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Role of Agro-Climatic Factors in the Epidemiological Dynamics of Cocoa Black Pod Rot in Côte d'Ivoire

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Abstract

Black pod rot of cocoa pods, caused by *Phytophthora* spp., accounts for production losses of up to 30% worldwide. The disease typically emerges at the onset of the rainy season, when pods at all stages of development are present on the trees. However, the role of environmental factors in its epidemiology remains poorly documented in Côte d'Ivoire. This study investigated the effects of rainfall, relative humidity, and temperature on the development of black pod rot, intending to identify predictive climatic indicators in five cocoa-growing localities (Duékoué, Yamoussoukro, Divo, Abengourou, and Aboisso) between June 2021 and June 2024. In each locality, four plots were monitored. On each plot, fruit production was recorded every 15 days on 100 trees, while climate data were collected daily. Statistical analyses included Spearman's correlation to assess non-linear relationships between climatic variables and disease incidence, autocorrelation to detect temporal dependencies, cross-correlation to evaluate interactions among variables, and logistic regression to model the probability of black pod rot occurrence. Results revealed a significant correlation between rainfall and symptom expression, with a lag of less than 15 days. *Phytophthora palmivora* and *P. megakarya* were isolated in all localities. These findings provide a basis for developing an early warning system to enhance phytosanitary management of cocoa.

Keywords

Theobroma cacao, *Phytophthora megakarya*, Black Pod Rot, Rainfall, Epidemiology

1. Introduction

Cocoa (*Theobroma cacao*) is a strategic crop for the economic development of Côte d'Ivoire. Global production is estimated at 4.726 million tons, with 76.1% originating from Africa. Since 1970, Côte d'Ivoire has remained the world's leading producer, supplying 2.150 million tons in 2021 [1]. At the macroeconomic level, cocoa accounts for approximately 40% of the country's national export revenues and contributes 15% to its Gross Domestic Product (GDP). Socially, approximately 1.100 million farmers sustain the production system, ensuring the livelihoods of nearly 8 million people.

Despite its importance, cocoa production faces multiple constraints, including environmental, economic, and social factors, as well as pests and diseases [2]. Among the latter, black pod rot, caused by species of the genus *Phytophthora*, is the most widespread and destructive disease of cocoa worldwide, responsible for yield losses of up to 30%. In Africa, losses range from 15% to 20% in Ghana to 30% to 75% in Nigeria, and sometimes exceed 50% to 80% in smallholder plots in Cameroon, Gabon, and Equatorial Guinea, where *P. megakarya* predominates [3]-[5]. In Côte d'Ivoire, black pod rot is among the most severe diseases, with yield losses estimated between 44% and 80% [6] [7]. Until 1979, *P. palmivora* was considered the sole causal agent [8]. Currently, more than seven *Phytophthora* species are recognized as causal agents of black pod rot worldwide, including *P. palmivora*, *P. megakarya*, *P. citrophthora*, *P. megasperma*, *P. arecae*, *P. heveae*, and *P. capsici* [9]. In Côte d'Ivoire, however, only *P. palmivora* and *P. megakarya* have been reported and confirmed as the main causal agents.

The control of black pod rot is therefore a major challenge [6] [10] [11]. Chemical control has been prioritized, relying mainly on systemic and contact fungicides [11]-[13]. However, their use raises concerns about heavy metal accumulation in cocoa beans and soils [11] [14] [15], with potential consequences for human health and soil microbiota. Agronomic practices such as sanitary harvesting, shade management, and mulching, as well as genetic approaches through breeding and selection, have also been implemented [16]-[18]. Biological control using biopesticides, particularly endophytic fungi naturally present in cocoa, has shown promise [19]-[21]. However, the effectiveness of all these methods remains highly dependent on local agro-climatic conditions [22]. Epidemiological studies on fungal diseases in tropical crops emphasize the importance of climatic thresholds and pathogen incubation periods. For example, *P. palmivora* infection is strongly influenced by leaf wetness duration, temperature, and relative humidity, while the incubation period plays a decisive role in epidemic development [23]. However, these parameters vary depending on strains and specific environmental contexts. In the field, the expression of black pod rot is modulated by multiple interacting factors, particularly rainfall, humidity, and temperature, as well as cropping practices such as planting density and shading.

This study, therefore, focuses on the influence of agro-climatic factors—rainfall, relative humidity, and temperature—on the development of black pod rot in

the major cocoa production zones of Côte d'Ivoire. The objective is to generate epidemiological data that will improve the understanding of disease dynamics, support the design of effective control strategies, and provide a basis for early warning systems to optimize phytosanitary interventions.

2. Materials and Methods

2.1. Study Areas Description

The study was conducted in five major cocoa-producing localities of Côte d'Ivoire. The departments of Aboisso (South-East Côte d'Ivoire), Abengourou (East Côte d'Ivoire), and Yamoussoukro (Centre Côte d'Ivoire) are located in agro-ecological zone I, while Duékoué (West Côte d'Ivoire) and Divo (South-West Côte d'Ivoire) belong to zones III and IV, respectively. These sites represent key cocoa production areas that significantly contribute to national output [24].

The climate of the study areas is characterized as a humid tropical one, with mean annual rainfall ranging from 1200 to 1400 mm [25] and average annual temperatures between 24˚C and 32˚C [26]. The vegetation is characterized by a mosaic of degraded and semi-deciduous dense forests in the central-western and eastern regions, evergreen dense forests in the south and west, mountain forests in the western highlands, and mangrove forests along the coastline.

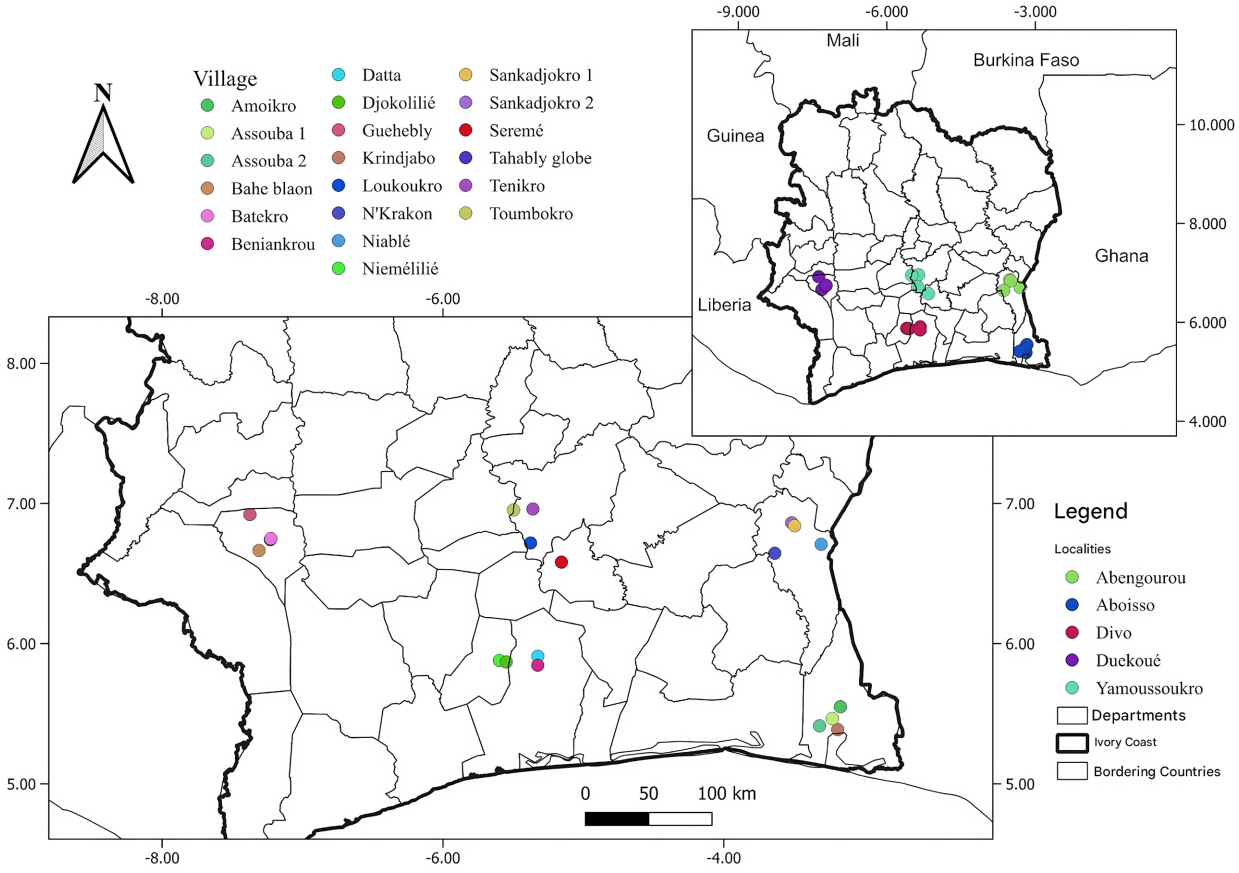

Figure 1. Location of the five study sites in Côte d'Ivoire.

Soils also vary across zones. The southwestern and southeastern areas are dominated by hyperdystric Ferralsols (pH > 5.5), while the eastern, central-western, and western zones are mainly composed of dystric and eutric Ferralsols, with pH values ranging from 4.5 to 6.5. In general, soil fertility is low to medium, with phosphorus and potassium deficiencies that often limit cocoa growth [27].

A total of 20 plots were surveyed across the five study sites, with four plots established per locality (**Figure 1**).

2.2. Plant Material

A total of 52 cocoa pods showing symptoms of black pod rot were collected from the surveyed plots (**Figure 2**). Sampling considered both maturation stages (green and ripe pods) and the presence of characteristic visual symptoms of the disease on the pod surface.

Figure 2. Cocoa pods affected by black pod rot on the cocoa tree.

2.3. Fungal and Laboratory Materials

The fungal material consisted of 260 isolates, along with reference strains of *Phytophthora palmivora* (BL7 11.2) and *P. megakarya* (13P30.1). Three types of culture media were used for isolation: water agar (WA), pea agar (PA), and carrot agar (CA). After purification, the isolates were maintained in tubes containing 2% pea agar and stored at 27˚C ± 1˚C in an incubation room.

2.4. Technical Equipment

The technical equipment included collection and preservation materials (coolers, plastic bags, secateurs, and labels) as well as instruments for environmental monitoring (thermohygrometers and rain gauges) installed in each plantation.

2.5. Selection of Sites and Plots

To assess disease incidence and the agro-climatic parameters influencing epidemic dynamics, four plantations were selected in each of the five study zones. The plantations were distributed along different axes within each zone, with a

minimum spacing of 5 km, in order to capture diverse agro-ecological conditions. Selection criteria for plots included: i) ease of access, ii) a minimum area of 1.5 ha, iii) a density of at least 1000 cocoa trees with homogeneous shade, iv) good field maintenance, and v) willingness of farmers to participate in the study.

2.6. Experimental Design

In each plot, 100 adult cocoa trees (>5 years old) were randomly selected using a grid layout, excluding trees within 10 m of plot borders. Each tree was georeferenced and individually monitored throughout the study (**Figure 3**) [28].

In plant epidemiology, a sample size of 50 - 100 observation units is commonly used in longitudinal studies to detect significant variations in disease incidence or severity while minimizing selection bias [29]. Although statistical power analyses can refine sample size determination, the choice of 100 trees was based on empirical recommendations from previous studies on cocoa pod diseases [30] [31]. This sample size represents a balance between statistical precision and operational feasibility.

Disease assessments were conducted every 15 days to allow the accumulation of a sufficient number of infected pods between observations, particularly in plots with low disease incidence. During each assessment, the number of healthy ripe pods and pods affected by black or brown rot was recorded. All pods, except those showing black rot symptoms, were removed after counting. Pods with black rot were left on the tree to avoid disrupting disease progress, but were marked by cutting their apex with a secateur to prevent double-counting in subsequent observations.

Figure 3. Experimental design for cocoa tree monitoring.

2.7. Data Collection

Data were recorded every two weeks from June 2021 to June 2024. These records enabled the calculation of the incidence of black rot for each observation period. The 15-day rot rate (RR_t) was calculated using the formula of [32]:

$$RR_t = \frac{\text{Number of rotted pods}_t}{\text{Number of healthy pods}_t + \text{Number of rotted pods}_t} \times 100 \quad (1)$$

where t represents the observation period ($t = 1$ for the first 15 days, 2, …, n), RR_t is the rot rate at time t, and the denominator includes the total number of ripe and unripe pods.

2.7.1. Epidemiological Variables (RR_t, RRC)

The rot rate (RR) was transformed into a binary variable to serve as the dependent variable for logistic regression analysis. This transformation produced a coded variable, RRC (Rot Rate Coding), with two levels (Table 1).

The rot pod rate was transformed into the binary variable RRC with a 10% threshold, as this level is a commonly used action threshold in epidemiological modeling for cocoa black pod rot. It defines the critical event that the logistic model is intended to predict: the risk of rotting beyond an economically significant incidence [33].

Table 1. Coding of the rot rate in the study areas.

RR (Rot Rate)	0 ≤ RR ≤ 10%	RR > 10%
RRC (Rot Rate Coding)	0	1

The binary variable RRC follows a Bernoulli distribution, suitable for logistic regression modeling.

2.7.2. Pedological and Agronomic Data

Planting density was estimated by randomly selecting four 100 m^2 subplots within each plantation. The average number of cocoa trees per subplot was multiplied by the total plantation area and compared to the reference standard of 1333 trees per hectare.

Shade level was assessed visually and classified into three categories: low, normal, and high (Table 2). Low shade corresponds to prolonged direct sunlight, which reduces humidity and may limit the development of pathogens. High shade creates a warm, humid microclimate with poor air circulation, conditions highly favorable for the production and spread of *Phytophthora* spores. Normal shade represents a balance, in line with recommended good agricultural practices.

Table 2. Agronomic parameters measured in the plots.

Parameter	Description	Categories/Levels
Planting Density	Average number of cocoa trees per hectare	Compared with the reference density of 1333 trees ha^{-1}
Shade Level	Visual assessment of light exposure	Low, normal, high

2.7.3. Climatic Parameters

Daily meteorological data (minimum, average, and maximum temperatures; rainfall; and relative humidity) were recorded in each of the four plots within the selected localities.

- **Rainfall:** measured with a rain gauge placed at the edge of each plot, with data

collected after each rainfall event.

- **Temperature and relative humidity:** monitored using four to five thermo-hygrometers per plot, installed at distinct locations to ensure adequate spatial coverage and minimize the effect of localized microclimates.

Daily meteorological data (rainfall, temperature, relative humidity) were obtained through automatic weather stations (Campbell CR10X, equipped with ARG 100 sensors for rain and HMP45C for temperature/hygrometry, Campbell Scientific Ltd.), installed directly in each locality and connected online via the website ng.fieldclimate.com.

2.8. Isolation and Identification of *Phytophthora*

2.8.1. Isolation Protocol

Culture media preparation. Three culture media were used: water agar (WA), pea agar (PA), and carrot agar (CA).

- **WA medium:** 2 g agar was dissolved in 100 ml of distilled water, homogenized in a water bath, and sterilized in an autoclave at 121˚C for 20 min.
- **PA medium:** 450 g of peas were rinsed, blended into a paste, and boiled with 500 mL of water for 45 minutes. The mixture was filtered three times, adjusted to 1500 mL with distilled water, and supplemented with 10 g of agar per 500 mL of filtrate before autoclaving.
- **CA medium:** 200 g of carrots were rinsed, boiled in 500 mL of distilled water for 45 min, blended, and filtered three times through cotton and filter paper.

Inoculation. Symptomatic cocoa pods were washed with tap water, disinfected with 96% ethanol, and flamed under a laminar flow hood. Small tissue fragments were excised from the lesion margins with a sterile scalpel and placed on 2% WA medium in 90-mm Petri dishes. Fragments were positioned 1 cm from the dish edge along a diametrical axis. Plates were incubated at 27˚C ± 1˚C in crystallizing dishes.

2.8.2. Purification and Storage

After four days of growth, mycelial fragments were transferred from WA to PA medium. Subculturing was repeated until pure cultures were obtained. Isolates were stored in tubes containing 2% PA medium at 27˚C ± 1˚C.

2.8.3. Confrontation Test

Each isolate was paired with the A2 reference strain *P. palmivora* BL7 11.2 on PA medium in 90 mm Petri dishes. Four-day-old mycelial fragments were placed opposite each other, incubated at 27˚C ± 1˚C for 10 days, and observed for interaction.

2.8.4. Study of Sexual Polarity

Mycelium sampled at the confrontation zone was mounted in water on glass slides and examined under a light microscope (400×). The presence or absence of oospores determined whether the two isolates were of different mating types. The type of antheridium–oogonium union was recorded as amphigynous or paragy-

nous.

2.8.5. Morphometric Study

The length and width of the sporangia and the pedicel length were measured under a light microscope using a micrometer. For each isolate, 15 sporangia were examined to characterize morphological variation.

2.9. Data Analysis

All collected data were entered into Microsoft Excel. Descriptive statistics (means, standard deviations, minima, and maxima) were first computed. Variables measured at 15-day intervals were treated as time series, with a two-week lag unit, implying that the observations were not randomly ordered.

Autocorrelations were calculated to analyze temporal patterns of disease evolution, defined as the correlation between the original series and its lagged version. Cross-correlations were also performed to determine the lag that maximized the relationship between rainfall and black pod rot incidence, thereby identifying the time interval between rainfall events and disease onset.

To further examine the influence of climatic factors on disease incidence, a logistic regression model was applied:

$$\log\left(\frac{\pi(X)}{1-\pi(X)}\right)=\alpha+\beta X \tag{2}$$

where $\pi(X)$ is the probability that RRC = 1, α and β are model coefficients, and X represents explanatory climatic variables.

The coefficient's significance was assessed using the Wald test:

- $p < 0.05$: the coefficient is significantly different from 0 (predictor X influences the probability of the event).
- $p \geq 0.05$: the coefficient is not significant (predictor X does not provide additional information to the model).

The selection of explanatory variables was based on the Spearman correlation matrix. All statistical analyses were performed using R (RStudio).

3. Results

3.1. Identification of *Phytophthora* Species

The confrontation between the isolates collected from affected pods and the reference strain BL7.11.2 (*Phytophthora palmivora*) allowed for the differentiation of two distinct groups of isolates. Overall, 64.84% of the isolates belonged to Group 2, while 35.16% were from Group 1. Isolates that produced oospores were classified in Group 1, corresponding to *Phytophthora megakarya*, while those that did not produce oospores were associated with Group 2, which is characteristic of *P. palmivora*.

3.1.1. Distribution of *Phytophthora* spp.

A differentiated geographic distribution was observed (**Figure 4**): isolates from

Yamoussoukro, Duékoué, Divo, and Aboisso primarily belonged to group 2 (*P. palmivora*), whereas in Abengourou, almost all isolates belonged to group 1 (*P. megakarya*). The observed antheridium-oogonium connection type was amphigynous (Figure 5), confirming the taxonomic identity. The predominance of P. *megakarya* in the Abengourou area can be attributed to specific climatic factors, including higher annual rainfall and prolonged periods of elevated relative humidity, which favor the sporulation and dissemination of this pathogen.

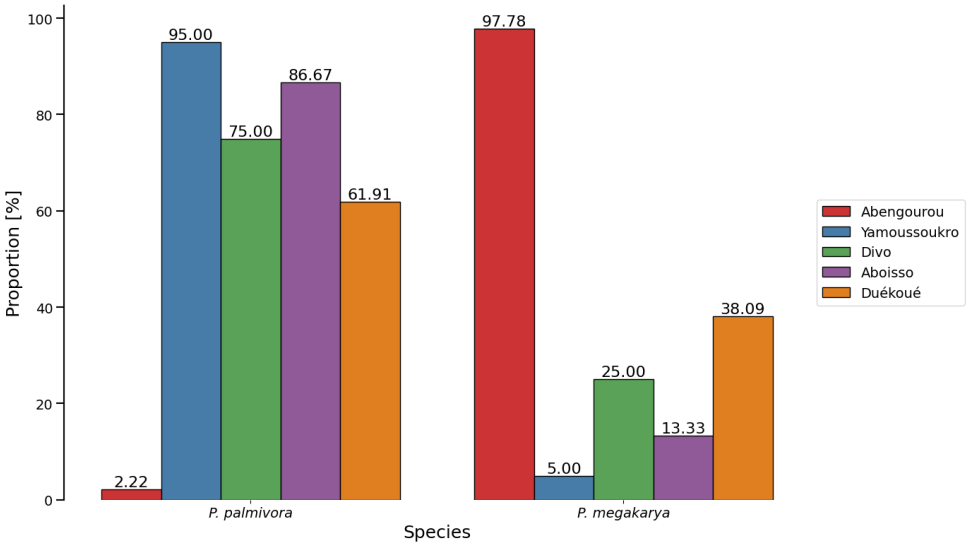

Figure 4. Proportion of the two *Phytophthora* spp. species in each study area.

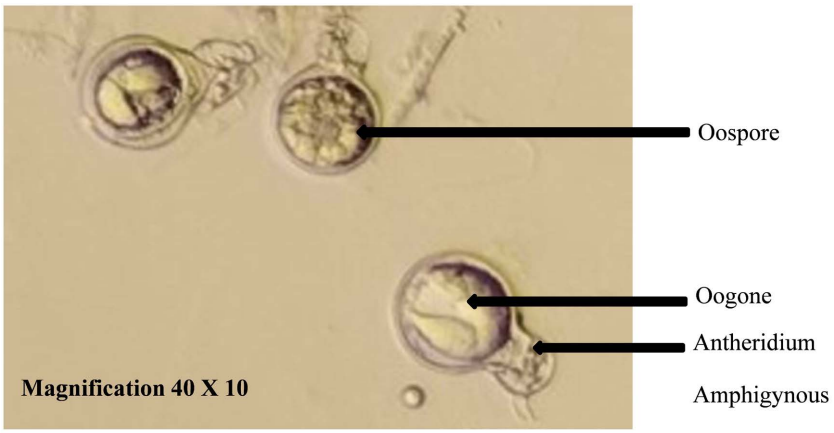

Figure 5. Microscopic observation of oospore formation.

3.1.2. Morphometric Study of Isolates

Morphometric measurements of the sporangia (Table 3) revealed significant differences between the two groups. Group 1 sporangia had an average length of 14.34 µm ± 0.94 µm, a width of 10.67 µm ± 0.53 µm, and a pedicel length of 11.38 µm ± 1.6 µm. In contrast, those from Group 2 had a higher average length (16.74 µm ± 1.45 µm) but a smaller width (9.09 µm ± 0.77 µm), and a significantly shorter pedicel length (1.12 µm ± 0.16 µm).

Table 3. Measurement of sporangia in the different *Phytophthora* spp. groups.

	Isolate Code	Sporangium Length (µm)	Sporangium Width (µm)	Length/Width Ratio	Pedicel Length (µm)
Group 1	13P30.1	15.8	11.6	1.36	8.73
	422P3.9	14.6	9.8	1.48	10.3
	122P1.28	14.2	10.33	1.37	10.13
	222P3.1	16.53	10.33	1.6	9.6
	422P2.19	15.26	11.13	1.37	10.06
	122P3.21	14.93	10.73	1.39	12.46
	422P3.5	13.53	10.33	1.3	14.13
	122P1.25	15	10.73	1.39	12.4
	422P2.14	13.6	10.4	1.3	10.53
	322P3.15	14.33	10.8	1.32	14.33
	522P1.9	13.26	10.4	1.27	12.13
	322P3.19	14.4	11.26	1.27	13.13
	322P3.12.1	14.68	11.13	1.31	11.86
	522P1.7	13.3	9.86	1.34	10.46
	522P1.2	14.33	11	1.3	10.46
	122P3.16	14.2	11	1.29	10.26
	322P3.6	14.46	11.53	1.25	12.4
	422P2.13	13.2	9.93	1.32	10.06
	552P1.19	12.8	10.4	1.23	12.93
	Mean	**14.34 ± 0.94**	**10.67 ± 0.53**	**1.34 ± 0.09**	**11.38 ± 1.6**
Group 2	BL7.11.2	16.46	10.8	1.52	1.33
	422P3.1	16.93	8.8	1.92	1.2
	422P4.9	15.6	8.86	1.76	1
	422P4.15	16.66	8.66	1.92	1.13
	522P1.25	18.66	9.2	2.02	1.06
	522P1.14	19	10	1.9	1.06
	522P1.20	15.06	8.13	1.85	1
	522P1.6	16.46	9.13	1.8	1.06
	222P4.6	16.13	9.26	1.74	1.2
	422P4.4	16.6	9.26	1.79	1.46
	522P1.13	17.46	9.93	1.75	1.53
	222P4.4	15.53	8.66	1.79	1.13
	422P4.3	15.5	8.6	1.8	1.16
	522P1.21	20.4	10	2.04	0.96
	222P2.6	15.56	8.66	1.79	1.03
	422P4.16	16.66	8.46	1.96	0.93
	422P4.7	15.06	7.4	2.03	1.1
	422P4.10	16.13	9.46	1.7	0.96
	522P1.15	18.36	9.4	1.95	1.03
	Mean	**16.74 ± 1.45**	**9.09 ± 0.77**	**1.84 ± 0.13**	**1.12 ± 0.16**

3.2. Impact of Agro-Climatic Factors on Cocoa Black Pod Rot Disease

3.2.1. Spatio-Temporal Dynamics of Disease Incidence

The bi-weekly monitoring of black pod rot rates and rainfall, conducted from June 1, 2021, to June 25, 2024, enabled the generation of five epidemic curves, one for each locality (Figure 6). These curves showed a sigmoidal epidemic dynamic, interspersed with phases of stagnation. In Duékoué and Aboisso, the pre-exponential phase was particularly pronounced between October and November from 2021 to 2023. Epidemic peaks were observed in Abengourou, Divo, and Yamoussoukro during the same periods.

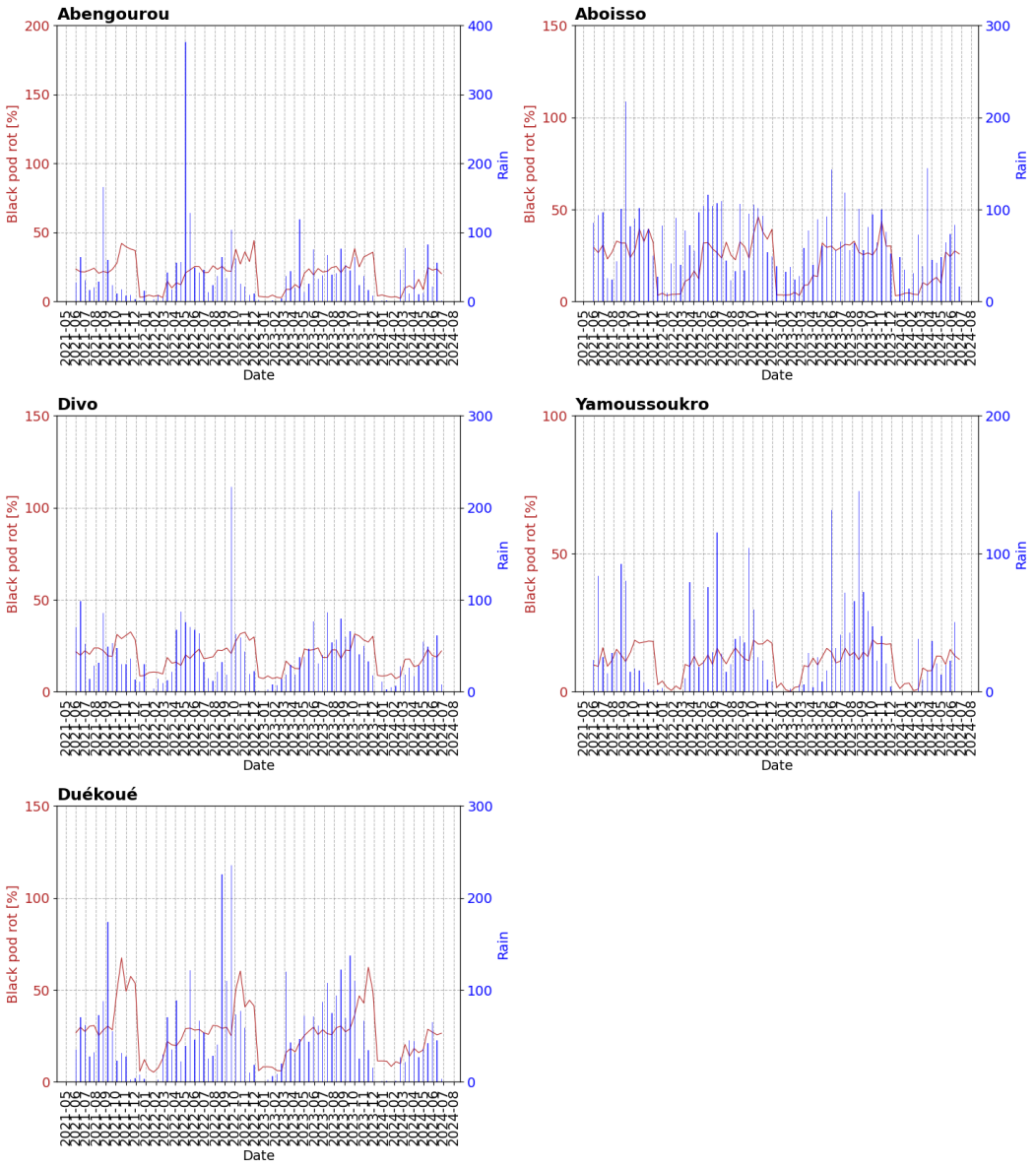

Figure 6. Biweekly evolution of cocoa black pod rot rates and daily rainfall at different locations: Abengourou, Aboisso, Divo, D. Duékoué, and Yamoussoukro. BRR = black rot rate, blue bars = rainfall in mm, grey curve = BRR in %.

Temperatures and relative humidity were not reported, as they remained relatively constant in each locality during the study period. Their variations during the study period were negligible between localities, due to the quasi-stable climate of the cocoa-growing zone during the observation season (rainy season).

3.2.2. Climate Summary over the Collection Period in Different Localities

Mean, minimum, and maximum temperatures, as well as relative humidity, varied significantly ($p < 0.001$) across the study localities over the entire study period. Abengourou recorded the highest temperatures, with a mean of 26.97˚C, a minimum of 22.50˚C, and a maximum of 35.54˚C, while also experiencing the highest relative humidity (92.79%). These results highlighted hotter and more humid climatic conditions in this locality compared to the others.

Aboisso, although close to Abengourou in terms of temperatures, showed slightly lower values, with a mean temperature of 26.34˚C and a relative humidity of 89.39%. Minimum temperatures were also lower in Aboisso, while remaining comparable to those observed in Divo, Duékoué, and Yamoussoukro.

Divo and Duékoué shared similar trends, but with lower mean temperatures of 26.08˚C and 25.56˚C, respectively. Duékoué recorded the lowest relative humidity (86.14%) compared to the other localities. Yamoussoukro, on the other hand, showed the lowest maximum temperatures (30.12˚C) and a relative humidity similar to that of Duékoué (86.66%) (Table 4).

The incidence of black pod rot varied significantly ($p < 0.001$) depending on the localities studied. On average, Duékoué recorded the highest percentage of infection, with 26.4%, followed by Aboisso (21.4%) and Abengourou (18.9%). Divo (19.1%) also showed an incidence similar to Abengourou and Aboisso, while Yamoussoukro displayed the lowest rate at 10.8% (Figure 7).

Table 4. Ambient temperature and relative humidity during the collection period at the study sites.

Location	Temperature (˚C)			Relative Humidity (%)		
	Minimum ± SD	Mean ± SD	Maximum ± SD	Minimum ± SD	Mean ± SD	Maximum ± SD
Abengourou	22.50 ± 1.59 a	26.97 ± 1.78 a	35.54 ± 3.41 a	71.27±4.98 a	92.79 ± 5.97 a	96.76 ± 6.08 a
Aboisso	21.68 ± 0.93 b	26.34 ± 1.44 b	34.50 ± 2.64 a	66.49±1.03 b	89.39 ± 1.87 b	92.09 ± 1.74 b
Divo	21.41 ± 0.98 b	26.08 ± 1.62 c	32.88 ± 3.07 b	61.54±2.29 b	88.14 ± 3.36 c	90.76 ± 4.03 b
Duékoué	21.24 ± 1.40 b	25.56 ± 1.43 d	32.86 ± 2.97 b	57.38±2.63 d	86.14 ± 3.39 d	87.21 ± 4.81 c
Yamoussoukro	21.22 ± 1.25 b	25.55 ± 1.81 d	30.12 ± 3.21 c	54.14±4.13 d	86.66 ± 5.09 d	88.17 ± 5.43 c

Note: Values ± SD (Standard Deviation) followed by different letters within a column are significantly different according to the Newmann-Keuls test ($p < 0.05$).

3.3. Agronomic Parameters

The black pod rot (BPR) rates observed in all plots are higher than the local reference rates, which can be explained by the high planting densities, ranging from 1550 to 1925 trees/ha, exceeding the optimal density of 1333 trees/ha generally recommended to limit humidity and disease spread.

Plot P3 in Duékoué stands out with the highest black pod rot rate (39.63% ± 4.2%), which is significantly higher than the reference rate (26.4%). This plot has an exceptionally high density of 1900 trees/ha, showing a difference of +10.23% compared to the expected rate (Table 5). Plot P4 in Aboisso also shows a significant rate (27.74% ± 3.1%), which is 6.34% higher than the reference rate (21.4%), likely due to a density of 1550 trees/ha and high shading that promotes moisture retention (Figure 7).

Table 5. Agronomic parameters in some plots.

Plot	Black Rot Rate (BRR, %)	Planting Density (trees/ha)	Shading	Reference BRR (%)	Difference (Observed BRR-Reference BRR)
P3 Duékoué	39.63 ± 4.2 a	1900	Heavy	26.4	10.23
P4 Aboisso	27.74 ± 3.1 b	1550	Heavy	21.4	6.34
P3 Divo	23.21 ± 2.8 bc	1725	Heavy	19.1	4.11
P1 Abengourou	21.01 ± 2.6 bc	1925	Heavy	18.9	2.11
P2 Yamoussoukro	15.56 ± 2.1 c	1725	Heavy	10.8	4.76

Note: Means ± standard deviation followed by the same letter are not significantly different according to Tukey's HSD multiple comparison test at $\alpha = 0.05$.

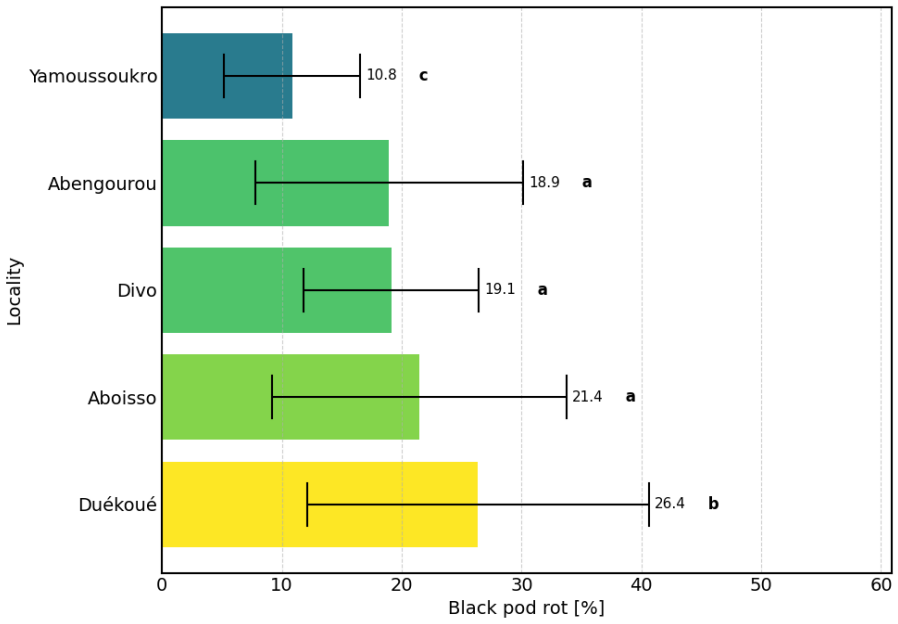

Figure 7. Overall evolution of black pod rot over the entire data collection period by locality.

Plot P3 in Divo (23.21% ± 2.8%) and Plot P1 in Abengourou (21.01% ± 2.6%) show intermediate rates, close to local references, with respective deviations of +4.11% and +2.11%. Finally, P2 in Yamoussoukro has the lowest rate (15.56% ± 2.1%), but it is still +4.76% higher than the reference rate of 10.8%. This could be explained by local conditions being slightly less favorable for *Phytophthora* spp.

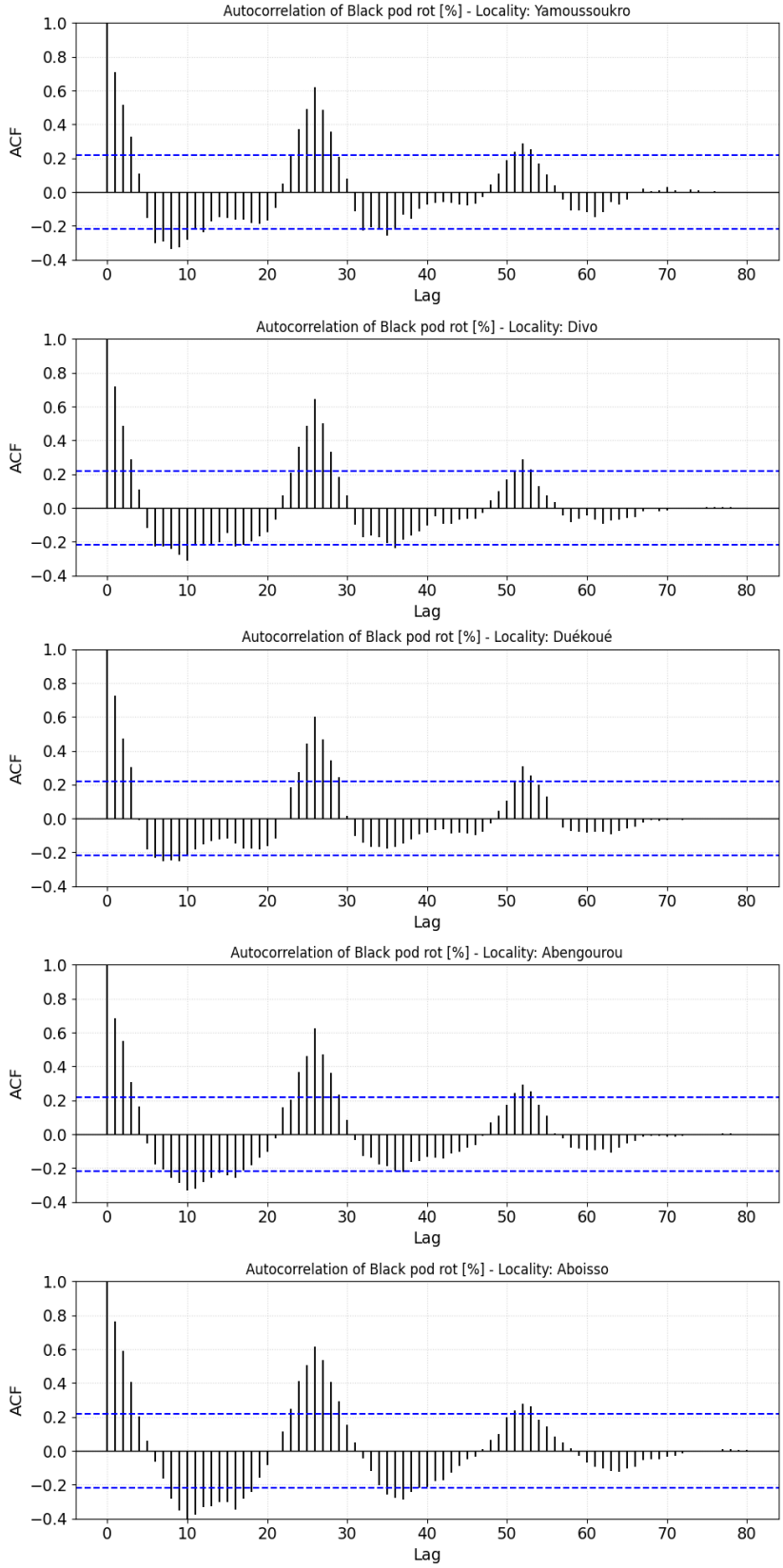

Figure 8. Autocorrelations of the cocoa black pod rot rate in the different localities over the entire study period from June 2021 to June 2024.

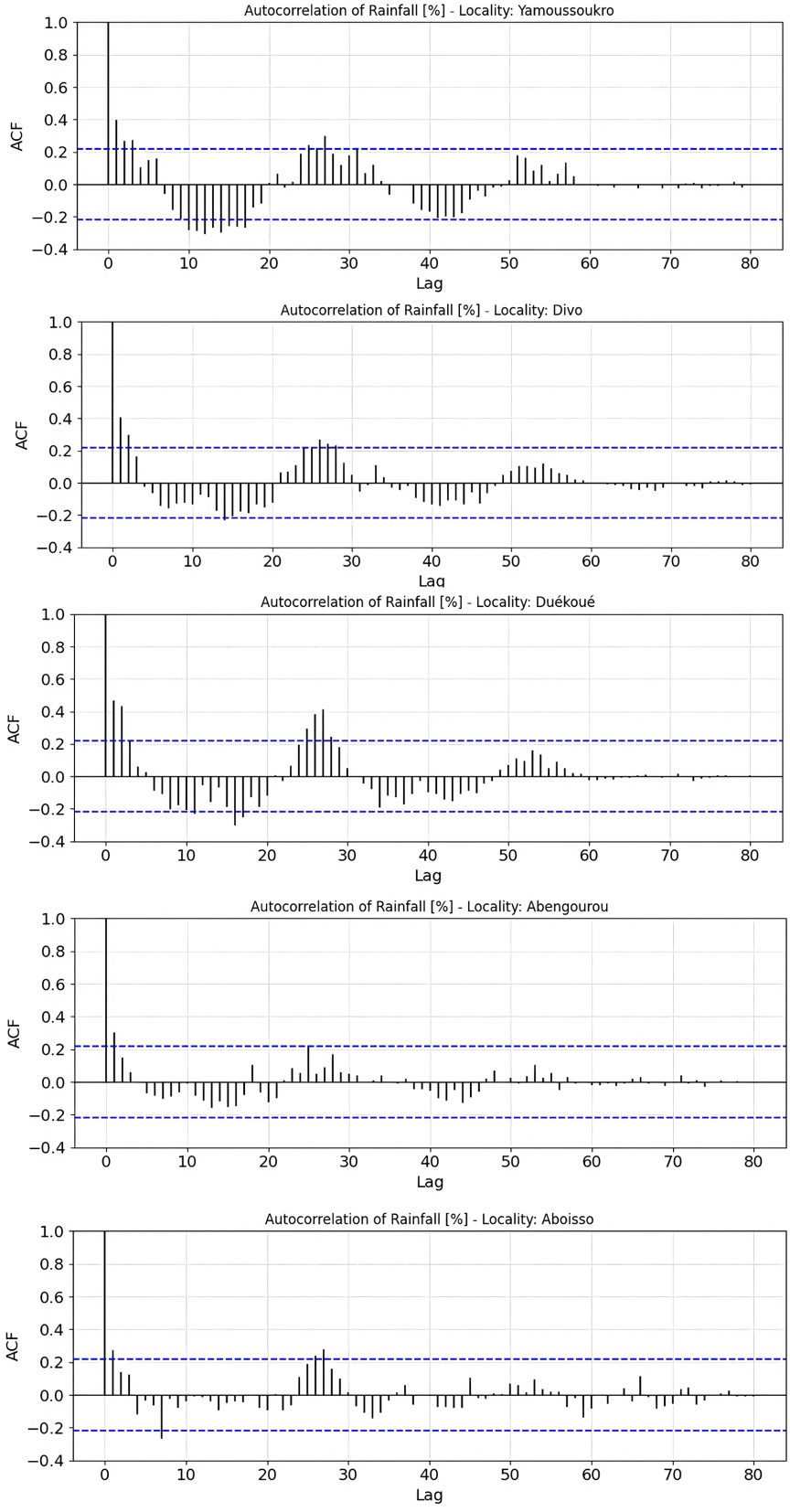

Figure 9. Autocorrelations of rainfall across the different localities over the entire study period from June 2021 to June 2024.

sporulation, despite a relatively high density of 1725 trees/ha. Plot P3 in Duékoué is significantly more infected than all other plots ($p < 0.05$), while Yamoussoukro shows the lowest incidence, with the other plots forming an intermediate group.

3.4. Temporal Analysis

Figure 8 shows the autocorrelations of cocoa black pod rot (BPR%) for the studied localities, with lags ranging from 0 to 80, corresponding to 15-day intervals. Significant autocorrelations, meaning those beyond the blue dotted lines (at a $p \leq 0.05$ threshold), were observed at the first few lags for all localities.

In Yamoussoukro, Duékoué, Divo, and Aboisso, statistically significant autocorrelation peaks were observed primarily at the initial lags (between 0 and 15 lags, corresponding to approximately 0 to 225 days). These localities also exhibited recurrent patterns with alternating positive and negative autocorrelation phases, indicating a seasonal trend in the disease's progression. The first lag (*i.e.*, 15 days) exhibited a particularly high autocorrelation, indicating strong short-term persistence of black pod rot. In contrast, in Abengourou, the autocorrelations were significant but less pronounced than in the other localities.

The results of the simple autocorrelation of rainfall during the overall study period are represented by Figure 9. The correlations were very weak ($p > 0.05$). This is characteristic of a random process, meaning that rainfall is irregular, with accumulation phases followed by periods of low or no rain.

3.5. Effect of Climatic Variables on Black Pod Rot

3.5.1. Relationship between Rainfall and Cocoa Pod Black Rot Rate

Figure 10 presents the cross-correlations between the black pod rot rate and rainfall in each of the localities over the data collection period.

For each locality, the results showed a significant positive correlation with rainfall for temporal lags close to zero, indicating that a short-term rise in the black pod rot rate followed an increase in rainfall. This immediate lag, observed in the different localities, indicates that the effect of rain on the appearance or increase of black pod rot manifests in less than 15 days.

This relationship was more pronounced in certain localities, such as Duékoué and Divo, where the correlation peaks were higher. Conversely, beyond these immediate lags, the correlations became non-significant and negative, indicating a decline in the effect of rain on black pod rot over time.

3.5.2. Choice of Climatic Variables in the Model

The black pod rot rate (BPR) showed a strong positive correlation with rainfall ($r = 0.48$), indicating that rainy episodes favored the development of the disease. In contrast, a negative correlation was observed with mean temperature (−0.55) and maximum temperature (−0.60), indicating that high temperatures reduced the severity of black pod rot. Relative humidity also had a moderate positive correlation (0.24) with the BPR [%], but its effect was less pronounced compared to rainfall.

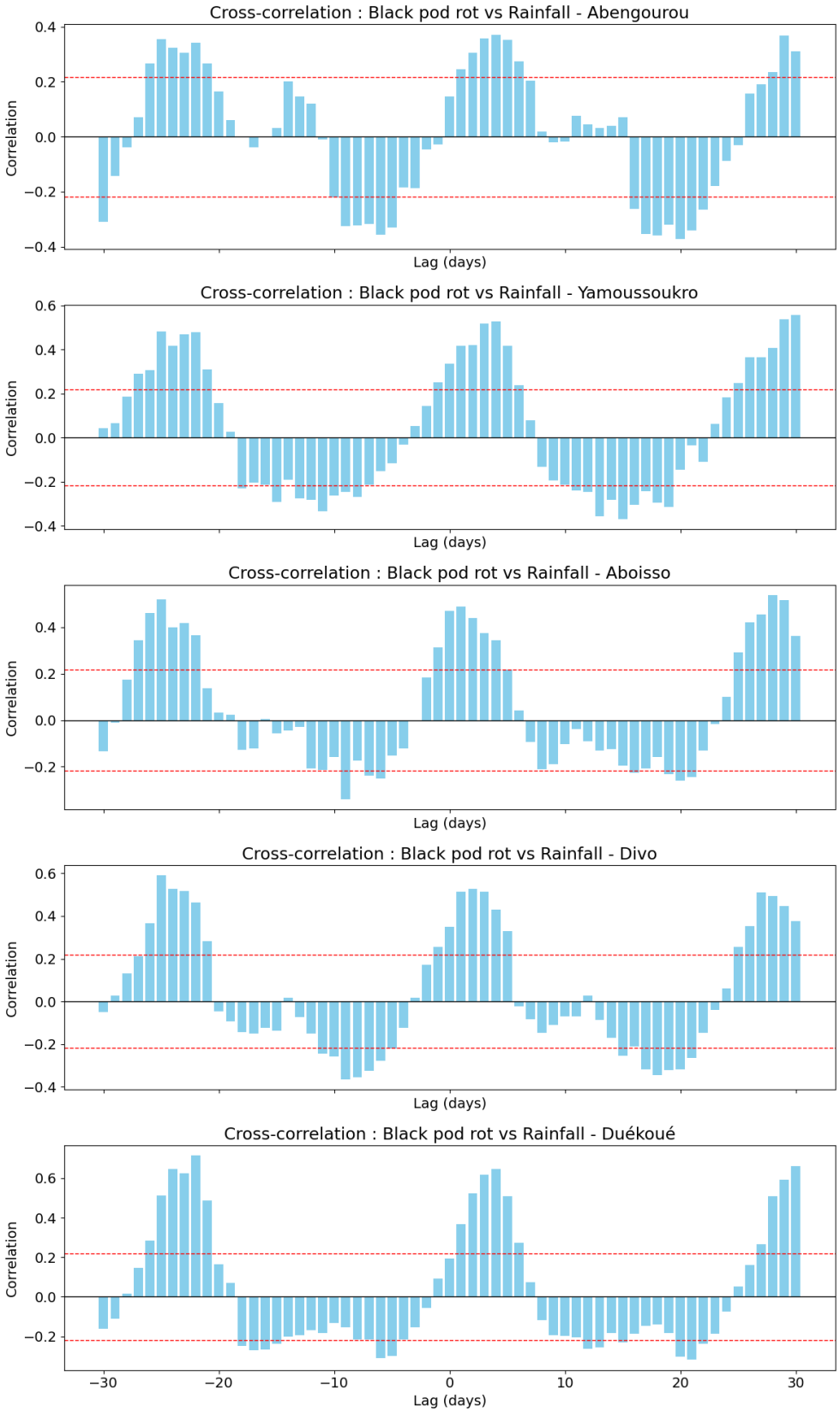

Figure 10. Cross-correlation between black pod rot rate and rainfall across the different localities over the entire study period from June 2021 to June 2024.

For the development of a predictive model, the most important variables to select were rainfall, mean temperature, and maximum temperature, given their significant correlations with the black pod rot rate (Figure 11).

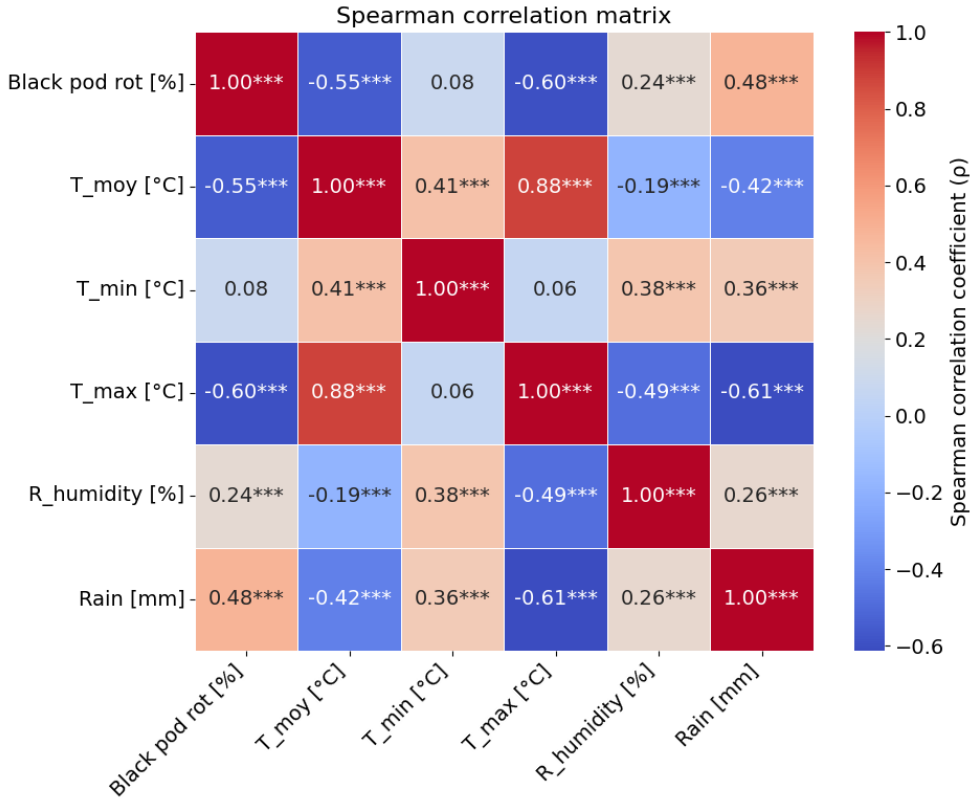

Figure 11. Spearman correlation between black pod rot and climatic variables.

3.5.3. Logistic Regression between Black Pod Rot and Climatic Factors

The results of the binary logistic regression show the influence of certain climatic variables on the probability of black pod rot occurrence. The maximum temperature (Tmax) had a significant and negative effect (p = 0.000378, $\beta = -0.38$), indicating that higher temperatures reduced the likelihood of black pod rot. Rainfall (Rain) had a significant positive effect (p = 0.034, $\beta = 0.014$), suggesting that an increase in rainfall increased the probability of black pod rot. Mean temperature (Tmean) did not have a significant effect (p = 0.68) (Table 6). The equation derived from this model within the scope of this study is:

$$\pi_t/1-\pi = \pi\left(T\max_t\,[^\circ\mathrm{C}],\ \mathrm{Rain}\ [\mathrm{mm}]_{t-1}\right)/[1-\pi\left(T\max_t\,[^\circ\mathrm{C}],\ \mathrm{Rain}\ [\mathrm{mm}]_{t-1}\right)]$$
$$= \exp[(15.573274 - (0.382385)\ T\max_t\,[^\circ\mathrm{C}] + (0.014021)\ \mathrm{Rain}\ [\mathrm{mm}]_{t-1}]$$

$\pi(\varkappa) = \Pr(\mathrm{CPD} = 1/X = \varkappa)$ describes the conditional probability that pods rot beyond 10% at time t, given the values of the climate variable.

Multicollinearity Diagnostics:

Multicollinearity diagnostics were performed on the climatic explanatory variables retained in the logistic regression model (maximum temperature and rainfall) using the variance inflation factor (VIF) and the condition index (CI). These

analyses aim to ensure the stability of the regression coefficients. The values obtained for the VIF, which are 2.23 for the maximum temperature and 3.08 for the rainfall, are significantly below the critical threshold of 5 (Table 7). These low values confirm the absence of significant collinearity between our two independent variables. Furthermore, the final diagnosis of independent variable collinearity is based on the Condition Index (CI), obtained from the eigenvalues. As a general rule, a CI < 15 signifies low multicollinearity. In our analysis, the maximum Condition Index observed is 2.15 (associated with Dimension 3). The variance proportions (for the dimension with the highest CI) show that the information of the variables is not concentrated: the maximum proportion of the variance of the variables (maximum temperature and rainfall) associated with the highest CI (2.15) is 0.25, or 25%, for both variables. All of these results (Table 7) indicate that there is no evidence of significant multicollinearity between the maximum temperature and rainfall.

Table 6. Modeling of the black pod rot rate and climatic variables using the logistic model approach.

Coefficients	Estimate	Std.Error	z value	Pr (>|z|)	IC 95%
(Intercept)	15.573 274	2.715 672	5.735	9.77×10^{-9}***	[10.25; 20.90]
Tmoy [˚C]	−0.069 562	0.169 064	−0.411	0.680 739 ns	[−0.401; 0.262]
Tmax [˚C]	−0.382 385	0.107 571	−3.555	0.000 378***	[−0.593; −0.172]
Rain [mm]	0.0140 21	0.006 622	2.117	0.034 225*	[0.001; 0.027]

Signif. codes: ***Pr(>|z|) < 0.001, **Pr(>|z|) < 0.01, *Pr(>|z|) < 0.05, ns: not significant.

Table 7. Collinearity diagnosis.

Collinearity Diagnostics between the Explanatory (or Independent) Variables						
Model	Dimension	Eigenvalue	Condition Index	Variance Proportions	Maximum Temperature	Rainfall
1	1	1.45	1.65	0.00	0.67	0.67
	2	1.01	2.09	0.00	0.08	0.08
	3	0.32	2.15	0.00	0.25	0.25
VIF					2.23	3.08

4. Discussion

4.1. Geographical Distribution of *Phytophthora* spp.

Laboratory identification revealed the presence of two species. The sporangium measurements of both groups matched the ranges reported by Coulibaly *et al.* [34], although ecological differences could explain other morphological variations. Factors such as host type, crop age, and environmental conditions may account for the observed size variations [35].

The heterothallism observed in our isolates agrees with Martin *et al.* [36], who

showed that *Phytophthora palmivora* and *Phytophthora megakarya* are heterothallic species with amphigynous antheridia. Based on the classification criteria of Martin *et al.* [36], our Group 1 likely corresponds to *P. megakarya* and Group 2 to *P. palmivora*.

According to [37], *P. megakarya* sporangia measure 20 - 60 × 13 - 41 µm (mean 36 × 25 µm) with a Length/Width (L/W) ratio of about 1.4 (1.2 - 1.6), while *P. palmivora* sporangia measure 29 - 115 × 13 - 46 µm (mean 36 - 52 × 23 - 29 µm) with an L/W ratio of 1.2 - 2.0. The overlap in these traits complicates classification and reduces their taxonomic value [38]. However, pedicel length remains a key diagnostic trait [36].

The decreasing proportion of *P. megakarya* from east to west supports the view that this species is still spreading westward across Africa [39], including Côte d'Ivoire. Both *P. megakarya* and *P. palmivora* colonize all parts of the tree. However, the prevalence of *P. megakarya* in Abengourou may be linked to higher rainfall and prolonged humidity, which favor sporulation and dissemination.

4.2. Effects of Agro-Climatic Conditions on Black Pod Rot Incidence

The rot rate remained extremely low for much of the year, corresponding to periods of low fruit production. Disease incidence increased with fruit abundance, confirming the strong correlation between fruit availability and rot rate [40]. The highest peaks occurred in October and November, while the rates were low from April to September, and from mid-December to March. This seasonality is associated with rainfall patterns that favor the establishment and spread of pathogens, consistent with the findings of Pohé *et al.* [11].

Other contributing factors include planting density and shade. Dense plots with closed canopies reduce light penetration, increase humidity, and thus enhance disease development. These results support those of Pohé *et al.* [11], who emphasized the role of cultural practices in disease epidemiology.

4.3. Relationship between Agro-Climatic Factors and Cocoa Pod Black Rot Rate

A key objective of this study was to assess the relationship between cocoa pod rot caused by *Phytophthora* spp. and environmental variables.

Temporal analysis revealed strong short-term autocorrelations, reflecting the cyclical and seasonal nature of black pod rot. Significant autocorrelations at 15-day lags in Yamoussoukro, Duékoué, Divo, and Aboisso indicate short-term persistence, likely driven by rainfall. Cross-correlation analyses confirmed that rainfall peaks are followed by disease outbreaks within about 15 days, consistent with Chui *et al.* [41] and Ji *et al.* [42], who linked humid conditions to higher fungal infection rates.

Negative correlations at longer lags (>15 days) suggest that the influence of rainfall diminishes as moisture dissipates or weather conditions vary. This agrees with [43], who showed that climatic effects on fungal diseases weaken over time.

Similarly, atypical sigmoidal epidemic curves of *P. megakarya* reported in Cameroon [44] were attributed either to new infection foci [45] or fruiting dynamics [46].

Local differences, such as weaker correlations in Abengourou, may reflect ecological variability or microclimatic effects, consistent with Mfegue *et al.* [39] and Ndoumbe-Nkeng *et al.* [31].

Finally, higher temperatures appeared to suppress disease development, with negative correlations observed for both mean (−0.55) and maximum temperatures (−0.60). Excessive heat is likely to reduce pathogen survival or delay development. Torres-de la Cruz *et al.* [46] similarly demonstrated that hot temperatures shorten the viability of *Phytophthora* spores by reducing available moisture.

5. Conclusions

Cocoa black pod rot remains a significant constraint to cocoa production, resulting in substantial yield losses. This study, conducted in cocoa-growing areas characterized by multimodal rainfall patterns, aimed to clarify the role of climatic factors in the epidemiology of the disease in order to inform improved control strategies.

Microscopic analyses confirmed the presence of two *Phytophthora* species responsible for black pod rot: *P. palmivora* and *P. megakarya*. Morphological traits, such as sporangium dimensions, pedicel length, and the length-to-width ratio, supported this identification. *P. palmivora* was the most frequent species overall (64.84%), whereas *P. megakarya* dominated in Abengourou (97.78%). Plot density and shading were also found to favor disease development.

Beyond descriptive statistics, cross-correlation analyses and logistic modeling provided new insights into the dynamics of the disease. The results showed that:

- In the presence of fruits, disease symptoms appeared within 15 days of rainy episodes.
- Disease incidence was strongly correlated with rainfall and maximum ambient temperature.

These findings provide valuable insights for enhancing cocoa pod rot management in Côte d'Ivoire. Control strategies should include:

- Preventive management and synchronization of treatments with rainfall patterns.
- Species-specific adaptation of control measures, depending on whether *P. palmivora* or *P. megakarya* predominates.
- Microclimate management through cultural practices, particularly regulating shade and planting density.

The main contribution of this work lies in providing decision-support tools grounded in climatic and epidemiological data. By integrating these parameters, management can shift from reactive, generalized interventions to initiative-taking, targeted, and locally adapted strategies, thereby enhancing the effectiveness of efforts to control black pod rot in Côte d'Ivoire.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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