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Research Article

SPATIOTEMPORAL ANALYSIS OF METEOROLOGICAL DRIVERS OF MAJOR FOLIAR FUNGAL DISEASES IN RUBBER BUDWOOD GARDENS IN COTE D'IVOIRE

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ABSTRACT

Latex production in Côte d'Ivoire is significantly influenced by meteorological conditions and various diseases, particularly foliar fungal diseases affecting *Hevea brasiliensis*, which can cause yield losses of up to 100%. This study aims to identify the climatic factors driving the severity of these diseases across different ecological zones. Surveys were conducted in budwood gardens (JBG) across six agroecological zones, with meteorological data collected on-site. The analysis identified *Helminthosporium heveae*, *Colletotrichum gloeosporioides*, and *Corynespora cassiicola* as the most prevalent fungi, exhibiting high incidence and severity in key production areas such as Tabou and Nouamou. Multiple regression analyses revealed that rainfall and relative humidity (correlation coefficients ranging from 0.4 to 0.55, $p < 0.0001$) and leaf wetness duration (correlation coefficient > 0.7, $p < 0.0001$) are critical predictors of disease severity. Specifically, each additional unit of leaf wetness increased infection severity by 0.642 for *H. heveae*, 0.435 for *C. gloeosporioides*, and 0.832 for *C. cassiicola*. These findings underscore the importance of meteorological factors in disease development and could support the establishment of early warning systems to manage foliar fungal diseases of *H. brasiliensis* in Côte d'Ivoire.

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INTRODUCTION

Plant diseases pose a significant threat to agricultural productivity (Anand and Rajeshkumar, 2022). Their rapid proliferation can lead to substantial crop losses, jeopardizing the food and nutritional security of millions (Reynolds, 2010; Ezrari et al., 2024). The emergence and impact of these diseases are intricately linked to the interaction between plants, pathogens, and environmental conditions.

Climate model projections suggest that extreme weather events may intensify these interactions, potentially exacerbating plant-pathogen dynamics (Ghini et al., 2012). Key meteorological factors, including temperature, rainfall, relative humidity, and leaf wetness, are critical in driving the infection processes and the spread of pathogens (Ghini et al., 2012). These factors also influence the onset and progression of crop diseases, potentially altering the geographical distribution of pathogenic species (Chakraborty and Newton, 2011; Pautasso et al., 2012). Rapid changes in these meteorological conditions could lead to unpredictable disease outbreaks, posing further challenges to agricultural systems (Kliejunas et al., 2009).

Fungal leaf diseases caused by microscopic fungi significantly affect the physiological processes of rubber trees and latex production, thereby impacting the economies of rubber-producing countries (Oktavia et al., 2021). The most common foliar fungal diseases are caused by *Corynespora cassiicola*, *Colletotrichum gloeosporioides*, *Helminthosporium heveae*, *Oidium heveae*, and *Phytophthora palmivora* (Aliya et al., 2022). Although these diseases are prevalent in rubber-growing regions, their incidence and severity vary, leading to substantial losses in natural rubber production, estimated at approximately 20-25% (Barthe et al., 2007).

Heng and Joo (2017) reported that elevated humidity significantly facilitates the spread of *O. heveae* in rubber trees. Key factors influencing the high infection rates of *C. gloeosporioides* during the refoliation period of rubber trees include temperature, humidity, and rainfall (Liu et al., 2023). Furthermore, the maximum dispersal of *C. cassiicola* spores occurs during the dry season when temperatures range between 25°C and 30°C (Jayasinghe, 2000).

H. heveae, also known as *Bipolaris heveae*, thrives in warm, temperate, and tropical regions (Manamgoda et al., 2014). This fungus has been reported to proliferate on rubber trees at temperatures ranging from 25 to 27°C and a relative humidity of approximately 75% under natural daylight conditions (Liang et al., 2019). During the rainy season, young plants with wounds are particularly susceptible to infection by *Phytophthora palmivora*. This pathogen sporulates actively on lesions, which develop into parallel vertical depressions (Mazlan et al., 2019).

Since 2010, Côte d'Ivoire has experienced recurring outbreaks of epidemic fungal diseases, particularly affecting the IRCA 18 clone. This highly productive rubber-yielding clone, which accounted for about 10% of the national rubber plantation area, has suffered severe economic losses. The incidence of diseases caused by these fungi is notably higher in the southeastern and southern regions of the country compared to other rubber production areas (Prosper et al., 2023).

However, the impact of meteorological factors on the development and severity of fungal diseases in rubber leaves has not been thoroughly investigated, despite their critical role in disease expression. This study aims to identify the climatic factors influencing the epidemiological dynamics of fungal leaf diseases in budwood gardens across rubber production basins of Côte d'Ivoire. The findings will help pinpoint disease-prone regions and the specific weather conditions that promote the expression of each disease. This information will provide a foundation for improved decision-making and effective management strategies for controlling foliar fungal diseases in Côte d'Ivoire.

MATERIAL AND METHODS

Description of sites and experimental design

The study identified meteorological factors influencing the presence and development of *Hevea* leaf diseases in village environments using a network of 6 graftwood gardens (JBG). These gardens were established in six localities: Tabou, Nouamou, Man, Daoukro, Zoukougbeu, and Gagnoa (Figure 1).

The selection of observation sites in Nouamou and Tabou, situated near the Ivorian-Ghanaian and Ivorian-Liberian borders respectively, was based on their shared rubber cultivation practices with neighboring countries. These areas also exhibit a high incidence of foliar fungal diseases in *Hevea* (Konan et al., 2023). The Man site was selected due to its unique microclimate, characterized by high annual rainfall (approximately 1,400 to 1,600 mm) and cool, dry conditions during drought periods. Daoukro, on the other hand, represents a marginal area for rubber cultivation, while Gagnoa and Zoukougbeu are recognized as key regions for crop development.

The experimental design consisted of three blocks, each containing 17 microplots (Figure 2). Each microplot featured the most widely cultivated rubber clones in Côte d’Ivoire, with an initial plant density of approximately 50 plants per microplot. Spacing was carefully maintained: one meter between plants, 1.5 meters between adjacent microplots, and two meters between blocks (Figure 3).

The observations focused on the presence or absence of leaf symptoms associated with diseases caused by rubber tree fungi in the existing plants at JBG. The primary symptoms identified included vein browning in stripes, a characteristic diagnostic of *C. cassiicola*, and white spots with brown borders at the center of the leaves, indicative of *H. heveae*. Additional symptoms observed were necrotic lesions at the base of the leaf blade caused by *C. gloesporioides* and fine white mycelial growth covering leaves, attributed to *O. heveae*. Lastly, typical symptoms of *P. palmivora* were noted, including brown lesions on petioles accompanied by white droplets of coagulated latex (Figure 4).

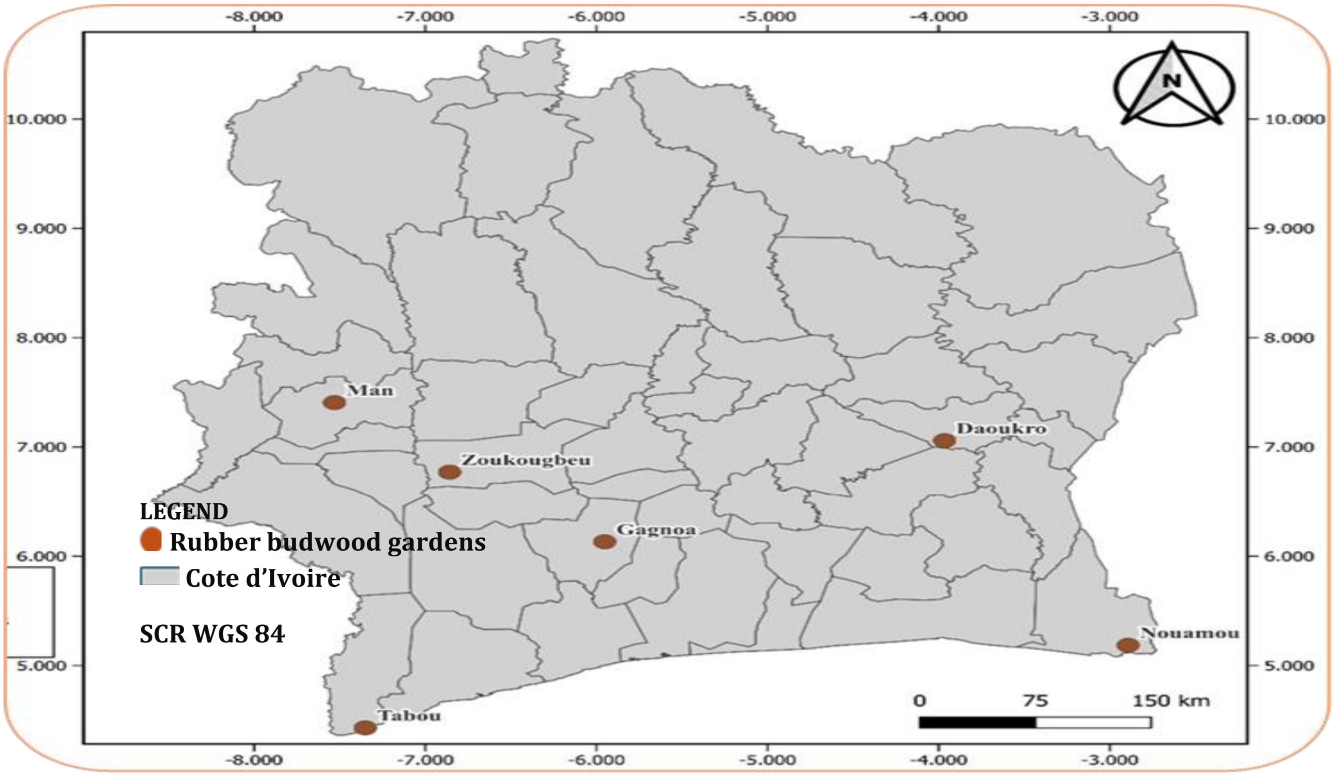

Figure 1. Study sites

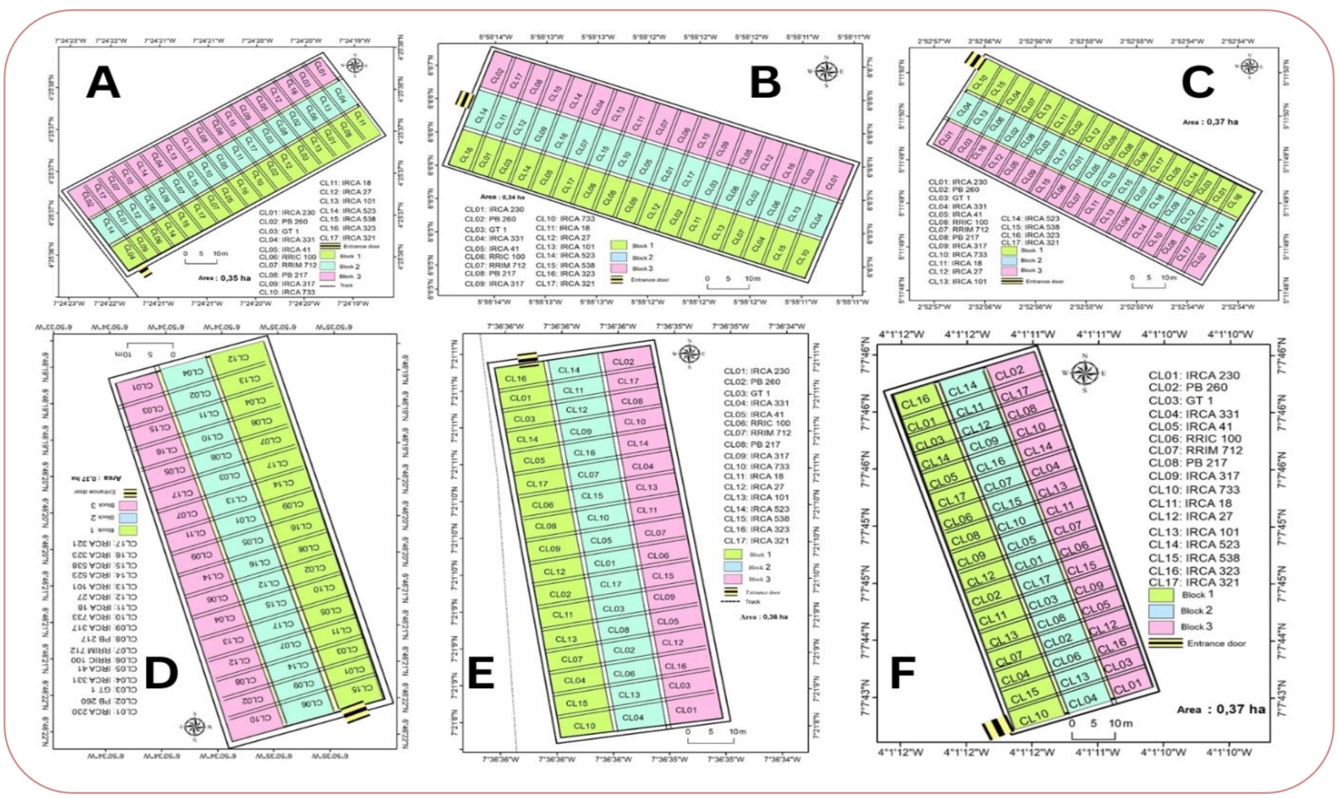

Figure 2. Experimental design of graft wood garden clones in the six localities (A. Tabou, B. Gagnoa, C. Nouamou, D. Zoukougbeu, E. Man, F. Daoukro).

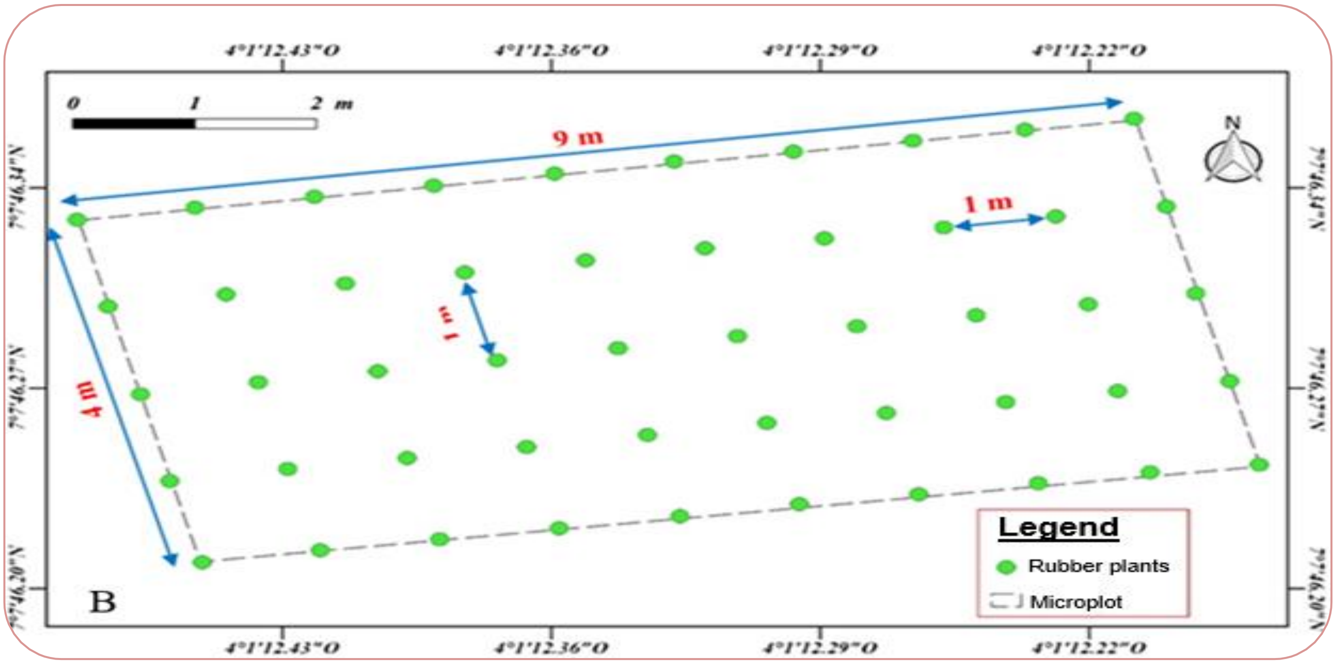

Figure 3. Rubber planting arrangement on an elementary plot.

Observations

Plant observations were conducted systematically for each plant, with plant health serving as the key variable. A total of six JBGs and 10,755 seedlings (Table 1) were monitored every two weeks over the study period from November 30, 2020, to June 16, 2023. During this period, two recutting phases were recorded: the first from October 7 to November 28, 2021, and the second from April 7 to May 29, 2022. This allowed for three distinct study periods: the first from November 30, 2020, to October 6, 2021; the second from November 29, 2021, to April 6, 2022; and the third from May 30, 2022, to June 16, 2023. Notably, no fungicides were applied to the experimental plots monitored during this study.

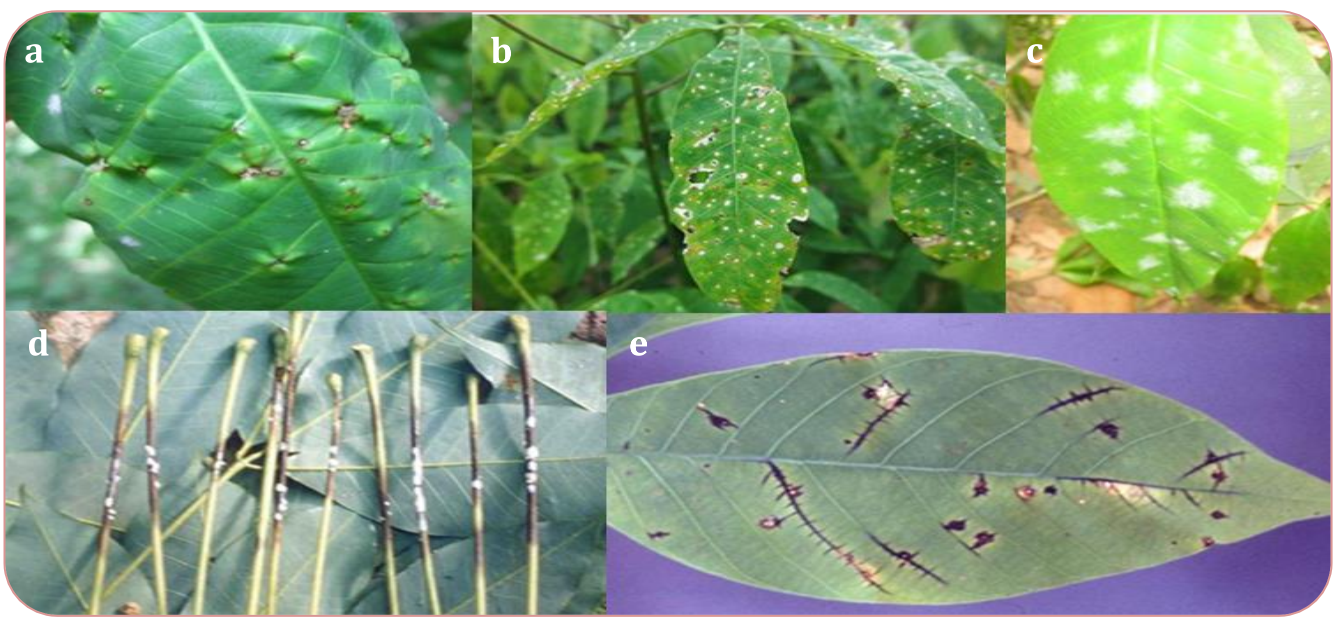

Figure 4. Fungal symptoms on rubber leaves. a: *C. gloesporioides*, b: *H. heveae*, c: *O. heveae*, d: *P. palmivora*, and e: *C. cassiicola*.

Table 1. Number of plants observed in the graftwood gardens.

Locality	Number of plants/ observation
Tabou	1489
Nouamou	2103
Zoukougbeu	1977
Gagnoa	1694
Daoukro	1518
Man	1974
Total	10755

Measured variables

Variable at plant level

The severity index (SI) was calculated using a 0-5 rating scale as described by Manju et al. (2002). Each plant was assessed based on the most severely affected leaves exhibiting the highest level of symptoms (Table 2).

Table 2. Disease rating scale for sassement of severity of disease.

Rating Scale	Description of symptoms
0	No infection (no leaf lesions)
1	Very weak attack (less than five lesions per leaf)
2	Weak attack (5-10 lesions and 10-25% defoliation)
3	Medium attack (more than ten lesions and 26-50% defoliation)
4	Severe attack (large lesions and 51-75% defoliation)
5	Very severe attack (large lesions and over 75% defoliation)

Derived variable at plot level

The incidence or attack rate for each disease observation date was calculated for each JBG using the following formula:

$$TA_t = \frac{Nx_t}{Nt_t} \times 100$$

Where TA_t is the attack rate at the observation date, Nx_t = Number of diseased plants, and

Nt_t = Total number of plants.

Weather variables

Regarding meteorology, daily records of mean temperature, rainfall, relative humidity, and leaf wetness were collected at each of the six JBGs in the selected localities. The data were obtained from the website ng.fieldclimate.com, which is linked to automatic weather stations (Figure 5) installed in each locality, 5 km from the JBGs. These stations are of the Campbell CR10X model (Campbell Scientific Ltd., Shepshed, United Kingdom) and are equipped with an ARG100 tipping bucket rain gauge, an HMP45C temperature and humidity sensor, and a 237F humidity sensor.

Figure 5. Weather station.

Statistical processing and data analysis

The data on disease parameters (severity and incidence) were analyzed using a randomized complete block design. This study examined the trends in the severity and incidence of fungal leaf diseases in rubber trees across the different study periods using descriptive statistical techniques. Pearson correlation analysis was performed to assess the relationship between weather conditions and the severity and incidence of diseases in the Graft Wood Gardens in Côte d'Ivoire. Furthermore, regression analysis was conducted to determine the influence of meteorological factors on the severity and incidence of foliar fungal diseases. No data were missing from the analyzed dataset. The statistical analysis was carried out using Python 3.11 (JupyterLab). The significance threshold for this analysis was set at $\alpha < 0.05$.

RESULTS

Severity and incidence of fungal diseases in rubber leaves across experimental sites in graft wood garden, Côte d'Ivoire

Recording of diseases in **graft wood gardens across study periods**

The findings of the study indicated that among the pathogens considered significant in rubber orchards of producing countries, *H. heveae*, *C. gloeosporioides*, and *C. cassiicola* were the most predominant in graftwood gardens in Côte d'Ivoire. Furthermore, the presence of *O. heveae* was confirmed in Côte d'Ivoire JBGs, but its incidence and severity were very low, ranging between 2.48% and 3.41% during the observation period.

The incidence and severity of leaf diseases in rubber trees in JBGs exhibited significant variation between two observation periods: the first from November 30, 2020, to October 6, 2021, and the final from May 30, 2022, to June 16, 2023. For *H. heveae*, the severity rates increased from 26.82% in the first period to 32.08% in the final period, while incidence rates decreased slightly, from 46.32% to 41.95%. For *C. gloeosporioides*, the severity decreased from 28.40% in the first period to 20.73% in the final period, and the incidence dropped from 53.97% to 46.29%. In contrast, leaf blight caused by *C. cassiicola* showed an increase, with severity rising from 15.64% in the first period to 29.33% in the final period and incidence increasing from 31.61% to 46.29%.

The lowest incidences and severities of all four fungi were recorded during the intermediate period (period 2) between two coppicing cycles (Table 3). Given the minimal impact of powdery mildew and the absence of *P. palmivora*-induced diseases, future research will prioritize fungal epidemics with the highest incidence and severity rates.

Table 3. Severity and incidence of diseases causing abnormal leaf fall in young rubber trees across different periods in Côte d'Ivoire.

Pathogen		Period	Severity (%)	Incidence (%)
Helminthosporium heveae		1	26.82	46.32
		2	9.57	15.49
		3	32.08	41.95
	LSD (0.01)		2.19	3.26
	CV (%)		0.61	0.61
Colletotrichum gloesporioides		1	28.40	53.97
		2	12.91	24.45
		3	20.73	46.29
	LSD (0.01)		1.45	2.53
	CV (%)		0.41	0.41
Corynespora cassiicola		1	15.65	31.61
		2	9.55	18.33
		3	29.33	46.29
	LSD (0.01)		2.27	4.00
	CV (%)		0.99	0.99
Oidium heveae		1	2.48	2.48
		2	1.88	1.88
		3	3.41	3.41
	LSD (0.01)		0.59	0.51
	CV (%)		1.54	1.34

Disease severity and incidence in graftwood gardens across different localities and observation period

Period 1 (from 30 November 2020 to 06 October 2021)

Disease incidence and severity caused by *H. heveae* across the six study localities, Daoukro, Gagnoa, Man, Nouamou, Tabou, and Zoukougbeu, ranged from 5.58% to 69.5% and 3.41% to 43.7%, respectively. The highest incidence and severity were recorded in Tabou and Nouamou, while the lowest were observed in Man.

For *C. gloeosporioides*, the incidence ranged from 27.5% to 80.3%, and severity from 16.2% to 36.3%. The highest values for both incidence and severity were observed in Tabou, with the lowest recorded in Man.

The incidence and severity of *C. cassiicola*-induced leaf blight ranged from 0% to 69.1% and 0% to 35.1%, respectively, with the highest rates observed in Tabou and zero incidence in Man. Statistical analysis revealed significant differences in disease incidence and severity across localities ($p < 0.05$).

The findings indicate that Tabou and Nouamou experienced the highest incidence and severity of the three fungal leaf diseases, while Zoukougbeu ranked third, with notable levels of disease caused by *C. cassiicola* and *H. heveae* (Figure 6).

Period 2 (from 29 November 2021 to 06 April 2022)

The incidence and severity of fungal diseases in graftwood gardens were generally mild across all localities. However, *C. cassiicola* emerged as the most prominent disease, with a high incidence of 41.7% recorded in Tabou and a severity of 22.2% observed in Nouamou. In contrast, no cases were reported in Man. These two localities showed significant differences from the others in terms of fungal presence ($p < 0.05$) (Figure 7).

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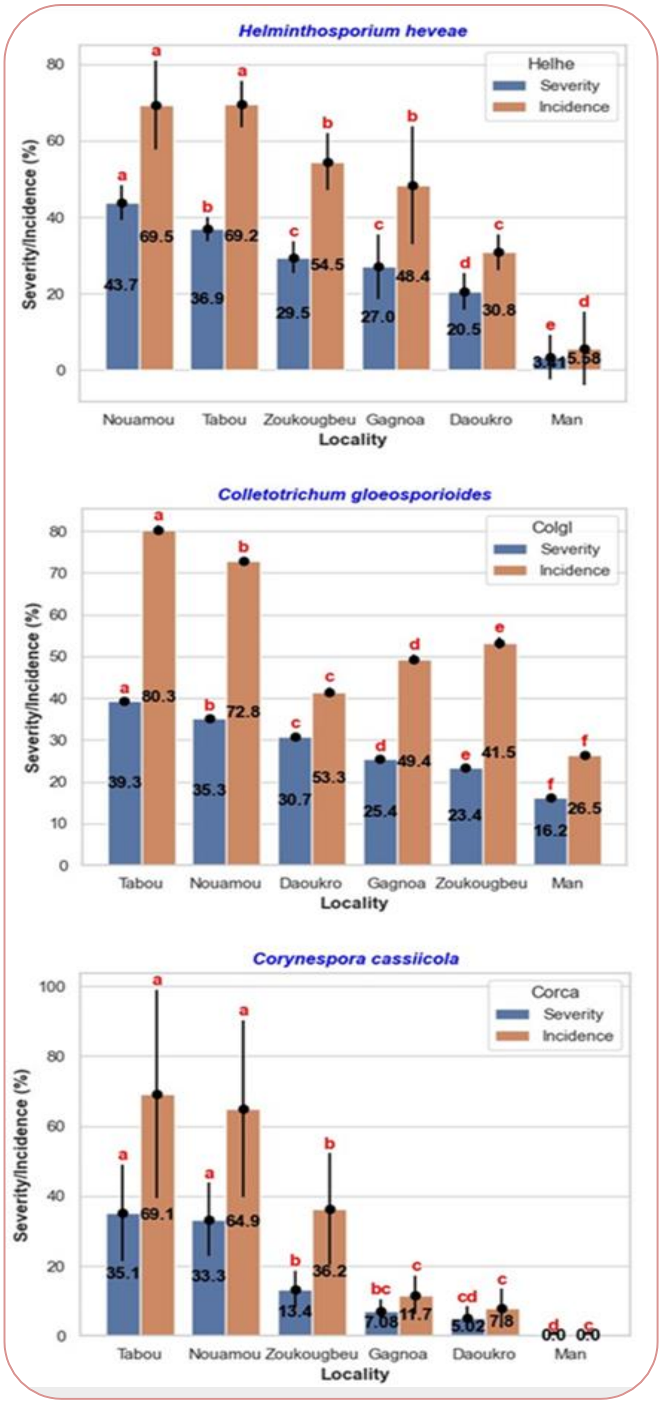

Figure 6. Incidence and severity of foliar fungal spot diseases in Hevea across localities in Côte d'Ivoire during observation period 1.
Helhe = *Helminthosporium heveae,* Colgl = *Colletotrichum gloesporioides* and Corca = *Corynespora cassiicola*.
Histograms with the same letter are not statistically different according to the Newman and Keuls test at the 5% significance level.

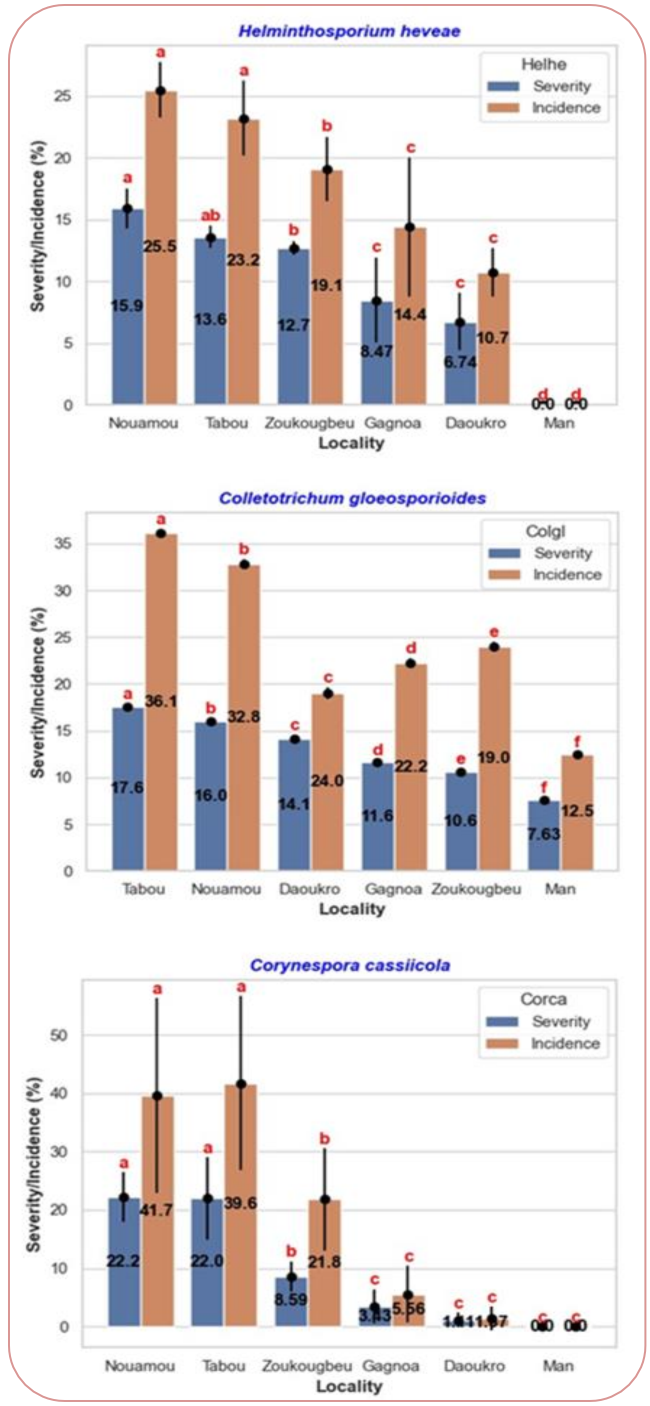

Figure 7. Incidence and severity of foliar fungal spot diseases in Hevea across localities in Côte d'Ivoire during observation period 2.
Helhe = *Helminthosporium heveae,* Colgl = *Colletotrichum gloesporioides* and Corca = *Corynespora cassiicola*.
Histograms with the same letter are not statistically different according to the Newman and Keuls test at the 5% significance level.

Period 3 (from 30 May 2022 to 16 June 2023)

Statistical analysis ($p < 0.05$) revealed significant differences in the incidence and severity of diseases caused by *H. heveae* and *C. gloeosporioides* across the six localities studied. The study period was marked by high rates of disease incidence and severity. Notably, *H. heveae* exhibited the highest incidence in Tabou (61.9%) and the highest severity in Nouamou (51.3%), while the lowest values for both incidence (4.67%) and severity (2.88%) were recorded in Man. Zoukougbeu ranked third, with incidence and severity rates of 50.2% and 35.1%, respectively.

C. gloeosporioides emerged as the most aggressive pathogen, showing a peak incidence of 70% and a severity of 44.3% in Tabou. The localities of Daoukro, Gagnoa, and Zoukougbeu displayed incidence rates ranging from 36.9% to 43.6% and severity values between 20.2% and 32.9%.

Disease caused by *C. cassiicola* was most prominent in Nouamou and Tabou, with incidence rates ranging from 64.8% to 69.9% and severity levels between 43.6% and 45.9%. Zoukougbeu followed with an incidence of 36.4% and severity of 18.5%. In contrast, Gagnoa and Daoukro recorded low incidence and severity rates, both below 15% and 10%, respectively. No *C. cassiicola* infection was observed in Man (Figure 8).

Effect of weather conditions on the severity and incidence of fungal leaf diseases in rubber trees

The highest temperatures were recorded from December 2020 to June 2021, with a notable shift in July and August 2021, followed by thermal stability from June to October 2022. A temperature drop occurred in July and August 2022 and 2023, marking a cool period, as shown in the histograms in Figure 9. Significant monthly precipitation was recorded from May (180 mm) to July (200 mm) and from September (210 mm) to October (225 mm) in 2021. In 2022, notable rainfall was observed from April (90 mm) to July (130 mm), from September (125 mm) to October (345 mm), and from April (125 mm) to June (225 mm) in 2023. Light rainfall was recorded from December (60 mm) 2020 to April (40 mm) 2021, from December (40 mm) 2021 to March (45 mm) 2022, and from December (55 mm) 2022 to March (50 mm) 2023.

During the disease observation period, December 2021 to February 2022, October 2022, and January 2023 were the least humid months, with average relative humidity between 87% and 89%. In contrast, relative humidity exceeded 90% in the remaining months. The longest wetting periods were observed from April to October 2021, with a decrease in August 2021. Prolonged wetting times were also noted in July and October 2022 and from April to June 2023, ranging between 60 and 110 hours.

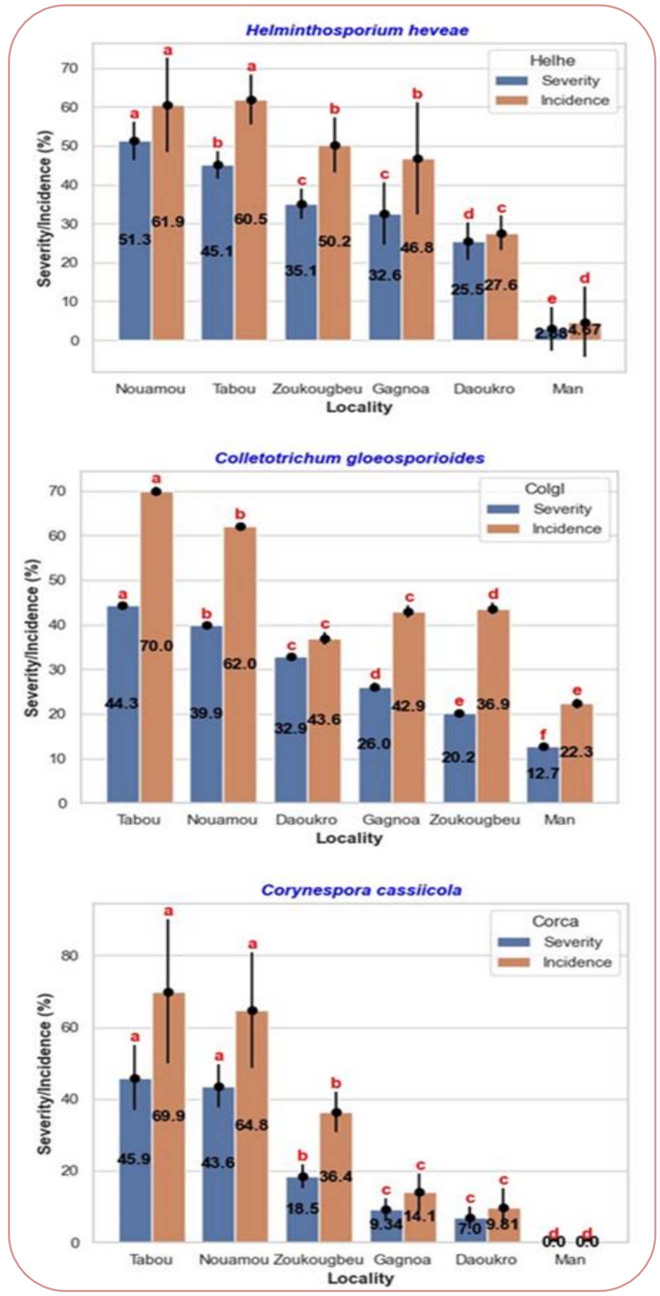

Figure 8. Incidence and severity of foliar fungal spot diseases in Hevea across localities in Côte d'Ivoire during observation period 3.

Helhe = *Helminthosporium heveae,* Colgl = *Colletotrichum gloesporioides* and Corca = *Corynespora cassiicola*.

Histograms with the same letter are not statistically different according to the Newman and Keuls test at the 5% significance level.

Based on the analysis of meteorological variations, six fungal leaf disease recording periods were selected to study the impact of weather on the incidence and severity of diseases affecting young rubber seedlings in graftwood gardens.

The lowest incidences and severities of *H. heveae* (15-18% and 10-11%) were recorded from December 2021 to April 2022, under weather conditions with temperatures ranging from 29°C to 31°C, relative humidity below 85%, rainfall below 50 mm, and wetting times under 45 h. Conversely, the highest incidences and severities (45-54% and 24-28%) occurred from April to October 2021 and from June to October 2023, with meteorological conditions including temperatures between 24°C and 29°C, relative humidity over 90%, precipitation exceeding 120 mm, and wetting times over 50 h (Figure 9).

For *C. gloesporioides*, the lowest incidences and severities (25% and 4%) were also recorded from December 2021 to April 2022, with temperatures between 29°C and 32°C, relative humidity between 83% and 88%, rainfall between 27 mm and 100 mm, and wetting times between 26 and 47 hours. On the other hand, the highest incidence and severity (46-54% and 28-30%) were observed from December 2020 to October 2021, and from June 2022 to June 2023, with weather conditions including temperatures between 27°C and 31°C, relative humidity between 85% and 94%, precipitation up to 350 mm, and wetting times of up to 110 h.

The lowest incidences and severities of *C. cassiicola* (3-11.5% and 3-7.5%) were recorded in February 2021 and January 2022, with temperatures between 29°C and 32°C, relative humidity between 86% and 90%, precipitation between 10 mm and 49 mm, and wetting times under 50 h. The highest incidence and severity (36-38% and 27.5-28.5%) were observed from March to October 2021, June to October 2022, and April to June 2023, with temperatures between 24°C and 28°C, relative humidity between 87% and 97%, rainfall ranging from 55 mm to 350 mm, and wetting times from 48 hours to a maximum of 110 h (Figure 9).

Relationship between the severity and incidence of fungal diseases on rubber leaves and climatic factors

Our study utilized Pearson's correlation coefficient to assess the collinearity of independent variables, such as meteorological factors. The correlation between disease incidence, severity caused by each fungus, and meteorological variables was analyzed, and the results are presented in Figure 10.

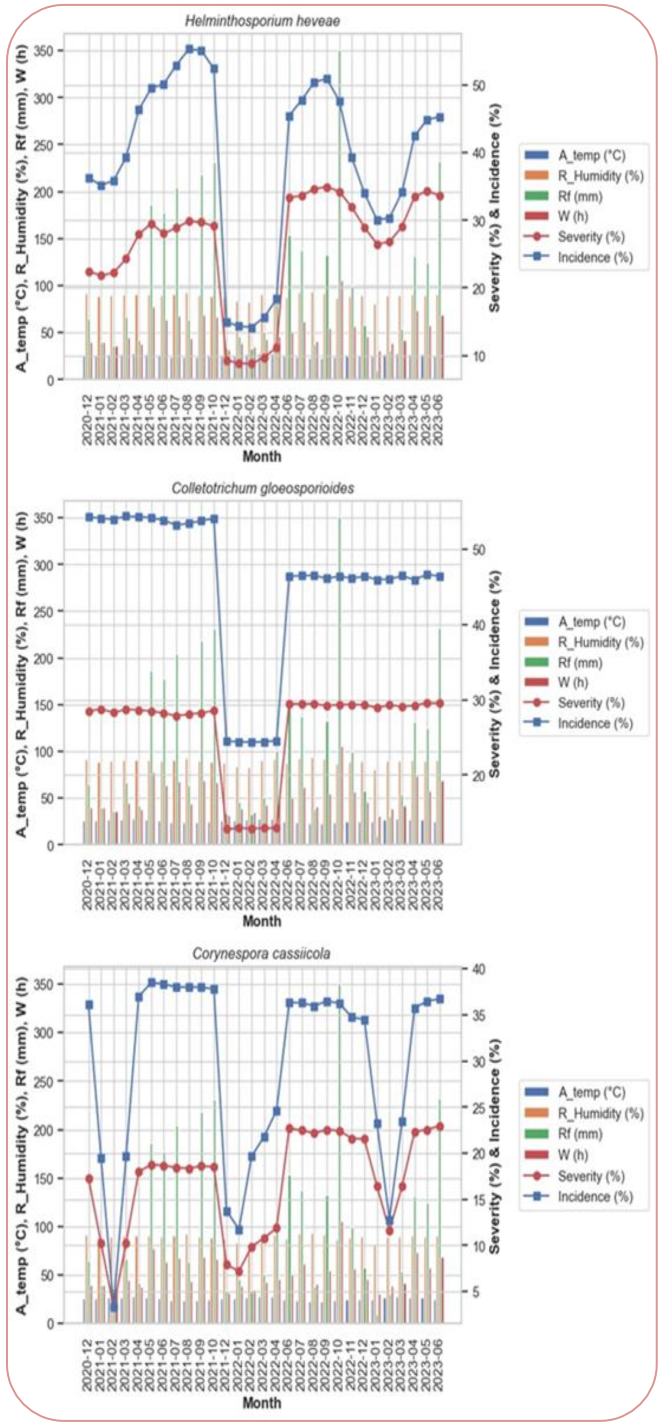

Figure 9. Impact of climatic factors on the incidence and severity of fungal foliar diseases in rubber trees. Meteorological factors: A_temp (°C) = average temperature, R_Humidity (%) = relative humidity, Rf (mm) = rainfall, W (h) = leaf wetness.

The data revealed a moderate, significant positive correlation between both the incidence and severity of each disease associated with the pathogens and factors like relative humidity and rainfall ($p < 0.001$). Specifically, the correlation coefficients for *H. heveae* incidence and severity with relative humidity were r = 0.48 and r = 0.47, respectively, and with rainfall, r = 0.48 and r = 0.41. For *C. gloeosporioides*, the correlation coefficients for incidence and severity with relative humidity were r = 0.55 and r = 0.48, respectively, and with rainfall, r = 0.48 and r = 0.43. Regarding *C. cassiicola*, the correlation coefficients for relative humidity were r = 0.51 and r = 0.54, and for rainfall, r = 0.55 and r = 0.55.

The data also demonstrated a positive, significant correlation between incidence, severity, and leaf wetness duration ($p < 0.001$). The highest correlation coefficients were observed between *C. cassiicola* incidence and severity and leaf wetness duration, with values of r = 0.86 for incidence and r = 0.88 for severity. In contrast, mean temperature showed a negative and non-significant correlation with incidence and severity for all diseases ($p > 0.001$), as shown in Figure 10a, b, c.

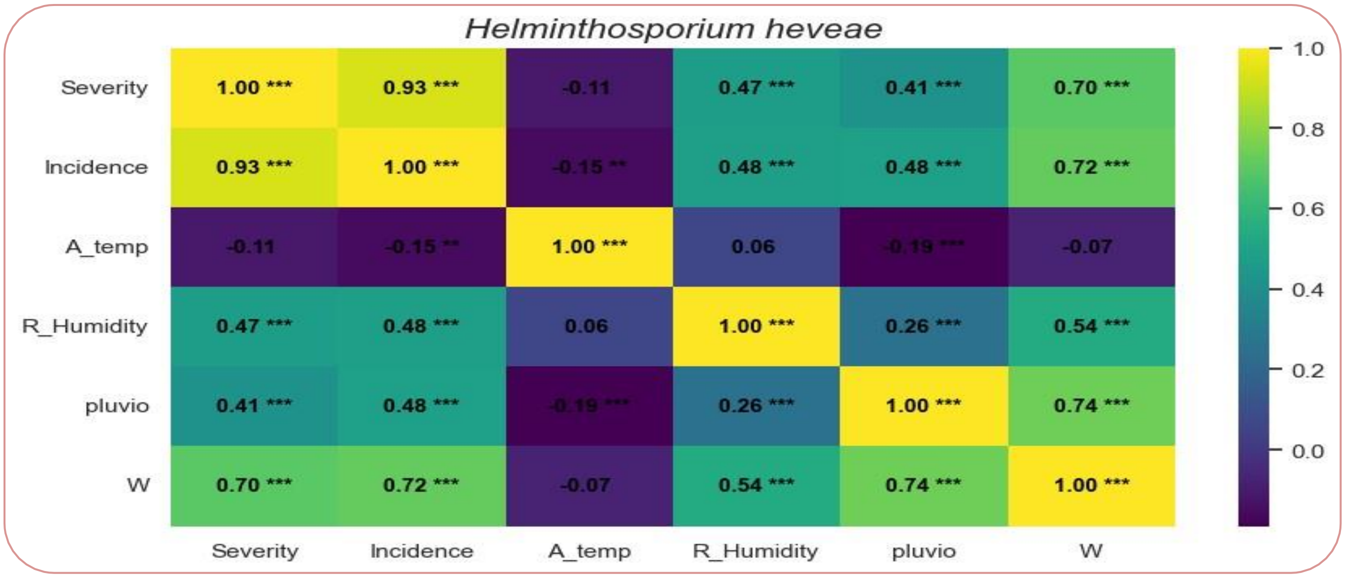

Figure 10a. Pearson correlation analysis between climatic factors and the severity of *H. heveae*. ** = p < 0,01, *** = p < 0,001.

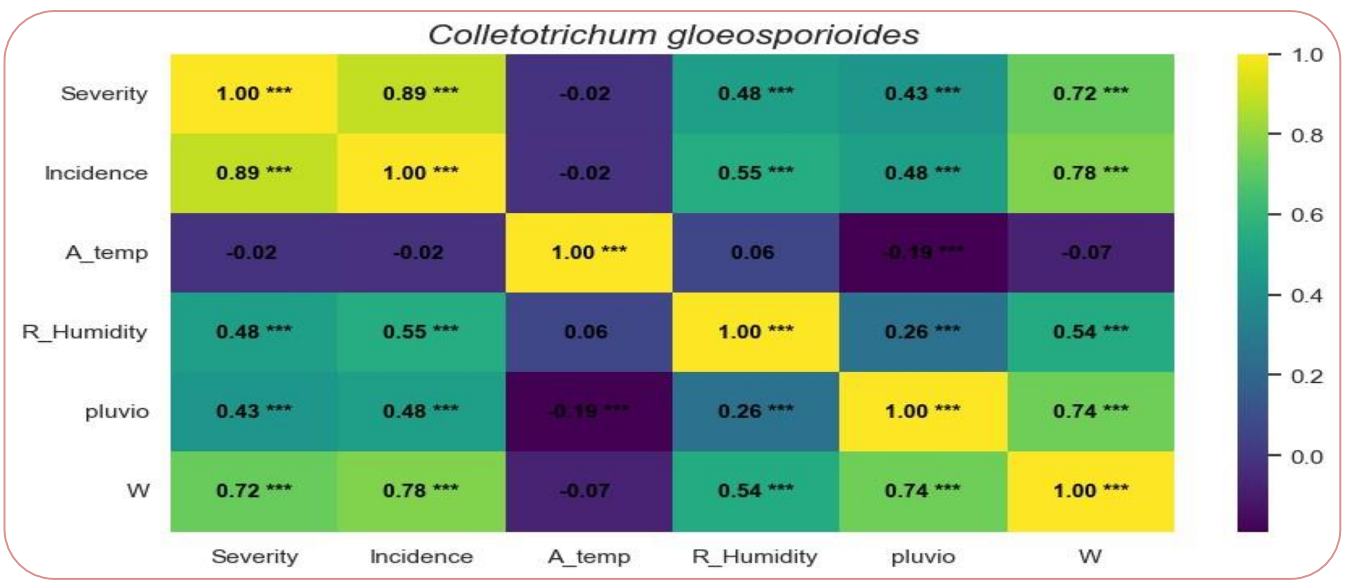

Figure 10b. Pearson correlation analysis between climatic factors and the severity of *C. gloeosporioides*. ** = p < 0,01, *** = p < 0,001.

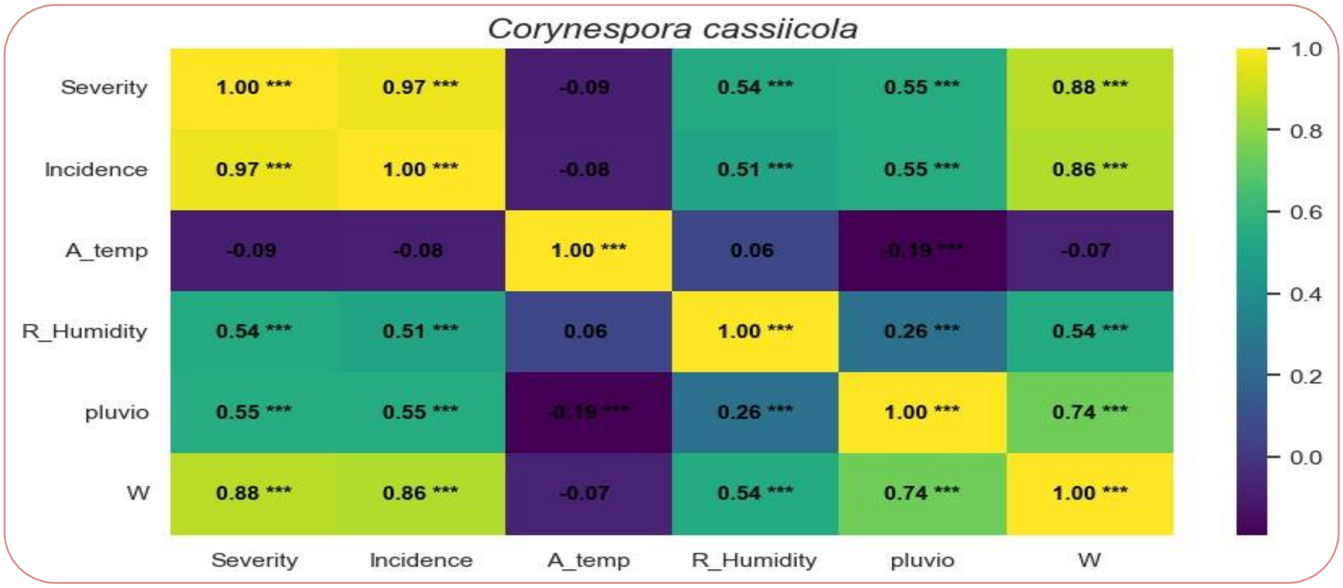

Figure 10c. Pearson correlation analysis between climatic factors and the severity of *C. cassiicola*. ** = p < 0,01, *** = p < 0,001.

Correlation between meteorological variables and disease severity associated with each fungus: detection of multicollinearity among independent variables

Multicollinearity among the independent meteorological variables was examined using various methods. The analysis began with multiple linear regression, which is well-suited for understanding the variation in the severity of fungal diseases on rubber leaves, as it identifies the meteorological factors influencing disease severity. The results showed that the y-intercept (B, constant) for each disease was insignificant ($p > 0.001$). The slope coefficients for the independent variable, relative humidity, were significant ($p < 0.05$). Moreover, the slope coefficients for the two independent variables, rainfall and wetting duration, were highly significant ($p < 0.001$).

The variance inflation factor (VIF) values for relative humidity, rainfall, and wetting duration were 1.505, 2.422, and 3.086, respectively, all of which are well below the threshold of 5. These low VIF values indicate that there is no collinearity problem among the three independent variables (Table 4a, b, c).

Finally, the diagnosis of multicollinearity among the independent variables was based on their condition index (CI), derived from the eigenvalues. A higher CI value suggests the presence of multicollinearity. As a rule of thumb, CI values less than 15 indicate low multicollinearity, values between 15 and 30 suggest moderate multicollinearity, and values greater than 30 indicate high multicollinearity (Young, 2017; Knoke et al., 2002). Table 5 shows the eigenvalues, CI, and variance proportions. The eigenvalue represents the variance of the linear combination of variables, while the CI is a function of the eigenvalues. For the three independent variables, relative humidity, rainfall, and wetting duration, the highest variance proportion (52%) was associated with dimension 1, which had an eigenvalue of 2.06 and a CI of 1.00. The highest CI, 3.26, was for dimension 4, but the variance proportions for the associated variables were zero, indicating no evidence of collinearity between the variables.

Table 4a. Results of multiple regression analysis for *H. heveae*.

Variable	Non-standardized coefficient		t	p	VIF
	Estimated values	standard deviation			
Y-intercept	14.433	13.967	1.033	0.302	
Relative humidity	0.288	0.124	2.316	0.021	1.505
Rainfall	-0.058	0.014	-4.060	0.000	2.422
Humectation	0.642	0.051	12.591	0.000	3.086

Table 4b. Results of multiple regression analysis for *C. gloesporioides*.

Variable	Non-standardized coefficient		t	p	VIF
	Estimated values	standard deviation			
Y-intercept	2.935	9.019	0.325	0.745	
Relative humidity	0.156	0.080	1.939	0.053	1.505
Rainfall	-0.032	0.009	-3.513	0.000	2.422
Humectation	0.435	0.014	13.258	0.000	3.086

Table 4c. Results of multiple regression analysis for *C. cassiicola*.

Variavle	Non-standardized coefficient		t	p	VIF
	Estimated values	standard deviation			
Y-intercep)	0.211	9.480	0.022	0.982	
Relative humidity	0.173	0.084	2.054	0.041	1.505
Rainfall	-0.058	0.010	-5.988	0.000	2.422
Humectation	0.832	0.035	24.043	0.000	3.086

Table 5. Collinearity diagnosis.

Diagnosis of collinearity [Target variable: Severity]							
Model	Dimension	Eigenvalues	condition index	Variance proportions	Relative humidity	Rainfall	Humectation
1	1	2.06	1.00	0.00	0.52	0.52	0.52
	2	1.07	1.39	0.00	0.05	0.05	0.05
	3	0.67	1.76	0.00	0.17	0.17	0.17
	4	0.19	3.26	0.00	0.27	0.27	0.27

DISCUSSION

Distribution of graftwood garden fungal diseases on hevea leaves by period and locality

A study of fungal diseases affecting rubber tree leaves in various graftwood gardens across the country from November 30, 2020, to June 16, 2023, identified *H. heveae*, *C. gloeosporioides*, and *C. cassiicola* as the most prevalent pathogens. This report marks the first documentation of these diseases in the rubberwood graft gardens of the country. Similar symptoms caused by these three fungi have been observed in several rubber-producing countries, including Malaysia (Aliya et al., 2022), India (Thakurdas et al., 2002), China (Cao et al., 2017), and some African countries (Déon et al., 2012). These findings are consistent with those of Omorusi et al. (2013), who identified *C. cassiicola*, *C. gloeosporioides*, and *H. heveae* as the main fungal diseases of rubber trees in Nigeria. Furthermore, these same pathogens were identified as the primary causes of leaf diseases in mature rubber plantations in the same areas where JBG is grown in Côte d'Ivoire (Konan et al., 2023). Thus, *C. cassiicola*, *C. gloeosporioides*, and *H. heveae* can be considered the main diseases affecting rubber trees in graftwood gardens in Côte d'Ivoire.

The diseases were more significant during periods 1 and 3, from November 30, 2020, to October 6, 2021, and from May 30, 2022, to June 16, 2023, respectively. During these periods, the average severity and incidence of disease caused by *H. heveae* exceeded 25% and 40%, respectively, while *C. gloeosporioides* exceeded 22% and 45%. For *C. cassiicola*, the average severity over the two periods exceeded 20%, and the average incidence was above 35%. The period from November 29, 2021, to April 6, 2022, characterized by low incidences and severities of the four fungi, was designated as the intermediate period (period 2). Periods 1 and 3 were full years of sanitary data collection, unlike period 2, which fell between two coppicing cycles. This discrepancy may be related to the succession of dry and rainy seasons during the extended observation periods, compared to the single dry season characteristic of the period between coppicings.

Moreover, the growth of immature plants is rhythmic, with regular leaf emergence, ensuring that young, susceptible leaves are always present, especially during periods 1 and 3. In contrast, during period 2, the conidia of the fungi present disappear entirely, and new infestations depend on the emergence of new leaves. Our results confirm those of Guyot (2007), who, in a study on the role of inoculum in the *Microcyclus ulei* epidemic in JBG in the Amazon region, indicated that coppicing shows that the spores from the fungi encountered in the plots indeed came from those experimental plots. Consequently, incidences and severities after coppicing were visibly low.

Disease assessment across the study area revealed the presence of *C. gloeosporioides* at all sites. The highest disease severity and incidence for the four fungi during each period were observed in the border localities of Tabou and Nouamou, located on the Côte d'Ivoire-Liberia and Côte d'Ivoire-Ghana borders, respectively. Moreover, there was variability in disease incidence and severity within each rubber-growing basin, with significant differences between the two basins (Tabou and Nouamou). However, the severity and incidence of *C. cassiicola* across the three periods were similar in both border localities.

In contrast, the Man locality showed a low prevalence of diseases caused by *C. gloeosporioides* and *H. heveae*, and *C. cassiicola* was not detected at all in this area. These results align with findings by Konan et al. (2023), who observed that the two border localities (Tabou and Nouamou) exhibited high incidence and severity of *C. cassiicola*, *C. gloeosporioides*, and *H. heveae*. Their study also revealed that in mature rubber plantations in these regions, rubber trees were infested little or not at all by these fungi.

Effects of microclimatic conditions on disease incidence and severity

The impact of meteorological variables on the severity and incidence of the three rubber leaf diseases revealed that prolonged, wet seasons play a significant role. Once a disease is established, climate variations largely account for fluctuations in disease intensity within the Ivorian climate context.

Major fungal diseases caused by *C. cassiicola*, *C. gloeosporioides*, and *H. heveae* have been recognized as destructive in both temperate and tropical countries, including Côte d'Ivoire (Jayasinghe, 2003; Silva et al., 2003; Oka et al., 2006; Hong et al., 2007). This can be attributed to the ability of the fungi to produce conidia across a broad temperature range (from 5 to 40°C) (Fernando et al., 2012), as well as the ability of conidia to germinate easily in the presence of free water (humectation) or under high humidity conditions, as demonstrated in this study.

In key regions such as Tabou and Nouamou, which experienced high disease prevalence, relative humidity is reported to be very high (90-100%), often associated with cloudy, stormy conditions and extended wetting periods. Average temperatures are generally above 24°C. These environmental conditions were particularly prominent during periods 1 and 3, as well as after coppicing (the start of refoliation). Therefore, the prevailing climatic conditions in the primary rubber-growing areas, especially during the refoliation period, are highly conducive to the establishment and growth of fungi. Experiments have shown that lesion development occurs on leaves at all immature stages, while mature leaves exhibit resistance (Fernando et al., 2010). This strongly suggests that pathogen establishment can occur freely during the refoliation period, with more continuous favorable conditions leading to an increase in both the incidence and severity of fungal diseases.

Relationship between microclimatic factors and disease incidence and severity

Several studies have established the importance of climatic conditions in the development of crop diseases in natural environments. Consequently, it is crucial to quantify the correlation between meteorological variables and the severity and incidence of rubber leaf diseases to mitigate their early onset (El Jarroudi et al., 2017; Mwakutuya and Banniza, 2010). The present study found a significant correlation between meteorological variables and disease severity and incidence, consistent with the findings of Syahfari et al. (2023), who also reported a significant relationship between the severity of fungal diseases caused by *Corticium* sp. on rubber and climatic factors. Similarly, the interpretations of Raj and Joseph 2011) support these results.

Specifically, climatic variables with a strong positive and significant correlation with disease incidence and severity ($r > 0.7$ and $p < 0.001$) include leaf wetting duration. Relative humidity and rainfall show a moderately positive and significant correlation with disease incidence and severity ($r > 0.5$ and $p < 0.001$). In contrast, mean temperature exhibited a very weak, non-significant negative correlation ($r < -0.2$ and $p > 0.01$) with disease incidence and severity. These findings are in line with those of Guyot et al. (2010), who demonstrated that mean temperature does not directly influence the development of *M. ulei*, the pathogen responsible for rubber leaf disease. This observation also aligns with the work of Torres-de la Cruz et al. (2023), who showed that elevated temperatures shorten the lifespan of *Phytophthora* spores by reducing available moisture.

The significant relationship between prolonged leaf wetting and the severity and incidence of fungal diseases can be explained by the creation of a humid microclimate on the leaves, which promotes the formation of water droplets that serve as entry points for fungi. When leaves remain moist for extended periods, they create a favorable environment for fungal spores to germinate, develop, and penetrate leaf tissue, initiating infection in the graftwood garden. These results are consistent with those of Silva et al. (2018) and Bélisario et al. (2020), who found that long wetting periods (≥72 hours) are necessary for the infection of *Cercosporiosis* and *Neopestalotiopsis* spp.

The positive correlation between fungal disease indicators (severity and incidence) and rainfall is due to its crucial role in disease development. Rainfall triggers the formation of fungal spores during the rainy season, while keeping environmental temperatures mild and plant surfaces moist, conditions essential for fungal growth and sporulation (Mehmood et al., 2013). Moreover, the significant correlation between relative humidity and fungal aerial diseases of rubber trees can be attributed to its role in disease development. Researchers hypothesize that relative humidity could trigger the release of ascospores. Turgor pressure inside the reproductive cells (asci) may force ascospore discharge (Prussin et al., 2015; David, 2016; Khanna et al., 2022), and the balance between moisture inside the asci and atmospheric vapor pressure may influence ascospore release. Therefore, frequent rainfall during the growing seasons of rubber trees is a critical factor in initiating fungal foliar infections and increasing both incidence and severity in JBG.

In this study, all epidemiological factors, except mean temperature, significantly influenced disease development. The results of the multiple linear regression analysis underscore the significant role of climatic factors in the severity of foliar diseases caused by the three fungi. The coefficients for humidity (0.642 for *H. heveae*, 0.435 for *C. gloeosporioides*, and 0.832 for *C. cassiicola*) indicate that for each unit increase in humidity, disease severity rises by 0.642, 0.435, and 0.832 units, respectively. Hence, humidity emerges as a critical factor driving the incidence of these fungal leaf diseases in rubber trees. By integrating these findings into the national alert system, it becomes possible not only to anticipate infection risks but also to optimize interventions, thereby reducing production losses and improving rubber tree crop management.

STUDY LIMITATIONS

This study has several limitations, primarily due to regional variability, as it was conducted across six different locations, each with distinct environmental, climatic, and agronomic conditions. These variations could influence the results, making it difficult to generalize the findings to other regions. While the two-and-a-half-year data collection period offers a reasonable timeframe to observe seasonal variations and long-term trends in fungal leaf diseases of rubber trees, it may still be relatively short for a comprehensive study, especially considering the potential fluctuations in environmental and climatic factors from year to year.

To address these limitations in future research, multi-regional studies with a comparative approach that considers local specificities would be advantageous. Utilizing more advanced statistical models, such as nonlinear or mixed models, could also help clarify the complex interactions among variables. Furthermore, collecting longitudinal data over multiple seasons and years would provide deeper insights into infection trends and patterns, enhancing the robustness of conclusions and recommendations for managing fungal diseases across various contexts.

CONCLUSIONS

One of the objectives of this study was to identify, based on characteristic symptoms, the fungal leaf diseases associated with *Hevea* seedlings in graftwood gardens across different localities. Moreover, the relationship between these diseases and four environmental factors (mean temperature, relative humidity, leaf wetness duration, and rainfall) was examined.

The results clearly indicated the presence of four fungal species in the Ivorian JBG throughout the three study periods. The most significant fungi encountered across all periods were *Helminthosporium heveae* (severity = 22.82% and incidence = 34.59%), *Colletotrichum gloeosporioides* (severity = 20.68% and incidence = 41.57%), and *Corynespora cassiicola* (severity = 18.17%

and incidence = 32.08%). The weakest fungus observed in these rubber-growing basins was *Oidium heveae* (severity = 2.59% and incidence = 2.59%). Furthermore, the highest severity and incidence were recorded during Periods 1 and 3, which were both long observation periods lasting an entire year. Period 2, the intermediate period between receptions, was characterized by lower severity and incidence.

Two basins were identified with a high prevalence of fungal diseases: the border localities of Tabou and Nouamou. In these areas, the severity of diseases caused by *H. heveae*, *C. gloeosporioides*, and *C. cassiicola* exceeded 30%. Incidences of these three key fungi in these zones were over 60%. The production basins of Zoukougbeu, Daoukro, and Gagnoa were identified as transitional areas for rubber tree health, particularly in terms of infection by the leaf diseases caused by the fungi observed. Observations in Man showed no significant prevalence of fungal leaf diseases caused by *C. cassiicola* and *O. heveae*. In this area, *H. heveae* was present with low incidence and severity (<10%), while *C. gloeosporioides* was the most prevalent fungus, with severity and incidence ranging between 15% and 25%.

During the overall study period from November 30, 2020, to June 16, 2023, the results of the climatic variations revealed that higher recorded temperatures were associated with increased disease incidences and severities. In contrast, conditions such as lower temperatures, moderate relative humidity, moderate rainfall, and shorter wetting durations were linked to lower incidences and severities.

To better understand the effects of weather conditions on the development of leaf diseases, a Pearson correlation and multiple regression analysis were conducted. Correlations between disease severity and meteorological variables were validated by detecting multi-collinearities between significantly correlated variables (leaf wetness duration, relative humidity, and rainfall). Based on multiple regression analysis and validation of correlations, it was concluded that rainfall, wetting duration, and relative humidity were the best indicators of the severity of fungal diseases on rubber leaves in Côte d'Ivoire. In contrast, variations in mean temperature did not significantly influence the development of disease epidemics.

These findings highlight the importance of considering weather conditions when managing fungal foliar diseases of rubber trees in JBG, particularly for disease monitoring and prevention during periods when weather conditions are favorable for pathogen development.

AUTHORS' CONTRIBUTIONS

KUUK established grafted rubber budwood gardens (JBG) in various locations, collected and compiled the data, and wrote the manuscript; APY, EOT, and ASY performed the data analysis, interpreted the results, and wrote the article; SO and KA critically revised the manuscript, made critical revisions, and gave final approval of the preliminary version; all authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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