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Environmental Influence of Altitude on Coffee Leaf Rust Severity in Arabica Coffee of Aceh Tengah, Indonesia

Teguh Arkadinata [1], Qalbin Salim Fazli [2,*], Alfizar Alfizar [1], Lukman Hakim [1] and Ghazi Mauer Idroes [3]

[1] Department of Plant Protection, Faculty of Agriculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia; teguharkadinata7@gmail.com (T.A.); alfizar@usk.ac.id (A.A.); lkm_hakiem@usk.ac.id (L.H.)

[2] Department of Plant Protection, Faculty of Agriculture, IPB University, Bogor 16680, Indonesia; qalbinsf@gmail.com (Q.S.F.)

[3] Department of Occupational Health and Safety, Faculty of Health Sciences, Universitas Abulyatama, Aceh Besar 23372, Indonesia; idroesghazi_k3@abulyatama.ac.id (G.M.I.)

* Correspondence: qalbinsf@gmail.com

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Abstract

Coffee leaf rust (CLR), caused by *Hemileia vastatrix*, remains one of the most damaging diseases affecting Arabica coffee worldwide. Understanding how environmental gradients influence CLR development is critical for sustainable management in tropical highland systems. This study examined the influence of altitude on CLR incidence and severity across five elevation ranges (800–1800 masl) in Arabica coffee plantations of Aceh Tengah, Indonesia. Field assessments were conducted on 25 farms using a standardized sampling layout and severity scoring scale. Analysis of variance (ANOVA) revealed that altitude had no significant effect on disease incidence ($F = 0.14 < F_{0.05} = 3.01$), which remained uniformly high across all sites (>75%), but significantly affected disease severity ($F = 3.34 > F_{0.05} = 3.01$). The highest mean severity (51.88%) occurred at 1600–1800 masl, differing significantly from lower elevations. These findings suggest that while CLR infection frequency is widespread, environmental conditions at higher altitudes favor greater lesion expansion and disease development. The results highlight the importance of considering local microclimatic variability in disease risk assessment and adaptive management. Further studies integrating microclimatic and agronomic measurements are needed to strengthen causal understanding and support environmentally based strategies for sustainable Arabica coffee production.

1. Introduction

Coffee leaf rust (CLR), caused by *Hemileia vastatrix*, is one of the most important diseases affecting Arabica coffee worldwide [1–4]. The pathogen attacks the leaves, causing premature defoliation and reducing the photosynthetic capacity of the plant, which eventually leads to yield losses [5–7]. The disease has been reported in almost all coffee-growing regions, and its outbreaks are closely linked to environmental conditions that favor fungal development [8–10]. Because coffee is generally cultivated in tropical highlands, understanding the ecological factors that influence CLR is essential for developing adaptive management strategies that maintain both productivity and environmental stability [11–13].

Environmental factors such as temperature, humidity, and rainfall play a major role in the epidemiology of coffee leaf rust [14–16]. The life cycle of *H. vastatrix* depends on the presence of free moisture on leaf surfaces and moderate temperatures that promote spore germination [17]. In many cases, lowland areas are described as more favorable for infection due to higher temperatures and longer wet periods after rainfall [2, 18]. However, several studies have also shown that the disease can be severe in cooler, high-altitude areas where prolonged leaf wetness and high humidity compensate for lower temperatures [19]. These differences indicate that elevation influences CLR development indirectly through its effects on local microclimatic conditions [9, 20].

The relationship between elevation and CLR intensity has been widely studied, but the results are often inconsistent. Some studies report a decline in disease severity at higher altitudes, while others show an opposite trend or no clear pattern. Such inconsistencies may result from variations in climate, shade level, or coffee variety. This suggests that elevation alone does not determine the occurrence of the disease but modifies environmental conditions that regulate pathogen growth and host susceptibility [21]. Understanding these relationships is important for improving the accuracy of disease risk assessments in different ecological zones.

In Indonesia, coffee is one of the main plantation commodities and a crucial source of income for smallholder farmers [22]. Arabica coffee is mostly grown in the highlands of Sumatra, where environmental gradients strongly influence crop performance. Aceh Tengah, located in the Gayo highlands, is one of the country's largest Arabica coffee-producing regions. The area is characterized by complex topography, with elevations ranging from about 800 to more than 1800 meters above sea level, and diverse agroecological conditions [23, 24]. Despite its importance, information on how elevation affects the intensity and distribution of coffee leaf rust in Aceh Tengah remains limited.

Research from other coffee-producing regions suggests that the interaction between environmental conditions and management practices shapes the spatial dynamics of coffee leaf rust. Factors such as shade level, pruning, fertilization, and cultivar type can influence disease expression by modifying the microclimate within coffee canopies [25]. However, such relationships under the specific growing conditions of Aceh Tengah have not been adequately documented. Without local evidence, it is difficult to determine which environmental factors are most responsible for disease variation in this area.

From an environmental perspective, assessing the effect of elevation on coffee leaf rust is important not only for plant pathology but also for understanding how ecological gradients shape disease behavior in tropical mountain ecosystems. Climate variability and ongoing environmental change are expected to alter the distribution and intensity of plant diseases, potentially shifting the areas of highest risk. Studying coffee leaf rust across altitudinal gradients can therefore provide insights into how environmental factors affect disease development and help identify strategies that support sustainable coffee production in the face of changing environmental conditions.

This study aimed to evaluate the variation in coffee leaf rust incidence and severity across different elevation ranges in Arabica coffee plantations of Aceh Tengah, Indonesia. The research was conducted to determine whether altitude influences infection frequency or disease severity, and to explore the environmental factors that may contribute to these differences. It was hypothesized that while infection incidence would not vary significantly with altitude, disease severity would increase at higher elevations due to cooler temperatures and higher humidity. The findings are expected to provide baseline information for developing environmentally based disease management strategies and improving understanding of the relationship between elevation, microclimate, and plant disease dynamics in tropical highland coffee systems.

2. Materials and Methods

2.1. Study Area

The study was conducted in Arabica coffee plantations across Aceh Tengah District, Gayo Highlands, Indonesia. Five elevation groups were defined to represent local agroecological gradients: 800–1000 masl, 1000–1200 masl, 1200–1400 masl, 1400–1600 masl, and 1600–1800 masl. In each elevation group, five farms (observation plots) were selected to represent local variation in topography and management. The spatial distribution of sampling sites is shown in Figure 1, and detailed site names, coordinates and elevation assignment are presented in Table 1.

2.2. Sampling Design and Plot Layout

A purposive sampling technique was used to select farms across the elevation gradients based on the availability of active Arabica stands and the presence of CLR symptoms. At each selected farm a 25 m × 25 m observation plot was established; each plot contained approximately 100 Arabica coffee trees. From each plot, 10% of the plant population was sampled using a zigzag sampling pattern to ensure spatial representation within the plot. This resulted in five farm-level replicates per elevation group (n = 5 farms per group). Farm-level means were used as experimental replicates in the ANOVA described below.

From each sampled tree, 36 leaves were collected: 12 leaves from the lower canopy, 12 from the middle

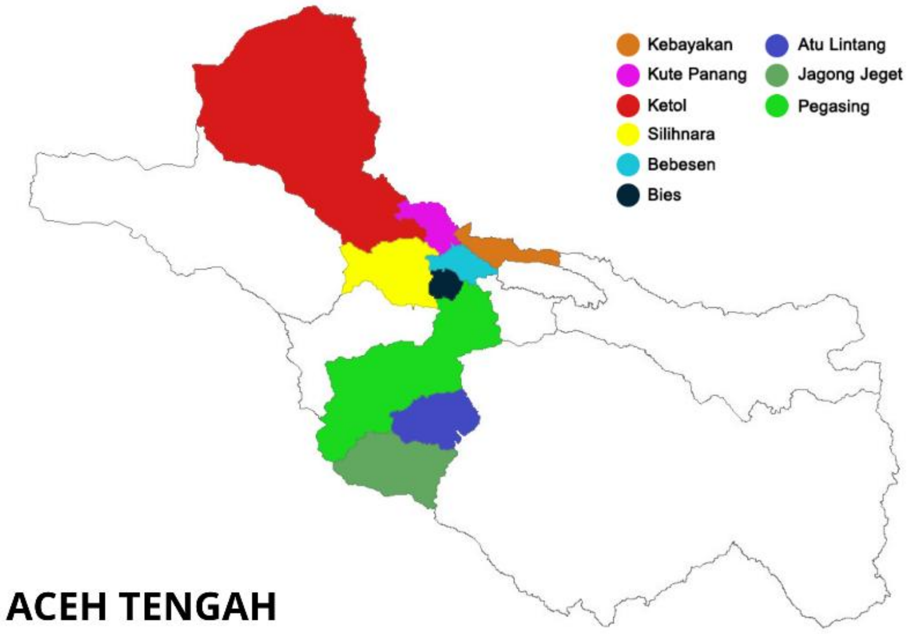

Figure 1. Map showing the locations of Arabica coffee plantation observation sites across different elevation groups in Aceh Tengah District, Indonesia.

Table 1. Coffee Arabica plantation locations by elevation group in Aceh Tengah District.

No.	Elevation Group (masl)	Sites		Elevation (masl)
1	800-1,000	a.	Selon/Ketol	907
		b.	Selon/Ketol	932
		c.	Selon/Ketol	985
		d.	Kute Gelime/Ketol	932
		e.	Blang Balik/Kute Panang	950
2	1,000-1,200	f.	Wihni Durin Silih Nara	1,140
		g.	Wihni Durin/Silih Nara	1,166
		h.	Kute Gelime/Ketol	1,016
		i.	Jaluk/Ketol	1,140
		j.	Jaluk/Ketol	1,147
3	1,200-1,400	k.	Kute Lintang/Pegasing	1,284
		l.	Kute Lintang/Pegasing	1,374
		m.	Mendale/Kebayakan	1,322
		n.	Paya Tumpi/Kebayakan	1,336
		o.	Paya Tumpi/Kebayakan	1,351
4	1,400-1,600	p.	Pucuk Deku/Bies	1,406
		q.	Pucuk Deku/Bies	1,427
		r.	Blang Gele/Bebesen	1,483
		s.	Kedelah/Pegasing	1,532
		t.	Merah Muyang/Atu Lintang	1,563
5	1,600-1,800	u.	Berawang Dewal/Jagong Jeget	1,662
		v.	Pantan Damar/Atu Lintang	1,647
		w.	Tanoh Abu/Atu Lintang	1,760
		x.	Merah Mege/Atu Lintang	1,774
		y.	Merah Mege/Atu Lintang	1,796

canopy, and 12 from the upper canopy. For each canopy level, three leaves were sampled from each cardinal direction (north, south, east and west), providing representative coverage of the tree canopy. The sampling layout procedure are illustrated in Figure 2.

2.3. Plant Material and Management Context

Sampled trees were Arabica coffee (local smallholder stands). Varietal identity was not recorded as a primary variable; however, trees in the observation plots ranged approximately 2–15 years in age. Management practices

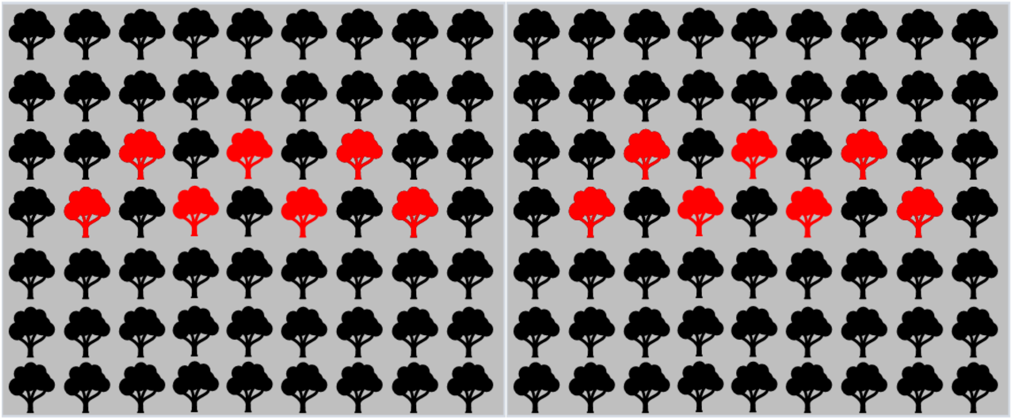

Figure 2. Illustration of selected plants for sampling.

Table 2. Disease severity scoring scale.

Scale Value	Visual Scale Image	Criteria
0		No infection
1		Mild infection (1-25%)
2		Moderate infection (26-50%)
3		Severe infection (51-75%)
4		Very severe infection (>75%)

were recorded qualitatively during farm visits: at higher elevations (1600–1800 masl) pruning and weed control were commonly performed twice per year, whereas in lower-elevation plots (800–1600 masl) these practices were more frequent (up to four times per year), resulting in relatively cleaner canopies and improved air circulation.

2.4. Disease Assessment and Scoring

Disease assessment focused on two metrics: incidence and severity of coffee leaf rust (CLR). Only leaves with visible rust pustules were recorded as symptomatic. Disease incidence at the farm level was calculated as the percentage of sampled plants showing at least one symptomatic leaf. Disease severity was estimated at the leaf level using a categorical severity scale; the scale and category values are provided in Table 2. The formulas used are shown in Equation 1 and 2 [26]:

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

$$Disease\ severity\ (\%) = \frac{\sum(ni\ x\ vi)}{Z\ x\ N}\ x\ 100\% \quad (2)$$

where n_i= number of leaves in severity category i, v_i= value assigned to category i, N= total leaves observed, and Z= maximum category value.

3. Results and Discussion

3.1. Coffee Leaf Rust Incidence Across Elevations

The analysis of variance (ANOVA) indicated that elevation had no significant effect on coffee leaf rust (CLR) incidence across the five elevation ranges ($F = 0.14 < F_{0.05} = 3.01$). The average incidence ranged from 81.18% at 800–1000 masl to 78.99% at 1600–1800 masl, with a mean of 78.75% across all sites.

Table 3. Coffee leaf rust incidence and severity across elevation ranges in Aceh Tengah, Indonesia.

Elevation (masl)	Mean Incidence (%)	Mean Severity (%)	LSD Group (Severity)
800–1000	81.18	39.22	a
1000–1200	78.11	40.25	a
1200–1400	79.11	35.51	a
1400–1600	76.38	37.94	a
1600–1800	78.99	51.88	b

Note: Different letters indicate significant differences according to the LSD test ($p < 0.05$). CLR = Coffee Leaf Rust (Hemileia vastatrix).

Table 4. Site-level variation in coffee leaf rust incidence and severity across elevation groups in Aceh Tengah, Indonesia.

Elevation Group (masl)	Sites	Disease Incidence (%)	Disease Severity (%)
(800-1,000)	1. Selon/Ketol	55.83	22.57
	2. Selon/Ketol	95.28	48.40
	3. Selon/Ketol	93.33	44.37
	4. Kute Gelime/Ketol	72.50	32.64
	5. Blang Balik/Kute Panang	88.94	48.12
(1,000-1,200)	1. Wihni Durin/Silih Nara	86.94	45.41
	2. Wihni Durin/Silih Nara	91.39	51.73
	3. Kute Gelime/Ketol	75.00	36.11
	4. Jaluk/Ketol	50.27	22.98
	5. Jaluk/Ketol	86.94	45.00
(1,200-1,400)	1. Kute Lintang/Pegasing	67.77	22.50
	2. Kute Lintang/Pegasing	75.55	28.00
	3. Mendale/Kebayakan	83.61	41.45
	4. Paya Tumpi/Kebayakan	80.27	39.65
	5. Paya Tumpi/Kebayakan	88.33	45.97
(1,400-1,600)	1. Pucuk Deku/Bies	72.22	32.77
	2. Pucuk Deku/Bies	76.11	39.44
	3. Blang Gele/Bebesen	76.94	40.55
	4. Kedelah/Pegasing	79.16	38.33
	5. Merah Muyang/Atu Lintang	77.50	38.63
(1,600-1,800)	1. Berawang Dewal/Jagong Jeget	75.83	48.61
	2. Pantan Damar/Atu Lintang	75.27	53.10
	3. Tanoh Abu/Atu Lintang	81.11	49.46
	4. Merah Mege/Atu Lintang	79.72	53.63
	5. Merah Mege/Atu Lintang	83.05	54.62

Although minor differences occurred among locations, the overall infection frequency remained consistently high, with more than 75% of trees affected across all altitudes. These results suggest that altitude did not influence the likelihood of infection, possibly due to the widespread distribution of inoculum sources and similar management practices among farmers in different elevation zones (Table 3). Site-level values of coffee leaf rust incidence and severity within each elevation group are presented in Table 4. These data show considerable within-group variability, particularly at higher elevations, reflecting microclimatic and management differences among farms.

As shown in Table 3, incidence values fluctuated slightly with altitude, but no consistent pattern emerged. The overall mean incidence remained above 75% in all elevation groups, confirming that CLR is widespread and well established across the entire altitudinal gradient in Aceh Tengah. This uniformity indicates that the initial infection process is not restricted by temperature or humidity differences, and may instead depend on the availability of spores and host susceptibility (Figure 3).

3.2. Coffee Leaf Rust Severity Across Elevations

In contrast to incidence, the severity of CLR showed a significant variation with elevation ($F = 3.34 > F_{0.05} = 3.01$). The average severity ranged from 35.51% at 1200–1400 masl to 51.88% at 1600–1800 masl, representing a gradual increase with altitude as shown in Table 3. The post hoc LSD test (BNT = 10.43) confirmed that the highest elevation group (1600–1800 masl) differed significantly ($p < 0.05$) from all lower-elevation groups (800–1600 masl). As depicted in Figure 4, the trend suggests that although infection frequency was stable, disease development and lesion expansion were more intense at higher elevations, likely influenced by cooler temperatures and longer leaf wetness periods.

Overall, these results indicate that altitude exerts little influence on CLR incidence but significantly affects severity. This implies that environmental conditions

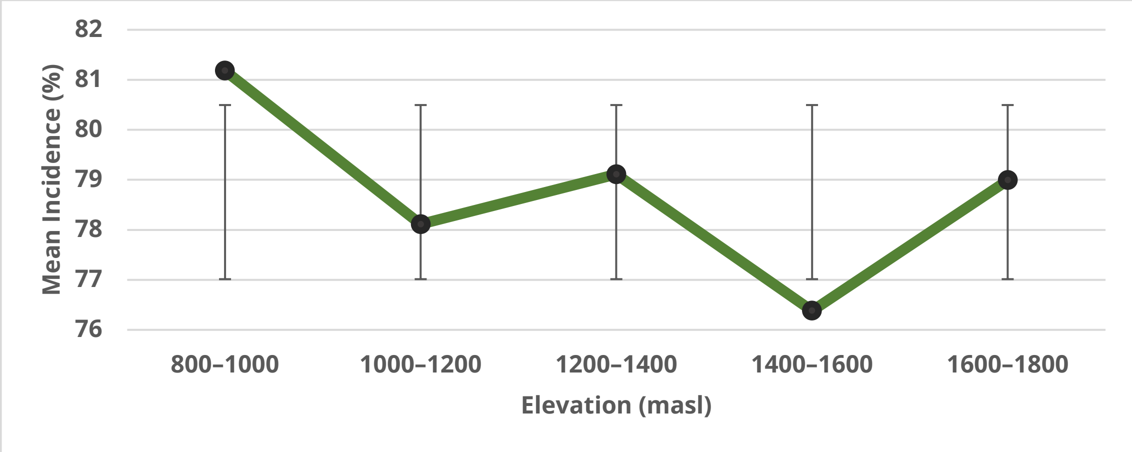

Figure 3. Mean coffee leaf rust (CLR) incidence (%) across elevation gradients in Aceh Tengah, Indonesia. Bars indicate standard deviation (SD).

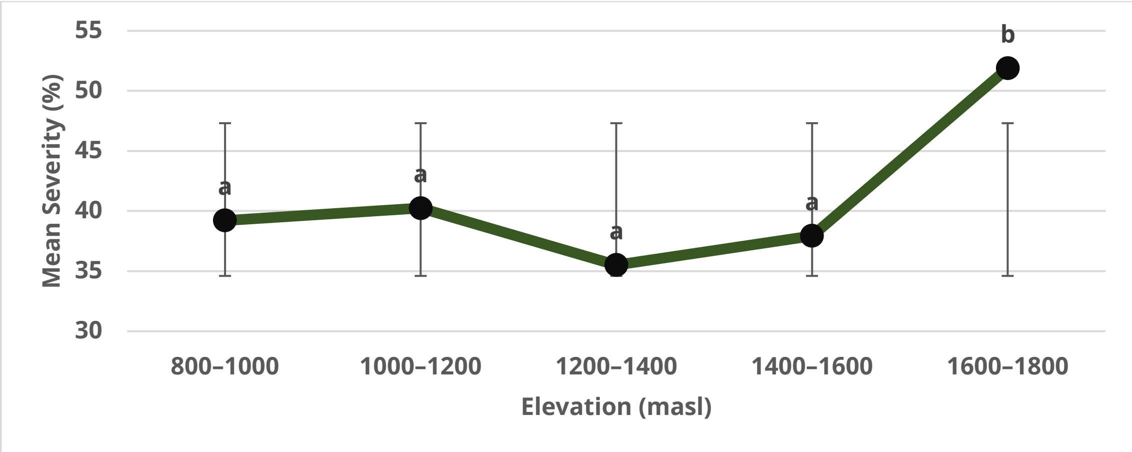

Figure 4. Mean coffee leaf rust (CLR) severity (%) across elevation gradients in Aceh Tengah, Indonesia. Bars with different letters differ significantly according to the LSD test ($p < 0.05$).

at higher elevations may favor pathogen development once infection has occurred. The distinction between infection frequency and lesion expansion highlights the need to consider altitude-specific microclimatic and agronomic factors in CLR management strategies.

3.3. Discussion

The present study demonstrates that elevation exerts different influences on coffee leaf rust (CLR) dynamics in Aceh Tengah. While the incidence of infection remained relatively constant across all altitudinal ranges, the severity of disease increased significantly with elevation. This finding suggests that the pathogen is widely distributed throughout coffee-growing areas and that local environmental conditions at higher elevations favor more rapid disease development once infection occurs [27]. The distinction between the patterns of incidence and severity reflects the combined effects of microclimate, host physiology, and pathogen performance along the altitudinal gradient [28].

The absence of significant variation in CLR incidence across elevation ranges indicates that the initial infection process is not strongly constrained by altitude [29]. High infection frequencies in all elevation zones may result from a uniform distribution of inoculum sources and similar cultivation practices among farmers [21]. Factors such as planting density, shade level, and pruning frequency were generally consistent across sites, which could reduce differences in disease establishment [9]. In addition, continuous spore dispersal by wind and rain splash during the wet season allows the pathogen to infect susceptible leaves regardless of elevation [30]. These conditions contribute to the widespread presence of CLR across the landscape, explaining the lack of significant differences in incidence.

In contrast, the clear increase in disease severity at higher elevations highlights the influence of local environmental factors on fungal development. Cooler temperatures, prolonged periods of leaf wetness, and higher relative humidity are known to enhance urediniospore germination and lesion expansion [7]. At elevations above 1600 masl, these conditions are more prevalent, leading to longer infection cycles and greater sporulation potential. The microclimatic environment at higher altitudes may also slow leaf drying and maintain surface moisture for extended periods, creating favorable conditions for secondary infection [31]. Thus, altitude indirectly affects CLR intensity by modifying temperature–moisture interactions that regulate the pathogen's life cycle [32].

The results of this study are consistent with observations in other coffee-producing regions where highland microclimates contribute to greater disease intensity despite reduced infection frequency [33]. This pattern reflects a complex trade-off between temperature and humidity, where cooler conditions limit some physiological processes of the host but simultaneously support fungal persistence [34]. However, unlike some regions where extremely high altitudes suppress disease due to low temperatures, the upper range of elevations in Aceh Tengah appears to remain within the optimal microclimatic window for CLR development. This finding suggests that the climatic threshold for rust suppression may occur at even higher elevations in this region, influenced by local topography and canopy conditions.

Although the present study provides valuable insights into the altitudinal dynamics of CLR, several limitations must be acknowledged. The study did not include direct measurements of microclimatic parameters such as air temperature, relative humidity, or leaf wetness duration. These variables likely explain much of the observed variation in severity between elevation zones. Furthermore, the uniform management systems assumed across sites were not quantitatively assessed, which may contribute to residual variation in disease expression. Future studies should integrate environmental monitoring and farm management data to improve causal inference and strengthen predictive models of disease distribution.

Overall, the findings suggest that altitude primarily influences coffee leaf rust through its effect on microclimate rather than by changing pathogen presence or host exposure. Understanding how environmental parameters shift with elevation is essential for predicting disease risk under future climate scenarios. The observed increase in severity at higher altitudes emphasizes the need for location-specific disease management strategies that consider elevation, temperature, and moisture conditions. This study provides baseline evidence to support the development of environmentally tailored approaches to rust control, aligning with the broader goal of sustainable coffee production in ecologically diverse landscapes.

4. Conclusions

This study shows that elevation influences the intensity of coffee leaf rust in Arabica coffee plantations of Aceh Tengah. The variation in disease development is more related to environmental differences than to the presence of the pathogen itself. Local microclimatic conditions such as temperature, humidity, and the duration of leaf wetness appear to play a key role in increasing rust severity at higher elevations.

The findings highlight the need to include environmental factors in disease monitoring and management programs. Adjusting control measures according to elevation can help improve the effectiveness and sustainability of coffee cultivation. Further research that combines field observations with microclimatic and agronomic data will be important for developing better predictions of disease behavior under changing environmental conditions.

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