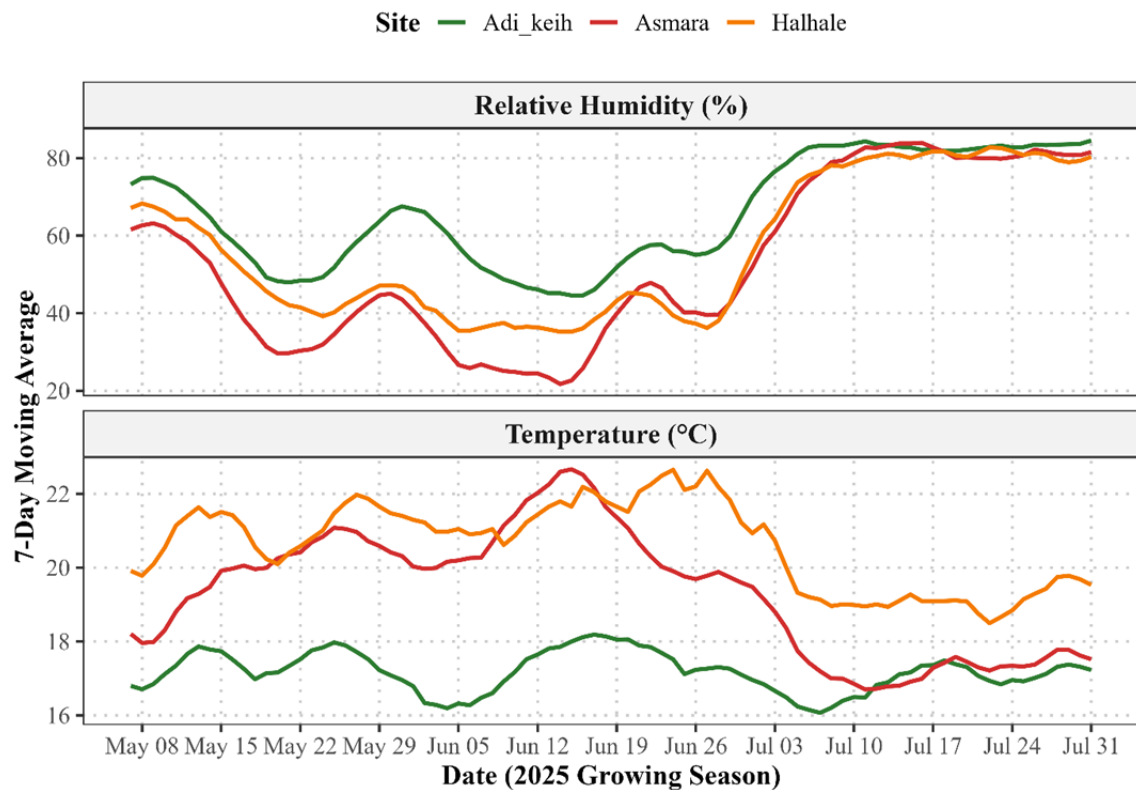


Figure 1. Seasonal patterns of relative humidity (%) and temperature (°C) recorded at Adi keih (green), Asmara (red), and Halhale (orange) during the 2025 growing season (May 1-July 31). The upper panel shows 7-day moving averages of relative humidity, while the lower panel displays temperature variations across the experimental period

3.2 Climate-Disease Relationships

The correlation analysis revealed a negative relationship between mean humidity and disease severity. The sites with lower mean humidity (Asmara: 54.1%, Halhale: 57.9%) but higher mean temperatures (19.2 °C and 20.5 °C, respectively) experienced more severe disease development than the high-humidity site (Adi Keih: 66.7%) with cooler temperature (17.2 °C) (Table 4).

Table 4. Climate-disease relationship

Site	Temp., °C (mean)	Humidity, % (mean)	EB Sev	BS Sev	EB Inc	BS Inc
Adi Keih	17.2	66.7	0.2	0.1	19.8	12.0
Asmara	19.2	54.1	4.2	3.1	100.0	100.0
Halhale	20.5	57.9	2.8	2.0	100.0	82.6

Note. EB Sev = Early Blight Severity, BS Sev = Brown Spot Severity, EB Inc = Early Blight Incidence, BS Inc = Brown Spot Incidence.

3.3 Disease Progression Patterns and Epidemic Dynamics

Disease progression analysis revealed different epidemic dynamics across the three sites (Figure 2). At Asmara, early blight exhibited rapid development with progression rates of 1.06-1.26 severity units per time point. Brown spot showed similar patterns with progression rates of 0.88-1.04 units per time point. These steep progression rates of the diseases indicate exponential epidemic development where disease severity increased by more than one full rating scale unit between successive assessments. Halhale showed intermediate progression patterns with early blight rates of 0.58-0.82 units per time point, approximately half the rate observed at Asmara. At Adi Keih, however, the disease progression was minimal with rates of 0.01-0.11 units per time point (Figure 3).

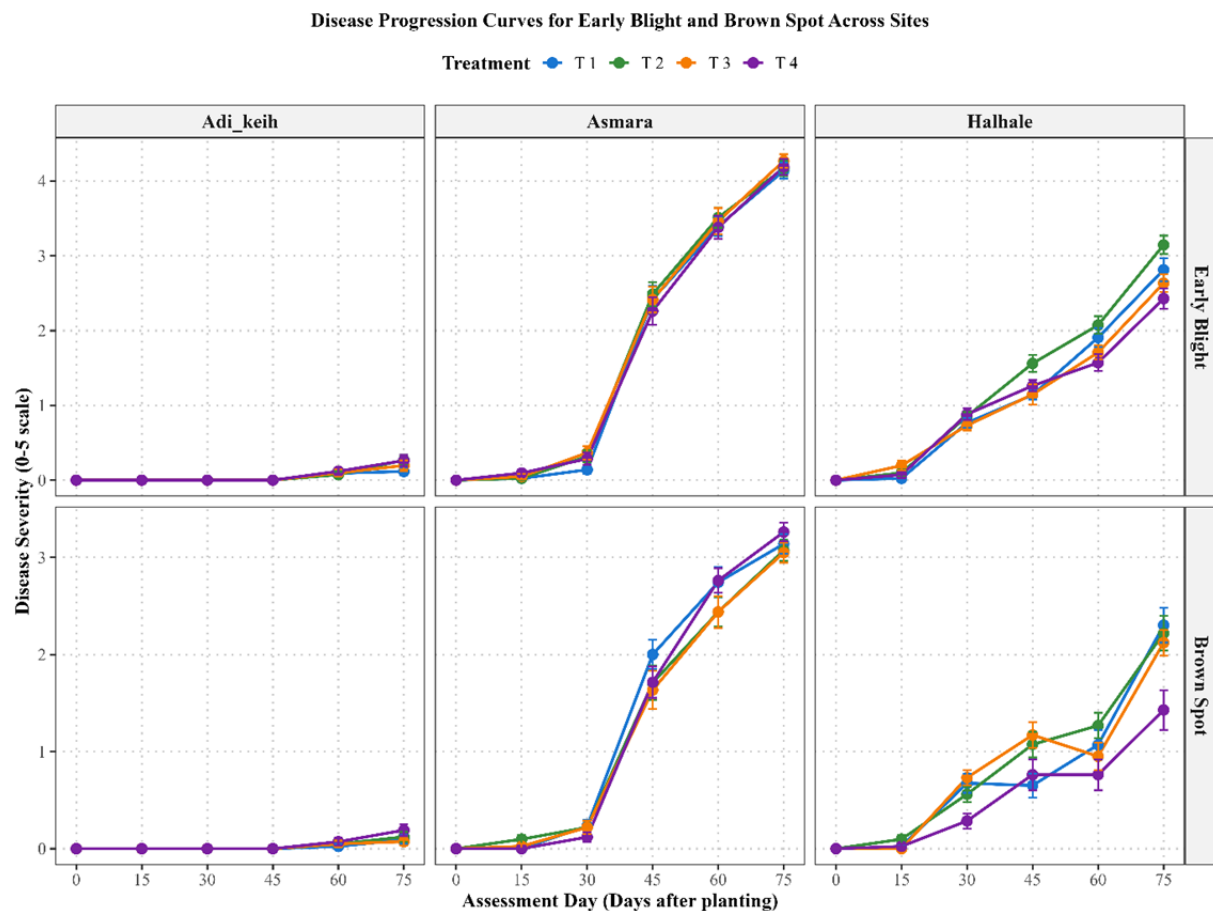


Figure 2. Disease severity progress over time for four treatments (T1-T4) at three experimental locations. Upper panels show Early Blight progression, lower panels show Brown Spot development



A. Brown spot symptom at Adi Keih



B. Early Blight symptom at Halhale



C. Alternaria disease severity at Asmara

Figure 3. Alternaria disease symptoms observed in the field

3.4 Transmission Efficiency

Apparent infection rates showed differences among locations and between diseases. Asmara exhibited the highest transmission rates for both pathogens ($> 10\%$ per day). Adi Keih showed the slowest disease spread. Brown Spot disease showed similar patterns (Figure 4). Asmara's transmission rates exceeded those of Adi Keih by 114% (Early Blight) and 140% (Brown Spot), representing medium effect sizes.

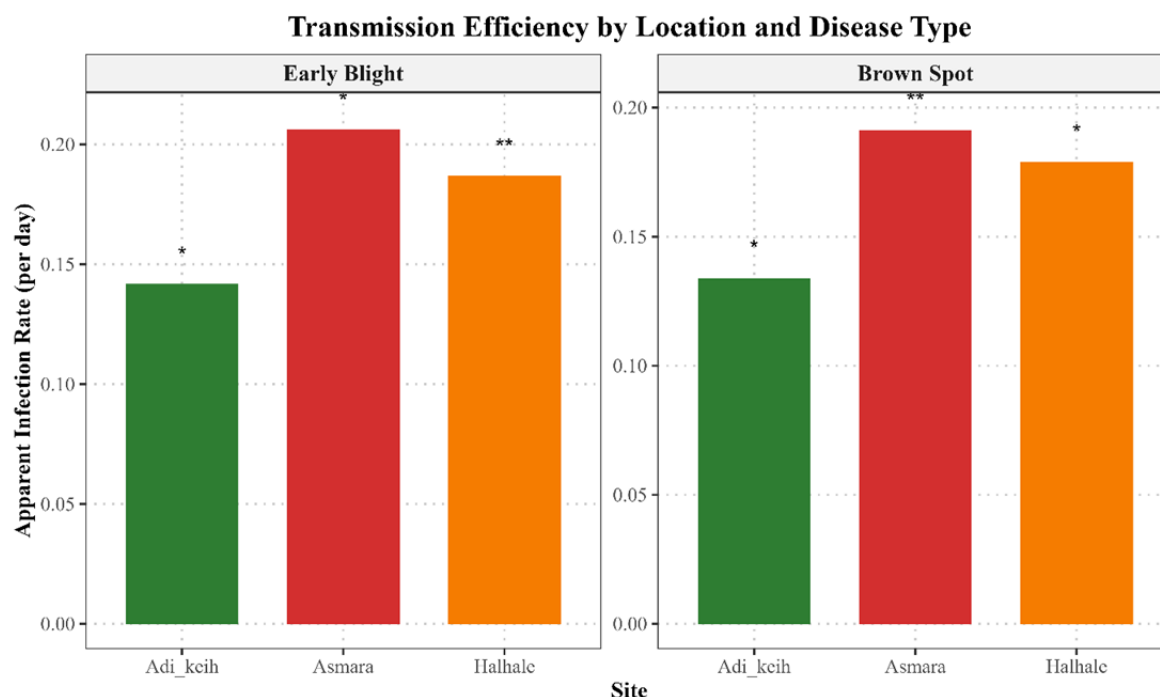


Figure 4. Apparent infection rates (per day) for Early Blight (left panel) and Brown Spot (right panel) across the three experimental sites

3.5 Treatment Timing Effects on Disease Development

The AUDPC analysis provided a quantitative assessment of cumulative disease intensity. At Asmara, the AUDPC values for Early Blight ranged from 8.03 to 8.41 across treatments, representing severe epidemic development. However, ANOVA analysis revealed no significant treatment timing effects for either disease (Early Blight: $P = 0.63$; Brown Spot: $P = 0.30$). Halhale showed intermediate AUDPC values with considerable variation among treatments (Early Blight: 5.75-7.63; Brown Spot: 4.50-8.50), but no significant treatment effects. Adi Keih, however, exhibited minimal disease cumulative development in all treatments with AUDPC values below 0.25 for both diseases.

3.6 Yield Loss Assessment and Economic Impact

Yield and economic loss analysis revealed that there is site-specific variation corresponding to disease pressure levels. Adi Keih, with minimal disease pressure, obtained an average yield of 30 t/ha. Asmara showed the lowest yields of 17 t/ha (Table 5). The 42% yield reduction of Asmara compared to Adi Keih represents a substantial economic loss. Further, the observed inverse relationship between the mean AUDPC of each site and mean yield demonstrates the economic importance of environmental disease pressure (Figure 5).

Table 5. Yield performance and economic losses of the two sites, relative to Adi Keih

Location	Yield (t/ha)	ERN/Ton	Value in ERN/ha	Value in USD/ha	% Loss/ha	Economic Loss (ERN/ha)	Economic Loss (USD/ha)
Adi Keih	30.4	10,000.00	304,000.00	20,266.67			
Halhale	22.7	10,000.00	227,000.00	15,133.33	25	77,000.00	5,133.33
Asmara	17.4	10,000.00	174,000.00	11,600.00	42	130,000.00	8,666.67

Note. The unit cost was taken from the MoA planning office for a wholesale of the potato from the farm at 10,000 Eritrean Nakfa(ERN) per ton, which is equivalent to 667 USD (1 USD = 15 ERN).

The economic loss analysis showed that the harvest from Asmara lost 42% of the achievable yield due to the high disease pressure and transmission. At current Eritrean market prices, this translates to ERN 130,000/ha

(USD 8,667/t/ha) in lost revenue. Even Halhale, with moderate transmission, suffered 25% yield loss worth ERN 77,000/ha (USD 5,133/ha) (Table 5).

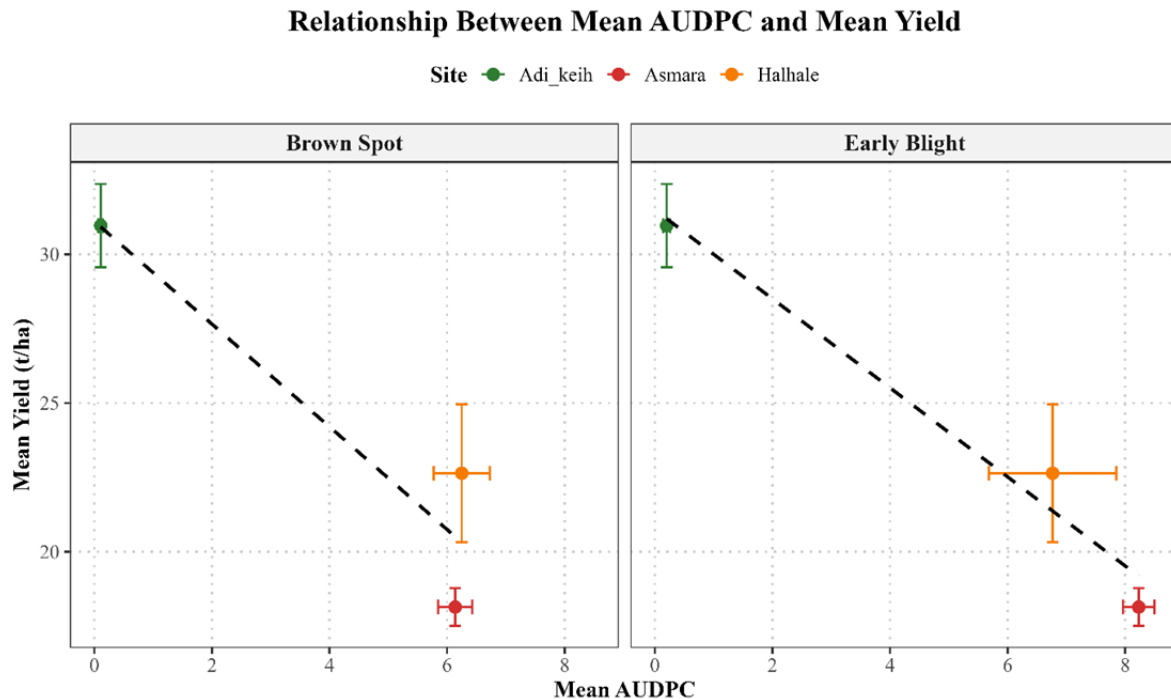


Figure 5. Scatter plots showing the relationship between Area Under Disease Progress Curve (AUDPC) and crop yield (t/ha) for Brown Spot (left) and Early Blight (right). Each point represents mean values for one site with error bars indicating standard error. The dashed trend line illustrates the negative correlation between disease severity and yield

4. Discussion

The global potato industry faces continual threats from foliar pathogens, particularly *Alternaria* species, whose impact is amplified by shifting climate patterns. Yield losses from *Alternaria* diseases range from 5% to 78% depending on pathosystem and environment (Savary et al., 2019; Singh et al., 2023). Our study provides new quantitative insights into climate-disease interactions, transmission dynamics, inoculation timing, and economic impacts under tropical high-altitude conditions in Eritrea. To our knowledge, this is among the first studies to integrate epidemiological dynamics, climate-disease modelling, inoculation timing experiments, and economic impact quantification within a single field-based investigation in an East African highland potato system.

Moderate humidity (54.1%) combined with warmer mean temperatures (19.2 °C) created conditions more favourable for severe epidemic development than higher-humidity, cooler environments. This balance of moisture for germination and conditions that promote efficient spore dispersal appears critical for dry-spored fungi such as *Alternaria* (Jambhulkar et al., 2016; Meno et al., 2022). The observed optimal temperature range (19-20 °C) aligns with previous reports (Mahapatra et al., 2022).

These microclimatic differences drove markedly different disease progression and transmission efficiencies. Asmara showed the highest apparent infection rates (> 10% per day), exceeding those at Adi Keih by 114% (Early Blight) and 140% (Brown Spot). The rapid progression between 30 and 45 days after planting coincides with active vegetative growth and tuber initiation, highlighting a critical vulnerability window requiring intensive monitoring (John, 2017; Jindo et al., 2021).

The absence of significant inoculation-timing effects on AUDPC (Early Blight: $P = 0.63$; Brown Spot: $P = 0.30$) confirms environmental dominance once conditions become conducive. This finding is consistent with Van der Plank's framework and recent polycyclic pathosystem studies, where ambient inoculum and secondary cycling rapidly override initial inoculum timing. It suggests that once favourable conditions persist, airborne secondary inoculum reaches levels sufficient to drive epidemics regardless of initial inoculation date. Future studies should

examine interaction effects between inoculation timing and specific microclimate variables (e.g., dew duration, temperature fluctuations) to identify conditions under which timing may become ecologically significant (Madden et al., 2007; Meno et al., 2024).

Yield losses reached 42% (13 t/ha) in high-transmission environments, translating to ERN 130,000/ha (USD 8,667/ha) at current Eritrean market prices. These losses align with global reports that found *Alternaria* diseases can reduce yields from 5% to 78%, depending on several factors (Kumar et al., 2017; van der Waals et al., 2011; Yuldashova et al., 2023) and underscore the economic justification for investing in climate-informed, integrated disease management rather than reactive fungicide programmes alone.

The strong environmental effect observed has important implications under climate change. Climate change is expected to significantly alter disease epidemiology by affecting pathogen evolution, host-pathogen interactions, and enabling shifts in pathogen distributions and increased virulence (Hossain et al., 2024; Singh et al., 2023). Climate change is expected to cause changes in disease pressure. Forecasts indicate that ideal potato cultivation regions may change, as conventional areas face increased heat stress, while regions at higher latitudes and elevations may become more favourable (Chaloner et al., 2021). Moderate humidity and warmer temperatures (19-20 °C) appear ideal for *Alternaria* epidemics; predictive models should therefore prioritise these temperature-humidity interactions. Advanced forecasting that incorporates vapour pressure deficit and multi-year data will be essential for adapting potato systems to future climate scenarios.

5. Conclusions

This epidemiological study, conducted across three agro-climatically distinct sites in Eritrea, demonstrates that the interplay of temperature and humidity is the primary driver of *Alternaria* disease severity and progression in potato. Moderate humidity (54%) combined with warmer temperatures (19.2 °C) produced the highest disease pressure and transmission rates. A critical vulnerability window occurs between 30 and 45 days after planting, underscoring the need for targeted monitoring and interventions during active vegetative growth and tuber initiation. The 42% yield loss observed in high-risk environments highlights that environment-based management strategies are both scientifically sound and economically prudent. Findings are based on a single growing season across three locations; conclusions should therefore be interpreted with appropriate caution. Multi-year and multi-site validation is necessary before these epidemiological parameters can be generalized. The economic analysis assumes yield losses are attributable solely to *Alternaria*; future assessments should include sensitivity analyses for other biotic and abiotic factors. Additionally, a limitation of the current study is the absence of direct leaf wetness duration measurements, which are a primary driver of *Alternaria* infection. Relative humidity was used as a proxy variable, consistent with the approaches proposed by Zito et al. (2020) for places lacking leaf wetness sensors. Future studies should incorporate multi-year validation, broader geographical coverage, molecular characterization of the pathogen isolates, dedicated leaf wetness sensors, controlled-environment experiments to determine cardinal temperatures for local isolates, and comprehensive economic evaluations that account for all production factors. Such work will strengthen site-specific, climate-informed integrated disease management for sustainable potato production in the face of changing climate conditions.

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Authors Contributions

MM, Dr. JN, and Dr. CM developed the study design and contributed to its revision. MM, Dr. JN, Dr. CM, and Prof. TM refined the design and experimental methodology. MM and MY carried out the fieldwork, laboratory work, and data collection. MM drafted the manuscript, while Dr. JN, Dr. CM, and Prof. TM provided revisions. All authors read and approved the final manuscript.

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