Atmospheric and Climate Sciences, 2026, 16(2), 311-338
https://www.scirp.org/journal/acs
ISSN Online: 2160-0422
ISSN Print: 2160-0414

Temporal Association between Ambient $PM_{2.5}$ and COVID-19 Incidence in Abidjan, Côte d'Ivoire, during the First Year of the Pandemic (March 2020-March 2021)

Julien Bahino[1*], Martin Konan[2], M'Begnan Coulibaly[3], N'Datchoh E. Touré[1], Marcellin Adon[4], Arsène Ochou[1], Sékou Keita[5], Véronique Yoboué[1]

[1] Laboratory of Matter, Environment and Solar Energy Sciences (LASMES), UFR SSMT, Félix Houphouët-Boigny University of Abidjan, Abidjan, Côte d'Ivoire
[2] Cell Biology Unit, Pasteur Institute of Côte d'Ivoire (IPCI), Abidjan, Côte d'Ivoire
[3] National Institute of Public Hygiene (INHP), Regional Public Hygiene Unit, Bouaké, Côte d'Ivoire
[4] Laboratory of Environmental Science and Technology, Jean Lorougnon Guédé University, Daloa, Côte d'Ivoire
[5] Department of Mathematics, Physics and Chemistry, Péléforo-Gbon-Coulibaly University, Korhogo, Côte d'Ivoire
Email: *julienbahino@gmail.com

How to cite this paper: Bahino, J., Konan, M., Coulibaly, M., Touré, N.E., Adon, M., Ochou, A., Keita, S. and Yoboué, V. (2026) Temporal Association between Ambient PM2.5 and COVID-19 Incidence in Abidjan, Côte d'Ivoire, during the First Year of the Pandemic (March 2020-March 2021). *Atmospheric and Climate Sciences*, **16**, 311-338.
https://doi.org/10.4236/acs.2026.162017

Received: January 28, 2026
Accepted: March 16, 2026
Published: March 19, 2026

Abstract

This study, conducted within the IAQWA (Improving Air Quality in West Africa) project funded by the European Make Our Planet Great Again (MOPGA) program, investigates the temporal association between ambient fine particulate matter ($PM_{2.5}$) concentrations and daily COVID-19 incidence in Abidjan, Côte d'Ivoire, during the first year of the pandemic (March 2020-March 2021). Empirical evidence on environmental determinants of COVID-19 dynamics remains limited in African cities, despite persistently high levels of urban air pollution. Daily COVID-19 case data were analysed together with *in situ* measurements of $PM_{2.5}$ and meteorological parameters. Temporal associations were first explored using descriptive statistics and lagged Spearman correlations for delays ranging from 0 to 14 days. Non-linear and delayed relationships were then quantified using a generalized additive model (GAM) including environmental predictors at a fixed lag identified from the temporal analysis. COVID-19 incidence exhibited three major epidemic waves over the study period. $PM_{2.5}$ concentrations showed significant positive correlations with daily COVID-19 cases across all investigated lags, with a dominant peak at approximately 8 days. The GAM revealed a strong and non-linear exposure-response relationship between $PM_{2.5}$ and COVID-19 incidence. Relative risk increased progressively with $PM_{2.5}$ levels and reached a maximum of approximately 2.0 at concentrations around 40 $\mu g \cdot m^{-3}$, indicating a doubling of daily COVID-19 incidence compared with low-exposure conditions. Meteorological variables showed weaker and more complex associations, while the $PM_{2.5}$ effect remained robust after adjustment. These findings provide rare city-scale evidence that ambient fine particulate matter acted as a significant environmental cofactor of COVID-19 dynamics in a West African megacity. They highlight the potential role of chronic urban air pollution in amplifying population vulnerability to respiratory epidemics and underline the importance of integrating air quality considerations into public health surveillance and epidemic preparedness strategies in rapidly urbanizing African cities.

Keywords

$PM_{2.5}$, COVID-19, Air Pollution, Time-Series Analysis, Relative Risk, Abidjan, Côte d'Ivoire, West Africa

1. Introduction

The COVID-19 pandemic, caused by SARS-CoV-2 and declared by the World Health Organization (WHO) in March 2020, rapidly evolved into an unprecedented global health crisis. It affected every continent and profoundly disrupted health systems, economies, and everyday life worldwide. From the very beginning of the outbreak, international epidemiological models warned that Africa could be particularly hard hit. These early concerns were driven by high urban population densities, fragile healthcare systems, a heavy burden of respiratory diseases, and persistent difficulties in access to medical care [1].

Contrary to these initial projections, the spread of SARS-CoV-2 across the African continent proved to be highly heterogeneous and, in many countries, less explosive than expected during the first pandemic waves. This unexpected pattern stimulated significant scientific interest and led to a growing number of studies in Africa aimed at better understanding the mechanisms influencing viral transmission beyond purely socio-demographic and healthcare-related factors. This has encouraged researchers to explore the potential contribution of environmental and atmospheric conditions as modulators of epidemic dynamics rather than primary drivers.

Several studies have investigated the influence of environmental, climatic and atmospheric factors on COVID-19 dynamics in Africa. Research has highlighted the role of seasonal variability, Saharan dust transport, ambient air quality, aerosols and key meteorological parameters in shaping the spatial and temporal patterns of the pandemic [2]-[5]. In West, Southern and North Africa, these studies have examined relationships between daily COVID-19 incidence and environmental drivers, the impacts of successive epidemic waves, and the effects of public health restrictions on air quality [6] [7]. More recently, modelling and machine-learning approaches have been applied to assess and predict COVID-19 trends from atmospheric parameters, highlighting the growing integration of air-quality science into infectious disease research [8]. However, most of these studies emphasise statistical associations and call for caution in interpreting environmental variables as direct causal agents of transmission. At the continental scale, the first and second waves of COVID-19 in Africa were characterized by strong regional heterogeneity in timing and intensity, with a generally more pronounced second wave in many countries [9]. This continental perspective underscores the importance of investigating local determinants and potential environmental modulators of epidemic dynamics within specific urban contexts such as Abidjan.

In Côte d'Ivoire, the first confirmed COVID-19 case was reported on 11 March 2020 and involved an Ivorian passenger arriving from Italy. One year after the onset of the pandemic, as of 10 March 2021, Côte d'Ivoire had recorded a total of 36,028 confirmed cases and 206 deaths. Nearly 97% of these cases were reported in the Autonomous District of Abidjan, the country's main urban centre [10]. Abidjan, the administrative and economic capital of Côte d'Ivoire, is characterised by high population density, intense road traffic, rapid urbanisation, and numerous industrial activities. These factors contribute to elevated levels of ambient air pollution, particularly fine particulate matter ($PM_{2.5}$), with concentrations frequently exceeding the World Health Organization (WHO) air quality guideline values [11]. In such an urban environment, chronic air pollution constitutes a persistent background exposure likely to interact with respiratory epidemics.

$PM_{2.5}$ concentration is widely recognised as a major aggravating factor for respiratory health. Fine particles can penetrate deep into the pulmonary system, trigger inflammatory processes, and weaken immune defences [12]. Numerous studies have shown that chronic exposure to high levels of air pollution increases population vulnerability to viral respiratory infections, including influenza and coronaviruses [13]-[15]. During the early stages of the pandemic, studies conducted in China, Italy, and the United States reported positive associations between $PM_{2.5}$ concentrations and increases in confirmed COVID-19 cases or COVID-19-related mortality [16]-[19]. These findings have increasingly supported the view of air pollution as a cofactor that may exacerbate the spread and severity of COVID-19 rather than as a standalone cause of infection.

Two main mechanisms have been proposed to explain these associations. The first hypothesis suggests that prolonged exposure to $PM_{2.5}$ increases individual susceptibility to infection by impairing immune responses and enhancing the expression of the ACE-2 receptor in lung tissues, thereby facilitating viral entry [20]. The second hypothesis proposes that fine particles may indirectly influence transmission dynamics by promoting the persistence of respiratory aerosols in the atmosphere, without demonstrating active transport of the virus by ambient particles [16] [21]. In both cases, $PM_{2.5}$ is considered a facilitating environmental factor rather than a direct cause of infection, interacting with biological vulnerability and transmission conditions. Accordingly, and particularly in observational time-series analyses, it is essential to distinguish statistical associations from causal relationships, as environmental variables may covary with social behaviour, mobility patterns, and public health interventions.

In this context, Abidjan represents a relevant case study. The city experiences recurrent air pollution episodes driven by road traffic, industrial activities, domestic combustion, and waste management practices. Analysing the temporal relationship between $PM_{2.5}$ concentrations and daily new COVID-19 cases can help elucidate how local environmental conditions may have influenced the progression of the pandemic in a West African urban setting, not as a primary cause, but as a potential co-determinant of population vulnerability and short-term transmission dynamics. Such empirical evidence on these interactions remains limited for this region.

This study aims to assess the association between daily $PM_{2.5}$ concentrations and the incidence of new COVID-19 cases in the Autonomous District of Abidjan. The analysis focuses on the first year of the pandemic, from 11 March 2020 to 10 March 2021, a critical period during which the absence of vaccination campaigns allows examination of the natural dynamics of infection. The study accounts for lagged effects related to the virus incubation period and adjusts for potential confounding meteorological factors. The objective is to evaluate whether fluctuations in ambient fine particulate matter levels were temporally associated with variations in COVID-19 incidence, thereby contributing to a better understanding of the potential role of air pollution in respiratory health crises in urban African contexts.

2. Materials and Methods

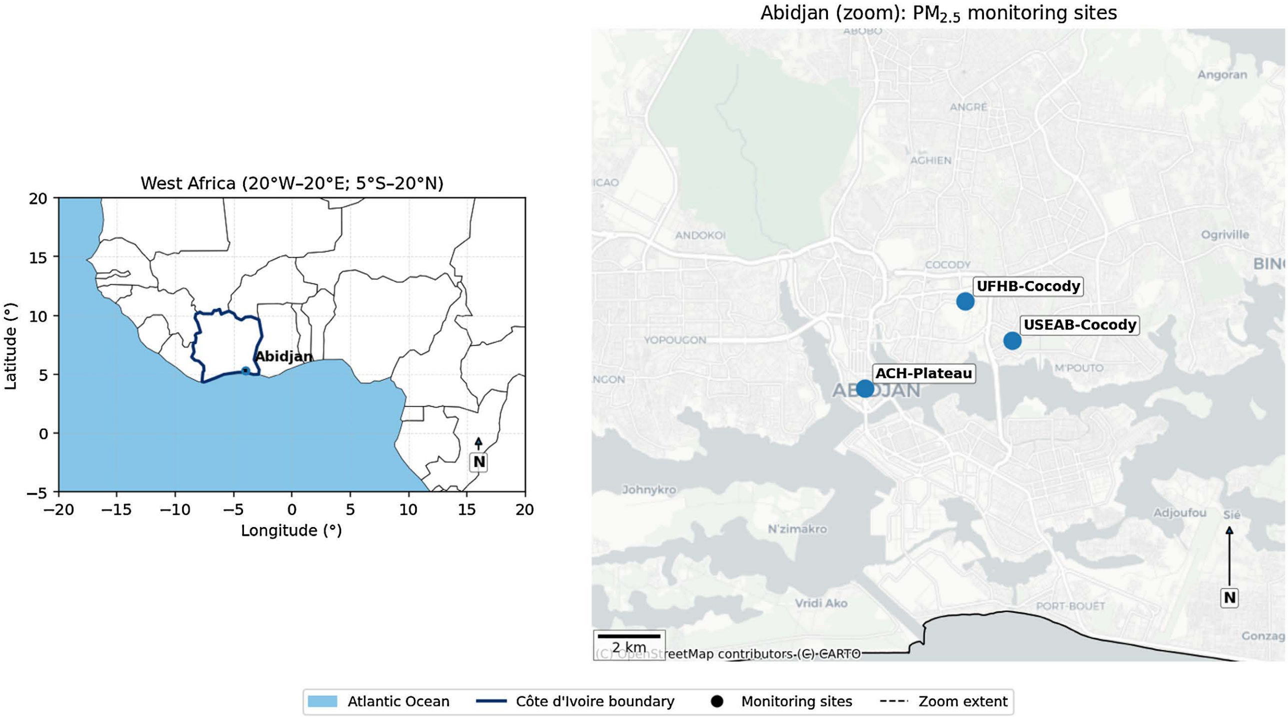
This study is based on a time-series epidemiological analysis designed to assess the association between daily exposure to fine particulate matter ($PM_{2.5}$) and COVID-19 incidence in the Autonomous District of Abidjan. The methodology described below was developed to ensure rigorous data collection, processing, and analysis, while accounting for major potential confounding factors, particularly meteorological parameters.

2.1. Study Area and Sampling Sites in the Autonomous District of Abidjan

The study was conducted in the Autonomous District of Abidjan, the economic capital of Côte d'Ivoire and the country's main urban area, characterized by rapid population growth and an estimated population of 6,321,000 inhabitants in 2021 [22]. Abidjan also hosts a high concentration of industries, economic activities, and intense road traffic. Air quality monitoring sites were selected to best represent population exposure, targeting high-traffic areas, urban background locations, and residential zones. **Figure 1** presents the location of the three measurement sites in the Autonomous District of Abidjan.

2.2. Atmospheric Pollution Data ($PM_{2.5}$)

Fine particulate matter ($PM_{2.5}$) concentrations were continuously measured at



Data: Natural Earth (countries, ocean). Abidjan boundary: OpenStreetMap (via OSMnx). Basemap: CartoDB/OSM contributors.

Figure 1. Location of the $PM_{2.5}$ monitoring sites in Abidjan, Côte d'Ivoire.

three sites representative of Abidjan's urban environment between March 2020 and April 2021. The first site was located on the campus of Félix Houphouët-Boigny University (UFHB) in Cocody, where a BAM-1022 (Beta Attenuation Monitor) was deployed as a reference instrument. This site offered stable installation conditions and a favorable institutional environment for high-quality measurements, making it the reference station of the monitoring system.

A second BAM analyzer, compliant with standard measurement requirements, was installed at the United States Embassy, also in Cocody. Data from this site provided an independent source to verify the consistency of measurements obtained in Côte d'Ivoire through an internationally calibrated monitoring network.

The third site was located at the Abidjan District Headquarters in Plateau, where a RAMP (Real-time Affordable Multi-Pollutant) sensor was used to measure atmospheric concentrations. To ensure measurement consistency and comparability across instruments, the RAMP sensor was previously co-located with the BAM-1022 following recognized calibration protocols, allowing adjustment of its instrumental response.

A summary of the main characteristics of the monitoring sites and their geographic coordinates is provided in **Table 1**.

The monitoring network thus covered two major municipalities, Cocody and Plateau, and encompassed contrasting environments including institutional areas, administrative zones, and densely populated urban sectors. The instruments recorded $PM_{2.5}$ concentrations at a 15-second time resolution, generating detailed time series throughout the study period. Raw data systematically underwent quality control procedures, including the identification of missing or outlier values, verification of instrumental consistency, and examination of periods affected by interruptions or maintenance. This process ensured the reliability of the time series retained for analysis. Measurement techniques, equipment characteristics, and detailed descriptions of the monitoring sites have been extensively documented elsewhere [23]. Based on the validated data, daily mean $PM_{2.5}$ concentrations were calculated separately for each of the three sites. A district-wide daily value representative of the entire Abidjan area was then derived by aggregating the daily concentrations from the three stations. This urban average was intended to reflect the overall daily population exposure to particulate pollution. The resulting daily time series forms the basis for comparative analyses with the temporal evolution of daily COVID-19 cases over the same period.

Table 1. Air quality ($PM_{2.5}$) monitoring sites in the Autonomous District of Abidjan and their characteristics.

Site name (abbreviation)	Coordinates (Latitude, Longitude)	Site characteristics and dominant emission sources	Main instrumentation
U.S. Embassy in Abidjan (USEAB)	5.3353˚N, 3.9761˚W	Residential area in Cocody. The site is mainly influenced by road traffic emissions, particularly from a nearby roundabout and toll station.	Met One BAM-1022 reference monitor
Félix Houphouët-Boigny University (UFHB)	5.3467˚N, 3.9900˚W	Mixed urban environment in Cocody. The site is surrounded by green areas (botanical garden) but also impacted by nearby congested roads. It is used as a reference location for sensor co-location and calibration.	Met One BAM-1022, RAMP sensors
Abidjan City Hall (ACH)	5.3211˚N, 4.0198˚W	Urban traffic site located in the Plateau district (city center). Strongly affected by intense road traffic due to its immediate proximity (<20 m) to a major road intersection.	RAMP sensors

2.3. Epidemiological Data (COVID-19)

Data on daily newly confirmed COVID-19 cases in Côte d'Ivoire were obtained from two complementary sources. National data were sourced from the official government portal dedicated to COVID-19 surveillance (https://info-covid19.gouv.ci/welcome/labonneinfos), managed by the Ministry of Health, Public Hygiene and Universal Health Coverage (MSHP-CMU), which serves as the national reference for epidemiological statistics. These data were complemented and cross-checked using the COVID-19 database of the Johns Hopkins University Center for Systems Science and Engineering (JHU-CSSE), which compiles official national reports and is widely used in epidemiological studies (https://coronavirus.jhu.edu/region/cote-d'ivoire).

Data production relied on coordinated actions between the Institut National d'Hygiène Publique (INHP) and the Institut Pasteur de Côte d'Ivoire (IPCI). As part of the national response to the COVID-19 pandemic, the Ivorian government implemented a strategic response plan formalized by Decree No. 470/PM/CAB of 10 April 2020. Within this framework, the INHP was mandated to conduct nasopharyngeal sample collection and community surveillance through officially designated testing centers, while the IPCI was responsible for laboratory diagnosis of SARS-CoV-2 infection, including confirmation of positive cases using reverse transcription polymerase chain reaction (RT-PCR). Results from both institutions are subsequently consolidated, validated, and published daily by the Ministry of Health on the official platform.

It should be noted that the data used in this study correspond to the total number of newly confirmed cases at the national level. However, according to national health authorities and official communications following the National Security Council meeting of 9 December 2021, approximately 95% of confirmed COVID-19 cases were reported in the Autonomous District of Abidjan, confirming its role as the national epicenter of the pandemic [24]. Although the available data do not allow full disaggregation by municipality, their strong representativeness of the epidemiological situation in Abidjan justifies their comparison with daily $PM_{2.5}$ concentrations measured exclusively at sites located within the Autonomous District of Abidjan.

2.4. Identification of Epidemic Waves

To characterize the temporal structure of the COVID-19 epidemic in Abidjan and contextualize the evolution of air pollution during major outbreak phases, epidemic waves were objectively identified from the daily time series of reported COVID-19 cases. Because daily epidemiological data are subject to strong short-term variability related to reporting delays, testing capacity, and weekly effects, the original series was first smoothed using a 7-day moving average to reduce high-frequency noise while preserving the underlying epidemic signal.

Epidemic waves were then detected using a peak-based approach applied to the smoothed incidence curve. A wave was operationally defined as a sustained period of increasing daily cases leading to a local maximum, followed by a subsequent decline. Local maxima were identified as points where the first temporal derivative of the smoothed series changed sign from positive to negative and where incidence exceeded the surrounding baseline for several consecutive days. For each wave, the start date corresponded to the onset of continuous growth preceding the peak, and the end date to the return to a stable or declining phase.

This objective procedure allowed the identification of the main epidemic phases and their durations. The detected waves were not used as predictors in the statistical models but served to describe the temporal organization of the epidemic, compare pollution levels across major outbreak phases, and support the interpretation of lagged associations between $PM_{2.5}$ exposure and COVID-19 incidence.

2.5. Meteorological Parameters

Daily meteorological data used in this study were obtained from the reanalysis of observations from Ivorian meteorological stations, compiled and provided by the Iowa Environmental Mesonet through the Côte d'Ivoire ASOS (Automated Surface Observing System) network. These data, available via https://mesonet.agron.iastate.edu/, offer homogeneous and continuous coverage over the entire study period. Variables recorded at synoptic hours were aggregated to derive daily mean values, which were subsequently included in the statistical models as potential confounding factors. The meteorological parameters considered were:

- Air temperature at 2 m (T2M), in degrees Celsius (˚C);
- Dew point temperature at 2 m (D2M), in degrees Celsius (˚C);
- Relative humidity (RH), expressed as a percentage (%);
- Mean wind speed, in meters per second ($m \cdot s^{-1}$);
- Mean wind direction, expressed in degrees relative to geographic north.

These parameters were selected because of their well-documented influence on atmospheric pollutant dispersion, boundary-layer stability, and viral persistence in the environment. Their inclusion in the models ensures that any observed association between $PM_{2.5}$ concentrations and COVID-19 incidence is evaluated independently of prevailing meteorological conditions.

2.6. Statistical Analysis

All statistical analyses were conducted using Python and R. Daily time series of urban mean $PM_{2.5}$ concentrations (ABJ-$PM_{2.5}$), meteorological parameters, and COVID-19 incidence were first explored using descriptive statistics. The distribution of each variable was assessed using the Shapiro-Wilk and D'Agostino-Pearson normality tests to determine whether parametric or non-parametric statistical methods were appropriate. Based on these diagnostic tests, correlation analyses were performed using methods consistent with the distributional properties of the data. Associations between daily PM2.5 concentrations, meteorological parameters, and COVID-19 incidence were evaluated using correlation analysis. To account for potential delays between particulate matter exposure and reported COVID-19 cases, a lagged analysis was performed by computing correlations for lag times ranging from 0 to 14 days, where positive lags correspond to $PM_{2.5}$ concentrations preceding COVID-19 incidence. Lag selection was based on this temporal lag-correlation analysis and on biological plausibility related to the incubation period and reporting delay of SARS-CoV-2. The lag showing the strongest and most epidemiologically consistent association was subsequently used in the generalized additive model (GAM) to investigate delayed environmental effects.

To further investigate potential non-linear and threshold-type relationships, a concentration-stratified analysis was conducted. Daily $PM_{2.5}$ concentrations were grouped into eight classes covering the full observed range. For each class, the mean $PM_{2.5}$ concentration and the corresponding mean COVID-19 incidence at the selected lag were calculated. All statistical tests were two-sided, and results were considered statistically significant at $p < 0.05$. These exploratory statistical analyses were used to guide and complement the GAM framework with lagged predictors described in the following section.

3. Results

3.1. Descriptive Statistics Distributional Properties of $PM_{2.5}$ and COVID-19 Incidence

The analysis is based on daily time series of $PM_{2.5}$ concentrations measured at three sites in Abidjan and daily COVID-19 incidence. The dataset covers n = 366 consecutive days from 11 March 2020 to 10 March 2021, with complete $PM_{2.5}$ observations available for the entire period. The distributions of the variables are illustrated in Figure 2, while descriptive statistics and normality test results are

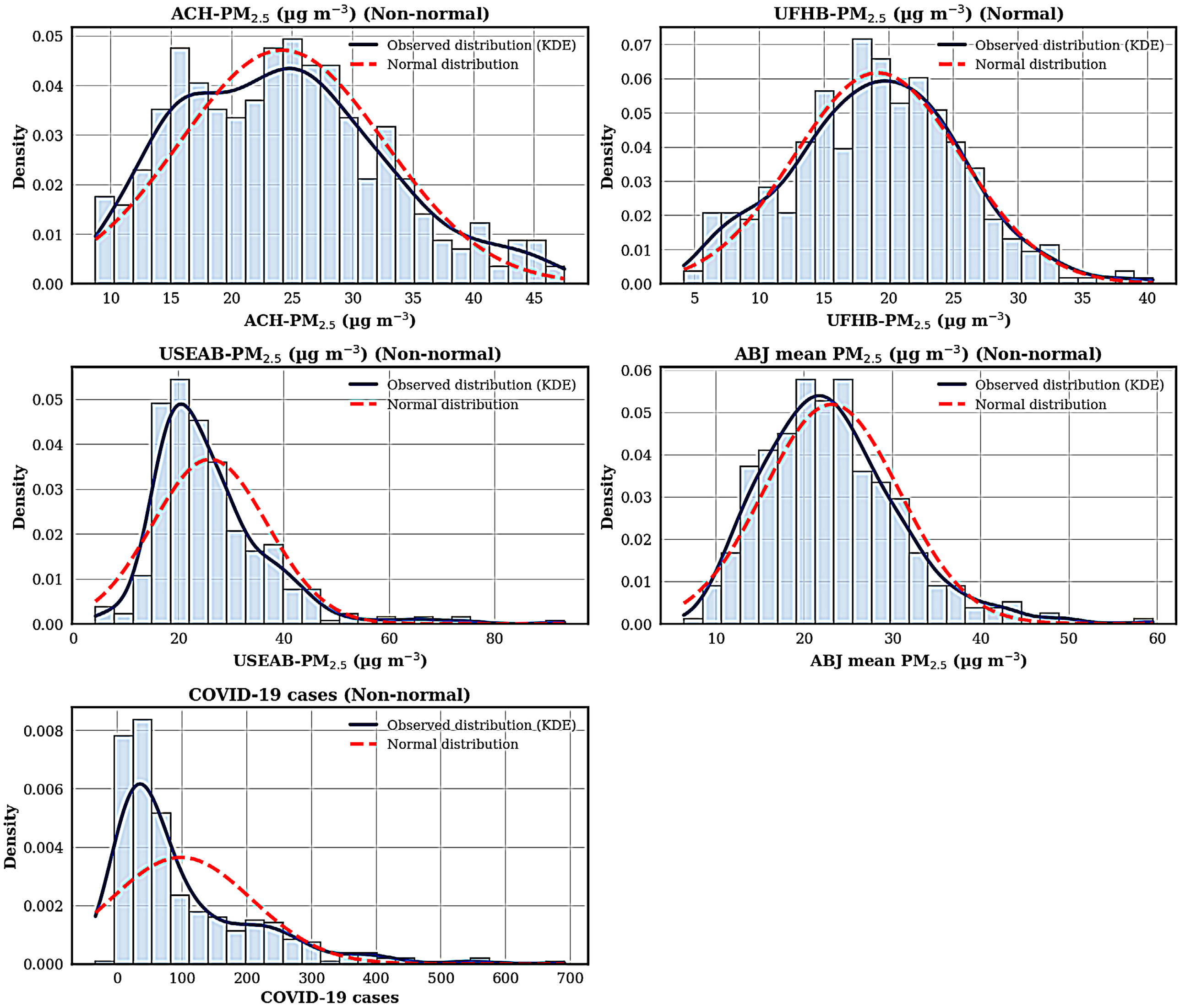


Figure 2. Empirical and theoretical distributions of daily $PM_{2.5}$ concentrations at three monitoring sites and of daily COVID-19 incidence in Abidjan (March 2020-March 2021).

summarized in **Table 2**.

Figure 2 and **Table 2** show that $PM_{2.5}$ concentrations exhibit marked spatial variability across the monitoring sites. At the Abidjan District Hotel site (ACH), the mean daily concentration reached 24.2 ± 8.5 $\mu g \cdot m^{-3}$, with values ranging from 8.7 to 47.5 $\mu g \cdot m^{-3}$. The University Félix Houphouët-Boigny (UFHB) site recorded lower and more stable concentrations, with a mean of 19.2 ± 6.5 $\mu g \cdot m^{-3}$ and reduced variability. In contrast, the U.S. Embassy site (USEAB) showed the highest pollution levels and the largest dispersion, with a mean concentration of 26.0 ± 10.9 $\mu g \cdot m^{-3}$ and extreme values reaching 93.2 $\mu g \cdot m^{-3}$, indicative of episodic pollution events.

The city-wide average $PM_{2.5}$ concentration (ABJ-$PM_{2.5}$), obtained by aggregating the three stations, was 23.1 ± 7.7 $\mu g \cdot m^{-3}$, with daily values between 6.4 and 59.5 $\mu g \cdot m^{-3}$. This mean level exceeds the WHO 2021 daily guideline value (15 $\mu g \cdot m^{-3}$) by approximately 54% and is more than four times higher than the recommended annual guideline (5 $\mu g \cdot m^{-3}$), confirming chronic population exposure to elevated particulate pollution in Abidjan.

Table 2. Descriptive statistics and normality tests for daily COVID-19 cases and $PM_{2.5}$ concentrations in Abidjan (2020-2021).

Variable	ACH-$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	UFHB-$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	USEAB-$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	ABJ-$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	COVID-19 cases
n	366	366	366	366	366
Mean	24.2	19.2	26.0	23.1	98.4
SD	8.5	6.5	10.9	7.7	109.2
Min	8.7	4.2	4.3	6.4	0.0
25%	17.0	14.9	18.7	17.5	26.0
50%	23.8	19.4	23.4	22.2	55.0
75%	29.5	23.4	29.9	27.4	142.0
Max	47.5	40.4	93.2	59.5	691.0
Skewness	0.4	0.1	1.9	0.9	1.9
Kurtosis	−0.3	−0.04	6.3	1.6	4.2
SW (p)	1.3×10^{-5}	1.4×10^{-1}	3.4×10^{-17}	3.4×10^{-8}	3.5×10^{-21}
DA (p)	1.7×10^{-3}	6.6×10^{-1}	2.6×10^{-36}	4.3×10^{-12}	9.1×10^{-33}
Normality	Non-normal	Normal	Non-normal	Non-normal	Non-normal

Daily COVID-19 incidence displayed even greater variability. Over the study period, the mean daily number of confirmed cases was 98.4 ± 109.2, with values ranging from 0 to 691 cases per day. The median value (55 cases/day) was substantially lower than the mean, reflecting a strongly right-skewed distribution dominated by epidemic peaks occurring over limited time intervals.

Normality tests corroborate these descriptive findings. Shapiro-Wilk and

D'Agostino-Pearson tests indicate that only the UFHB-$PM_{2.5}$ series follows a normal distribution ($p > 0.05$ for both tests). All the other series data, including ACH-$PM_{2.5}$, USEAB-$PM_{2.5}$, ABJ-$PM_{2.5}$, and COVID-19 cases, exhibited highly significant departures from normality ($p < 0.01$). These results are consistent with the skewness and kurtosis coefficients. In particular, USEAB-$PM_{2.5}$ showed pronounced positive skewness (1.9) and high kurtosis (6.3), reflecting extreme pollution episodes, while COVID-19 incidence was also strongly right-skewed (1.9) with elevated kurtosis (4.2), characteristic of epidemic surges.

Given that four out of five variables do not satisfy the normality assumption, non-parametric statistical methods were considered more appropriate for subsequent analyses. Parametric approaches such as Pearson correlation would be sensitive to extreme values and distributional asymmetry. Therefore, Spearman's rank correlation coefficient was selected, as it is robust to non-normality, captures monotonic relationships, and reduces the influence of extreme pollution or epidemic peaks. This statistical structure justifies the use of non-parametric methods to investigate potential associations between $PM_{2.5}$ exposure and COVID-19 transmission dynamics in the Abidjan metropolitan area.

3.2. Daily Variations in $PM_{2.5}$ Concentrations and COVID-19 Incidence

During the first year of the COVID-19 pandemic in the Abidjan district, the daily number of newly confirmed cases exhibited several pronounced phases of increase, reflecting the occurrence of successive epidemic waves. To characterise the temporal organisation of these outbreaks, we first analysed the smoothed daily incidence curve to objectively identify periods of rapid epidemic intensification. Epidemic waves were objectively detected using a peak-based approach applied to the 7-day moving average of daily COVID-19 cases, allowing the identification of sustained growth phases followed by clear epidemic peaks. This objective procedure led to the detection of three major epidemic waves over the study period. The corresponding start and end dates, as well as their durations, are summarised in **Table 3**.

Table 3. Identified COVID-19 epidemic waves in Abidjan and wave-specific correlations between $PM_{2.5}$ concentrations and COVID-19 incidence.

Wave	Start date	End date	Duration (days)	Spearman's ρ	p-value
1	08 Jun 2020	25 Jul 2020	46	0.047	0.755
2	07 Jan 2021	16 Feb 2021	36	−0.028	0.873
3	01 Mar 2021	15 Mar 2021	14	−0.420	0.135

To investigate whether particulate air pollution could have contributed to the observed epidemic dynamics, we compared the daily evolution of $PM_{2.5}$ concentrations with the daily incidence of reported COVID-19 cases. The temporal evolution of both variables is presented in **Figure 3**. The superposition of the

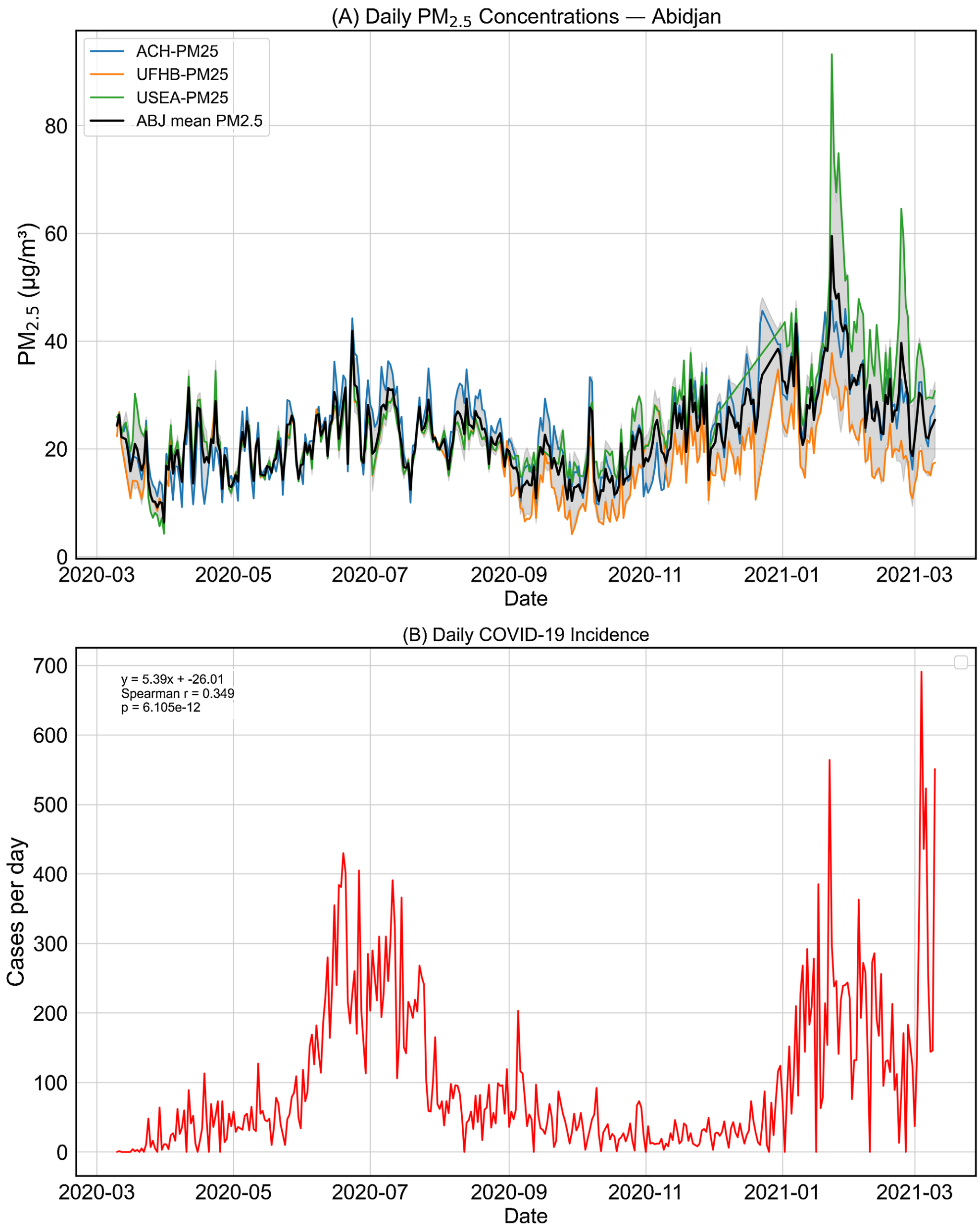


Figure 3. Temporal evolution of (A) daily $PM_{2.5}$ concentrations measured at ACH-Plateau, UFHB-Cocody, and USEAB-Cocody, as well as the city-wide mean (ABJ mean $PM_{2.5}$), and (B) daily reported COVID-19 cases in the Autonomous District of Abidjan.

two-time series reveals a clear temporal co-variation between periods of elevated $PM_{2.5}$ concentrations and increases in COVID-19 incidence. Over the entire study period, this co-variation is supported by a statistically significant positive Spearman correlation coefficient ($\rho = 0.35$, $p < 0.001$), indicating that higher daily $PM_{2.5}$ levels tended to coincide with higher numbers of reported cases.

Two distinct epidemic phases were particularly evident. The first occurred between June and August 2020, during which a first epidemic peak was recorded, reaching approximately 430 new daily cases. The second phase took place between January and February 2021 and was characterized by a more pronounced peak, with a maximum of 691 daily cases. This second epidemic phase coincides with the December-February dry season in West Africa, which is frequently associated with enhanced mineral dust transport during the Harmattan period. During this season, a substantial fraction of $PM_{2.5}$ may originate from Saharan and Sahelian dust, suggesting that the observed pollution peak likely reflects not only local combustion sources but also regional mineral aerosol contributions [25]. During both periods, daily $PM_{2.5}$ concentrations frequently exceeded the World Health Organization (WHO) air quality guideline values. Concentrations ranged mainly between 20 and 40 $\mu g \cdot m^{-3}$ during the June-July 2020 period and between 20 and 55 $\mu g \cdot m^{-3}$ during the December 2020-February 2021 period.

When the analysis was restricted to the epidemic wave periods identified in **Table 3**, no statistically significant monotonic correlation was observed between daily $PM_{2.5}$ concentrations and COVID-19 incidence. Specifically, Spearman correlation coefficients were very low and not significant during the first two epidemic waves ($\rho = 0.047$, $p = 0.755$ for Wave 1; $\rho = -0.028$, $p = 0.873$ for Wave 2), and although a stronger negative association was observed during the third wave ($\rho = -0.420$), it remained statistically non-significant ($p = 0.135$). This result suggests that the major epidemic waves were primarily driven by overriding epidemiological and social factors, including intrinsic viral transmission dynamics, population behaviour, and public health interventions. Consequently, short-term variations in $PM_{2.5}$ are unlikely to have constituted a primary trigger of epidemic surges. Instead, the potential influence of air pollution is more plausibly expressed outside peak transmission periods and/or through delayed effects, acting as a background environmental cofactor that may modulate, rather than initiate, epidemic dynamics. In this sense, elevated particulate matter levels may have acted as an aggravating environmental factor during major epidemic phases. However, given the incubation period of SARS-CoV-2 and the delay between exposure and case detection, contemporaneous comparisons may fail to capture delayed responses to air pollution exposure. We therefore extended the analysis to investigate lagged associations between $PM_{2.5}$ concentrations and COVID-19 incidence. In the following section, a systematic time-lag analysis is performed to determine whether delayed relationships, consistent with viral incubation and reporting dynamics, can be identified.

3.2.1. Temporal Lag Analysis between $PM_{2.5}$ and COVID-19 Incidence in Abidjan

The temporal relationship between daily fine particulate matter concentrations and COVID-19 incidence in Abidjan was investigated using the non-parametric Spearman rank correlation coefficient (ρ), calculated for lag times ranging from 0 to 14 days. This approach enables the assessment of delayed associations between exposure to particulate pollution and the subsequent reporting of COVID-19 cases, while remaining robust to non-normal data distributions and the presence of extreme values. Given the large sample size ($n = 366$), the lagged correlations could be robustly estimated and were found to be statistically significant at the 95% confidence level ($p < 0.05$), with values well above the minimum threshold commonly considered meaningful for large samples ($|\rho| = 0.10$). As shown in **Figure 4**, all correlations are positive and significant with p-values ranging from 10^{-10} to 10^{-18}. This result indicates a consistent and robust association between $PM_{2.5}$ exposure and COVID-19 incidence across all investigated lag times.

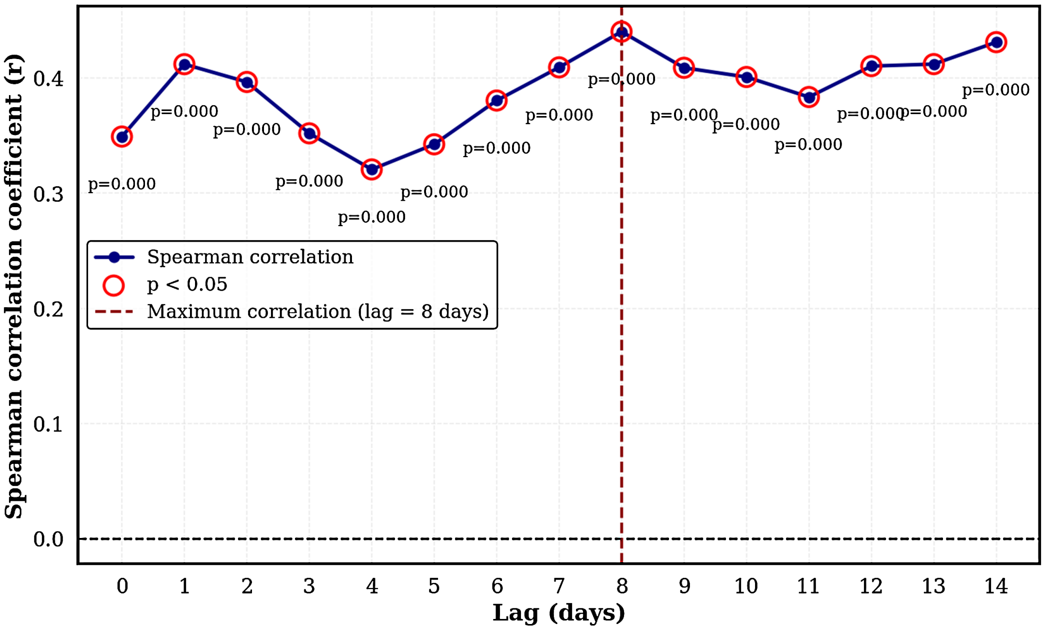


Figure 4. Lagged Spearman correlations between daily $PM_{2.5}$ concentrations averaged over Abidjan and daily COVID-19 cases for lags from 0 to 14 days. Red circles indicate statistically significant correlations ($p < 0.05$).

The lag-correlation profile reveals the presence of two distinct and epidemiologically relevant peaks, suggesting different underlying mechanisms linking $PM_{2.5}$ exposure to COVID-19 dynamics.

The first peak occurs at short lags (0-2 days), with Spearman correlation coefficients ranging from $\rho = 0.35$, $p = 6.1 \times 10^{-12}$ at lag 0 to $\rho = 0.41$, $p = 2.1 \times 10^{-16}$ at lag 1. However, this very short lag (0 - 2 days) should be interpreted with caution. Given the incubation period of SARS-CoV-2 and delays associated with testing and reporting, such an immediate association is unlikely to reflect a direct causal effect of $PM_{2.5}$ on new infections. It may instead be partially driven by behavioural factors, health-seeking behaviour, or unmeasured short-term confounders, and therefore should be considered as a potential spurious or indirect association rather than evidence of rapid symptom aggravation. A second and more pronounced peak is observed at lag 8 days, where the correlation reaches its maximum value ($\rho = 0.440$, $p = 2.0 \times 10^{-18}$). This delayed peak likely reflects the time required for $PM_{2.5}$ exposure to increase host susceptibility to infection and for infected individuals to progress through the incubation period and develop clinically detectable symptoms. This time scale is consistent with the established incubation period of SARS-CoV-2, which generally ranges from 2 to 14 days, with respiratory symptoms most often developing within approximately 3 to 7 days after exposure [26].

The delayed association observed at approximately one week supports well-established biological mechanisms linking fine particulate matter exposure to respiratory viral infections. Fine particulate matter $PM_{2.5}$ can penetrate deep into the lower respiratory tissues, impairs mucociliary clearance, alters alveolar macrophage function, and promotes chronic inflammation, all of which may facilitate viral entry and replication. These processes can increase both the probability of infection and the severity of clinical outcomes [27].

The temporal pattern identified in Abidjan closely mirrors findings from previous international studies. [28] reported that $PM_{2.5}$ exposure was significantly associated with COVID-19 incidence in multiple Chinese cities, with the strongest effects observed at lags between 7 and 14 days. Similarly, [17] documented a maximum association around 8 - 9 days in Northern Italy, attributing this delay to immune modulation and disease progression following exposure to particulate pollution.

An additional hypothesis proposed in recent literature is that airborne particles may act as vectors for viral material, potentially prolonging viral residence time in the atmosphere and increasing the likelihood of inhalation. Although the viability of SARS-CoV-2 on particulate matter remains under investigation, the detection of viral RNA on ambient particles reported in several studies lends plausibility to this mechanism and may contribute to the sustained correlations observed at longer lags.

3.2.2. Identification of Critical $PM_{2.5}$ Levels Associated with Increased COVID-19 Incidence at the Optimal Lag of 8 Days

To further characterize the exposure-response relationship between ambient $PM_{2.5}$ concentrations and COVID-19 incidence in Abidjan, a stratified analysis by concentration classes was conducted using the optimal temporal lag identified in the previous section (lag = 8 days). Daily $PM_{2.5}$ concentrations were grouped into eight intervals covering the full range observed during the study period. For each interval, the mean $PM_{2.5}$ concentration and the corresponding mean number of COVID-19 cases reported eight days later were calculated. The stratified PM2.5 concentration classes and the corresponding mean COVID-19 incidence at an 8-day lag are presented in **Table 4**. This categorical approach allows the identification of potential threshold effects and non-linear responses that may not be fully captured by correlation analysis alone.

The results reveal a clear and progressive increase in COVID-19 incidence with rising $PM_{2.5}$ concentrations, strongly suggesting the existence of critical concentration thresholds beyond which the epidemiological response becomes markedly amplified.

In the lowest exposure class (6.4 - 14.3 $\mu g \cdot m^{-3}$), where $PM_{2.5}$ concentrations remain below the WHO daily guideline of 15 $\mu g \cdot m^{-3}$, the mean number of COVID-19 cases reported eight days later is approximately 32 cases per day. This level can be considered a reference baseline under relatively low pollution conditions. Once daily

Table 4. Stratified $PM_{2.5}$ concentration classes and corresponding mean COVID-19 incidence at lag 8 days.

$PM_{2.5}$ interval ($\mu g \cdot m^{-3}$)	n*	Mean $PM_{2.5}$ ($\mu g \cdot m^{-3}$)	Mean COVID-19 cases (lag = 8)
[6.4 - 14.3]	45	12.4	32.3
[14.3 - 17.4]	45	16.2	62.0
[17.4 - 20.0]	44	18.8	82.1
[20.0 - 22.1]	45	21.1	75.7
[22.1 - 24.5]	45	23.3	88.4
[24.5 - 27.3]	44	25.9	123.3
[27.3 - 31.6]	45	29.3	146.9
[31.6 - 59.5]	45	37.4	194.4

*n represents the number of observations (sample size) in each $PM_{2.5}$ concentration class.

$PM_{2.5}$ concentrations exceed the WHO guideline, a sharp increase in COVID-19 incidence is observed. In the intermediate exposure range (17 – 22 $\mu g \cdot m^{-3}$), mean daily cases rise to approximately 75-82 cases, representing more than a twofold increase compared with the lowest exposure class. This finding indicates a strong sensitivity of COVID-19 incidence to even moderate exceedances of international air quality standards. The most pronounced increase occurs beyond a second empirical threshold, identified around 25 $\mu g \cdot m^{-3}$. When $PM_{2.5}$ concentrations fall within the 24.5 - 27.3 $\mu g \cdot m^{-3}$ range, the mean number of cases increases to 123 cases per day, nearly four times higher than under low-pollution conditions. This threshold corresponds closely to the former WHO annual guideline (25 $\mu g \cdot m^{-3}$) and appears particularly relevant in the context of short-term epidemic amplification.

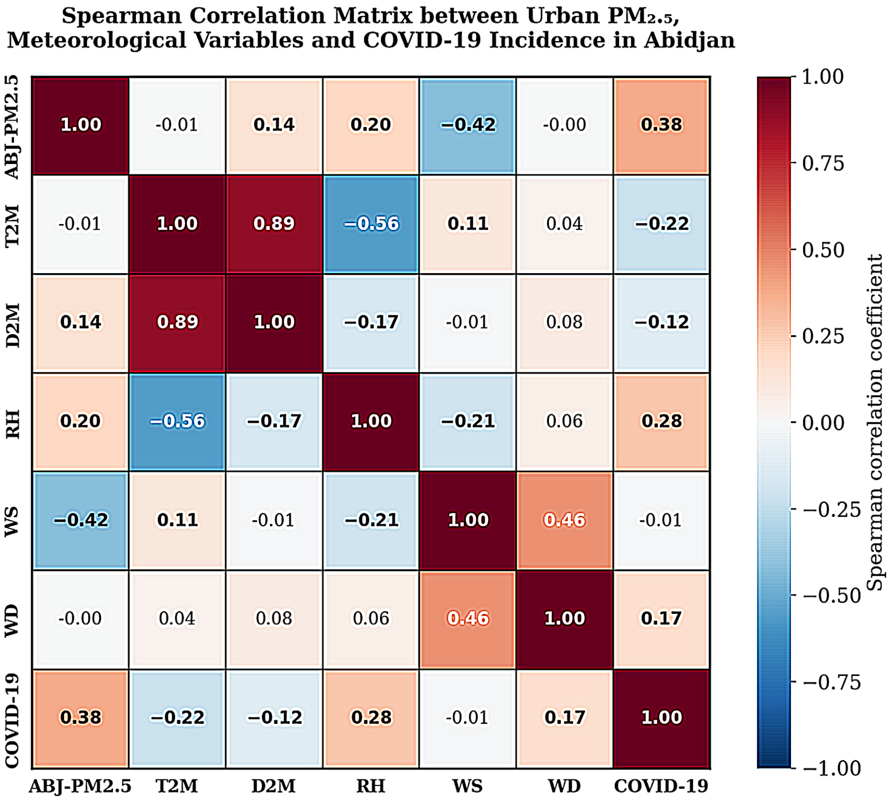
At the highest exposure levels (31.6 - 59.5 $\mu g \cdot m^{-3}$), mean $PM_{2.5}$ concentrations of approximately 37 $\mu g \cdot m^{-3}$ are associated with an average of 194 COVID-19 cases per day, representing an increase by a factor greater than six relative to the lowest exposure class. This pronounced escalation provides strong evidence of a non-linear dose-response relationship, in which health impacts intensify rapidly beyond moderate pollution levels.

It is important to note that the observed increase is not perfectly linear. A slight decrease in mean COVID-19 incidence is observed for the [20.0 - 22.1] $\mu g \cdot m^{-3}$ $PM_{2.5}$ class (mean COVID-19 cases = 76). This irregularity may reflect internal variability in the time series, contextual factors such as changes in population behavior during periods of movement restrictions, the implementation of non-pharmaceutical interventions, public health measures, or the inherent heterogeneity of epidemiological data. Nevertheless, despite this localized fluctuation, the overall trend remains clearly increasing.

This class-based analysis confirms the existence of critical $PM_{2.5}$ concentration levels beyond which COVID-19 incidence increases markedly. Above the WHO daily guideline value of 15 μg·m^{-3}, COVID-19 cases rise substantially, while concentrations exceeding approximately 25 μg·m^{-3} are associated with a pronounced amplification of incidence. These findings are consistent with international evidence, including studies conducted in China, Italy and the United States, which report similar dose-response relationships between particulate matter exposure and COVID-19 incidence [19] [28] [29].

3.3. Influence of Meteorological Parameters on COVID-19 Incidence

The influence of meteorological conditions on daily COVID-19 incidence in Abidjan was assessed using Spearman rank correlation coefficients between reported cases and key meteorological variables, namely air temperature at 2 m (T2M), dew point temperature at 2 m (D2M), relative humidity (RH), wind speed (WS), and wind direction (WD). Statistical significance was evaluated at the 5% level ($p < 0.05$). The results of the Spearman correlation analysis between COVID-19 incidence, meteorological variables, and urban $PM_{2.5}$ concentrations are summarized in **Figure 5**.



Spearman Correlation Matrix between Urban $PM_{2.5}$, Meteorological Variables and COVID-19 Incidence in Abidjan

Figure 5. Spearman correlation matrix between urban $PM_{2.5}$, meteorological variables, and COVID-19 incidence in Abidjan.

Overall, meteorological variables exhibit weak to moderate associations with COVID-19 incidence, markedly lower than those observed for fine particulate matter ($PM_{2.5}$), suggesting a secondary and modulating role of weather conditions in the epidemic dynamics.

Air temperature (T2M) shows a weak but statistically significant negative correlation with COVID-19 incidence ($\rho = -0.22$, $p < 0.001$), indicating that higher temperatures are associated with slightly lower numbers of reported cases. This pattern is consistent with the reduced persistence and transmissibility of respiratory viruses under warmer conditions.

The dew point temperature (D2M) is also weakly and negatively correlated with COVID-19 incidence ($\rho = -0.12$), and this association is statistically significant ($p = 0.025$). Although modest in magnitude, this result suggests that higher atmospheric moisture content, when expressed through dew point temperature, does not favor increased transmission in the local context.

Relative humidity (RH) exhibits a weak but significant positive correlation with COVID-19 incidence ($\rho = 0.28$, $p < 0.001$). This relationship suggests that more humid conditions may indirectly contribute to higher case numbers, potentially through effects on human behavior, indoor crowding, or interactions with other environmental factors.

Wind-related parameters display contrasting behaviors. Wind speed (WS) shows no significant association with COVID-19 incidence ($\rho = -0.01$, $p = 0.81$), indicating the absence of a detectable direct effect. In contrast, wind direction (WD) is weakly but significantly positively correlated with COVID-19 cases ($\rho = 0.17$, $p = 0.001$), suggesting that prevailing circulation patterns may influence environmental exposure conditions, although this effect remains limited.

For comparison, the mean urban $PM_{2.5}$ concentration (ABJ-$PM_{2.5}$) presents a moderate and highly significant positive correlation with COVID-19 incidence ($\rho = 0.38$, $p < 0.001$), clearly exceeding the strength of associations observed for meteorological variables. This result highlights the more prominent role of particulate air pollution relative to meteorological factors in shaping the temporal variability of COVID-19 cases in Abidjan.

In summary, among the meteorological parameters examined, air temperature and relative humidity appear to exert the most consistent influences on COVID-19 incidence, although their effects remain modest. These findings indicate that meteorological conditions may modulate the epidemic dynamics but are insufficient to explain the observed variations on their own, thereby reinforcing the dominant contribution of air pollution and the need for integrated multivariate analyses.

4. Generalized Additive Modeling (GAM) of Environmental Determinants of COVID-19 Incidence

4.1. Model Specification

To assess the combined and potentially non-linear effects of air pollution and meteorological conditions on COVID-19 transmission in Abidjan, a generalized additive model (GAM) with a Poisson distribution and logarithmic link function was implemented. This modelling framework is well suited for epidemiological time-series involving count data and allows flexible representation of non-linear exposure-response relationships. The daily number of newly confirmed COVID-19 cases (raw daily counts) was used as the response variable. To account for potential administrative and reporting variability across the week, a categorical day-of-week term was also tested. The inclusion of this term did not substantially modify the estimated effects and was therefore not retained in the final model. The explanatory variables included the urban average $PM_{2.5}$ concentration (ABJ-$PM_{2.5}$) and key meteorological parameters, namely air temperature at 2 m (T2M), relative humidity (RH), wind speed (WS), and wind direction (WD). Based on the results of the temporal lag-correlation analysis and on the incubation and reporting timeline of SARS-CoV-2, all environmental predictors were included in the model at a fixed 8-day lag ($t - 8$) to capture delayed associations with reported infections.

The model can be expressed as:

$$\log(Y_t) = \beta_0 + f_1(PM_{2.5,t-8}) + f_2(T2M_{t-8}) + f_3(RH_{t-8}) + f_4(WS_{t-8}) + f_5(WD_{t-8}). \quad (1)$$

where (Y_t) denotes the daily COVID-19 cases and $f_i(X_{t-8})$ represent penalized spline smoothing functions capturing non-linear effects of lagged environmental predictors. Smoothing parameters were estimated using restricted maximum likelihood to balance model flexibility and overfitting.

4.2. GAM Performance and Goodness-of-Fit

As shown in **Figure 6**, the fitted Poisson GAM demonstrates strong explanatory power, with a pseudo-R^2 of 0.75, indicating that approximately 75% of the variability in daily COVID-19 incidence is explained by the environmental predictors included in the model. This level of performance is notable for epidemiological data, which are often influenced by unobserved behavioural and policy-related factors.

All smooth terms included in the model were found to be statistically significant ($p < 0.001$), confirming the relevance of both air pollution and meteorological conditions in shaping COVID-19 transmission dynamics. Among the predictors, $PM_{2.5}$ exhibits the most influential effect, with a relatively high effective degree

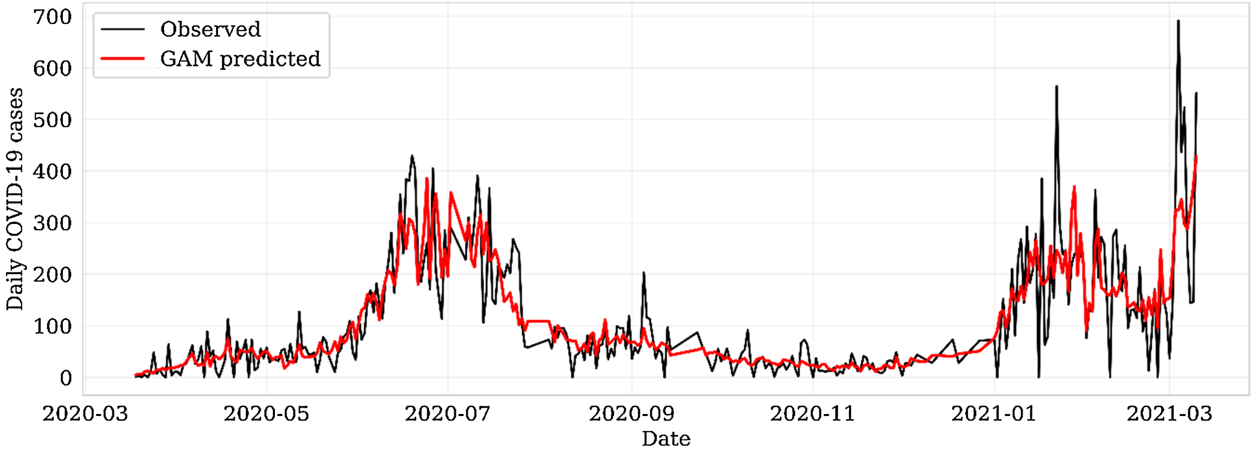


Figure 6. Observed and GAM-predicted daily COVID-19 incidence in Abidjan (March 2020-March 2021).

of freedom (EDoF = 8.3), highlighting a complex and strongly non-linear association with COVID-19 incidence.

Meteorological variables display significant but comparatively weaker effects. Air temperature and relative humidity show moderate non-linear contributions, suggesting that climatic conditions modulate transmission rather than act as primary drivers. Wind-related parameters present higher variability, reflected by larger EDoF values, which may capture broader atmospheric circulation patterns rather than direct causal mechanisms.

Error measures further confirm the model's performance. The root mean square error (RMSE = 61.28 cases) and mean absolute error (MAE = 38 cases) reflect moderate prediction errors, as these values are of the same order of magnitude as the actual daily variability of reported cases in Abidjan, which typically ranges from tens to hundreds of cases per day. Given that daily fluctuations are influenced by many factors not measured in this study, such as social behaviors, public health interventions, viral circulation dynamics, and effects related to the day of the week, these error values are considered realistic and consistent with the intrinsic complexity of the problem.

Overall, the goodness-of-fit diagnostics and information criteria indicate a robust and stable model with no signs of serious overfitting. Although the model is not perfectly predictive, which would be unrealistic for such a complex epidemiological system, it provides reliable and consistent estimates of epidemic trends associated with environmental conditions. The results are consistent with the correlation analysis presented in Section 3, while providing more in-depth information on the nonlinear relationships between exposure and response. Thus, the GAM is a relevant tool for analyzing the influence of atmospheric factors on the transmission dynamics of COVID-19. Residual diagnostics were also examined to assess potential serial autocorrelation. Partial autocorrelation functions (PACF) of the model residuals showed no remaining significant temporal structure, indicating that the GAM adequately accounted for serial dependence in the time series.

4.3. Effects of Environmental and Meteorological Factors on COVID-19 Incidence

4.3.1. Partial Effects of Lagged Environmental and Meteorological Variables

Table 5 presents the estimated partial effects of lagged environmental and meteorological variables on COVID-19 incidence, obtained from the generalized additive model (GAM) including environmental predictors at a fixed 8-day lag. These partial effects describe the magnitude, direction, and non-linear structure of the associations captured the by smooth terms of the GAM, while adjusting for the remaining covariates in the model.

The partial effects of $PM_{2.5}$ (lag 8) range from −0.40 to 0.70, with a total effect range of 1.10. The maximum effect is observed at a concentration of approximately 39.6 $\mu g \cdot m^{-3}$, indicating a shift from weak or negative effects at lower concentrations to a clearly positive association at higher pollution levels. This pattern reveals a non-linear and concentration-dependent exposure–response relationship, consistent with a threshold-like behaviour of particulate matter exposure. The associated relative risks range from 0.67 to 2.01, indicating that high $PM_{2.5}$ concentrations may be associated with approximately a twofold increase in COVID-19 incidence.

Table 5. Summary of partial effects and relative risks associated with lagged environmental and meteorological variables (lag = 8 days). Partial effects are expressed on the log scale. Relative risks were derived from the smooth terms of the generalized additive model. "Exposure at max effect" corresponds to the value associated with the maximum estimated effect at lag = 8 days.

Variable	Range of partial effects	Exposure at max effect	Range of relative risks
$PM_{2.5}$ (lag 8)	−0.40 to 0.70	39.64 $\mu g \cdot m^{-3}$	0.67 to 2.01
T2M (lag 8)	−0.02 to 1.12	30.47˚C	0.98 to 3.08
RH (lag 8)	0.20 to 1.03	92.21%	1.23 to 2.80
WD (lag 8)	−0.90 to −0.19	275.22˚	0.41 to 0.82
WS (lag 8)	−0.74 to 0.59	9.13 $m \cdot s^{-1}$	0.48 to 1.81
Time	−2.35 to 2.13	317 (index)	0.10 to 8.44

Air temperature (T2M, lag 8) exhibits a non-linear association with COVID-19 incidence. While the overall Spearman correlation indicates a weak negative relationship ($\rho = -0.22$), suggesting that higher temperatures are generally associated with fewer cases, the GAM reveals a more complex pattern once confounding factors and delayed effect are accounted for. The partial effect ranges from −0.02 to 1.12, corresponding to relative risks between 0.98 and 3.08, with a local maximum observed around 30.5˚C. This indicates that, although increasing temperature is associated with reduced incidence on average, specific high-temperature regimes may coincide with increased transmission risk. Such behaviour likely reflects indirect mechanisms, including changes in human mobility, increased indoor crowding under hot conditions, and interactions with air pollution, rather than a direct thermodynamic effect on viral viability.

Relative humidity (RH, lag 8) also shows a significant non-linear relationship, with partial effects ranging from 0.20 to 1.03 and relative risks between 1.23 and 2.80. The highest risk is observed at humidity levels close to 92%, indicating that moist atmospheric conditions may favor viral transmission, potentially through their influence on aerosol persistence and indoor environmental conditions.

In contrast, wind direction (WD, lag 8) shows exclusively negative partial effects, ranging from −0.90 to −0.19 corresponding to relative risks between 0.41 and 0.82. This consistent negative pattern suggests a mitigating role of prevailing wind regimes, likely linked to enhanced atmospheric dispersion and reduced pollutant accumulation in urban environments.

Wind speed (WS, lag 8) displays a mixed response, with partial effects spanning from −0.74 to 0.59 and relative risks between 0.48 and 1.81. This wide range reflects competing mechanisms, whereby increased wind speed may enhance dispersion and reduce exposure, while moderate wind conditions may coincide with increased outdoor human activity.

Finally, the smooth term for time presents the largest variability in partial effects (−2.35 to 2.13), reflecting the strong temporal structure of the epidemic, including epidemic waves, behavioral changes, and public health interventions throughout the study period. The associated relative risks range from 0.10 to 8.44, highlighting the dominant role of temporal dynamics in shaping COVID-19 incidence.

Overall, the partial effect analysis confirms the complex and non-linear nature of the relationships between environmental exposures, meteorological conditions, and COVID-19 incidence, justifying the use of flexible modeling approaches.

4.3.2. Relative Risk of COVID-19 Incidence Associated with $PM_{2.5}$ Exposure

Given the magnitude and consistency of the association observed in the GAM, this subsection focuses specifically on the relative risk (RR) of COVID-19 incidence associated with $PM_{2.5}$ exposure, in order to provide an epidemiologically meaningful quantification of the effect. Meteorological variables were retained in the model to control for confounding and to account for environmental co-variability, while the RR analysis emphasises the public health relevance of fine particulate matter.

Figure 7 presents the exposure-response relationship between $PM_{2.5}$ concentration at an 8-day lag and COVID-19 incidence, expressed in terms of relative risk. The estimated RR curve reveals a clearly non-linear pattern, characterized by a progressive increase in risk with rising $PM_{2.5}$ levels, followed by a pronounced peak at higher concentrations.

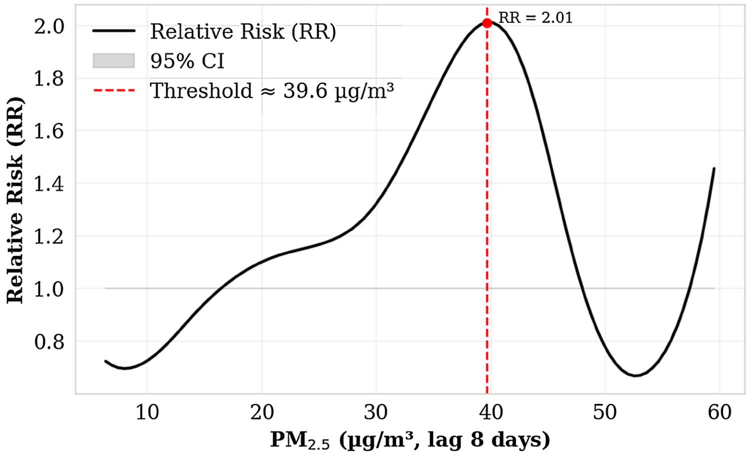


Figure 7. Dose-response relationship between $PM_{2.5}$ concentration and COVID-19 incidence expressed as relative risk (lag = 8 days).

At low $PM_{2.5}$ concentrations (<15 $\mu g \cdot m^{-3}$), the estimated RR remains below or close to unity, suggesting a limited or negligible effect on COVID-19 incidence. As $PM_{2.5}$ concentrations increase, the RR rises steadily, exceeding unity at moderate exposure levels and reaching a maximum RR of approximately 2.01 at around 39.6 μg·m^{-3}. This indicates that, at this concentration, COVID-19 incidence is approximately doubled compared with the reference exposure level. Beyond this threshold, the RR curve shows a decline, reflecting the non-monotonic structure of the association captured by the generalized additive model. This apparent decrease in relative risk at very high $PM_{2.5}$ concentrations should be interpreted with caution. It is likely influenced by the limited number of observations in the highest concentration range and by increased statistical uncertainty at extreme values, rather than reflecting a true protective effect or behavioural change. This behavior may reflect complex interactions between air pollution levels, population behavior, and other unmeasured contextual factors at very high concentrations.

The identification of a critical concentration threshold near 40 μg·m^{-3} is of particular public health relevance, as it lies well above the World Health Organization air quality guideline for $PM_{2.5}$ and is frequently exceeded in many urban environments in low- and middle-income countries. This finding suggests that episodes of elevated particulate pollution may substantially amplify the burden of COVID-19 transmission.

Overall, the relative risk analysis provides strong evidence that $PM_{2.5}$ acts as a significant environmental risk factor for COVID-19 incidence, independently of meteorological conditions. By translating the smooth GAM estimates into an intuitive epidemiological metric, these RR results highlight the potential benefits of air quality improvements as a complementary strategy for reducing vulnerability to respiratory epidemics in densely populated urban settings.

5. Discussion

This study provides evidence that ambient fine particulate matter ($PM_{2.5}$) was significantly associated with COVID-19 incidence in the Autonomous District of Abidjan during the first year of the pandemic. By combining in situ air quality measurements, lagged correlation analysis, and generalized additive modelling, we identified a strong, non-linear, and delayed relationship between $PM_{2.5}$ concentrations and reported COVID-19 cases. The dominant lag of approximately eight days is consistent with the incubation period of SARS-CoV-2 and supports the biological plausibility of the observed associations.

The lag-correlation structure revealed a short-term peak at 0 - 2 days and a stronger peak around one week. The near-immediate response should however be interpreted with caution and may reflect behavioural and health-seeking responses or short-term reporting artefacts rather than a direct aggravation of symptoms. The delayed peak is more consistent with increased susceptibility to infection, after which cases progress through the incubation period before being reported. These findings support the interpretation of $PM_{2.5}$ as an environmental cofactor that modulates vulnerability and short-term transmission dynamics rather than acting as a primary driver of epidemic waves.

The GAM results further showed a clearly non-linear exposure–response relationship. COVID-19 incidence increased progressively with $PM_{2.5}$ concentrations and reached a maximum relative risk of approximately two at around 40 $\mu g \cdot m^{-3}$. This concentration range is frequently exceeded in Abidjan and many other West African cities, suggesting that chronic urban air pollution may substantially amplify epidemic risk. Similar non-linear associations and lag structures have been reported in studies conducted in China, Europe, and North America, supporting the consistency of the pollution-COVID-19 relationship across diverse settings.

Several biological mechanisms support these observations. $PM_{2.5}$ penetrates deep into the respiratory tract, impairs mucociliary clearance, alters macrophage function, and promotes inflammatory responses, all of which can weaken host defenses against respiratory viruses. Experimental evidence also suggests that particulate matter exposure may enhance viral entry by modulating epithelial receptors, providing further biological plausibility for the observed delayed effects. The stronger second epidemic wave observed between December and January may also be interpreted in the context of seasonal changes in aerosol composition. In West Africa, this period corresponds to the Harmattan dry season, which is characterized by intense Saharan and Sahelian mineral dust transport [25] [30]. As a result, a substantial fraction of $PM_{2.5}$ mass during this period is likely dominated by mineral aerosols rather than by local combustion sources. Differences in particle composition may influence toxicity, respiratory irritation, and immune responses, and could partly contribute to the exposure-response patterns and non-linear relationships observed during the second epidemic wave. However, without chemical speciation data, the respective roles of mineral and combustion-related particles cannot be disentangled in the present study. In particular, mineral dust particles typical of the Harmattan season are likely to differ substantially in chemical composition and toxicological properties from combustion-derived particles, which are generally enriched in metals and organic compounds.

Meteorological variables showed weaker and more complex associations, consistent with their indirect influence on viral persistence, aerosol behaviour, and human activity patterns. After adjustment, $PM_{2.5}$ consistently emerged as the dominant environmental factor, indicating that weather variability alone does not explain COVID-19 dynamics in this urban context.

From a public health perspective, these findings highlight the potential value of integrating air quality into epidemic preparedness strategies. In cities where $PM_{2.5}$ levels are persistently high, pollution episodes may significantly increase population vulnerability to respiratory epidemics. Air pollution control policies may therefore offer important co-benefits by reducing both chronic disease burden and susceptibility to emerging infectious threats.

This study is subject to limitations inherent to observational time-series analyses, including the use of aggregated incidence data, potential under-reporting of cases, and unmeasured behavioural or policy-related confounders. Future multi-city studies across West Africa will be necessary to strengthen the statistical basis of the observed relationships and to assess their regional consistency. Nevertheless, the consistency of the findings across multiple analytical approaches, together with their biological plausibility, supports the robustness of the conclusions.

6. Conclusions

This study provides clear evidence that ambient fine particulate matter ($PM_{2.5}$) was significantly associated with COVID-19 incidence in the Autonomous District of Abidjan during the first year of the pandemic. By combining high-resolution air quality measurements, temporal lag analysis, and a generalized additive modelling framework, we identified a strong, non-linear, and delayed relationship between $PM_{2.5}$ concentrations and daily reported COVID-19 cases. The dominant lag of approximately eight days is consistent with the biological timeline of SARS-CoV-2 infection and supports the plausibility of pollution acting as an environmental cofactor influencing epidemic dynamics.

The results further highlight the existence of critical pollution ranges beyond which COVID-19 incidence increased markedly. $PM_{2.5}$ concentrations exceeding international air quality guideline values were associated with substantially elevated relative risks, with daily incidence approximately doubling at concentrations around 40 $\mu g \cdot m^{-3}$. These findings indicate that short-term exposure to elevated particulate pollution may significantly amplify population vulnerability to respiratory epidemics in densely populated urban environments.

Although meteorological conditions were found to modulate COVID-19 incidence, their effects were weaker and more complex than those of $PM_{2.5}$, and the pollution signal remained robust after adjustment. This underscores the central role of urban air quality, relative to weather variability, in shaping COVID-19 dynamics in Abidjan.

Overall, this study demonstrates that air pollution should be considered an integral component of epidemic risk assessment and management, particularly in rapidly urbanizing African cities where $PM_{2.5}$ levels are chronically high. Integrating air quality indicators into public health surveillance systems could strengthen early warning capabilities and support targeted interventions during high-pollution periods. More broadly, sustained reductions in $PM_{2.5}$ through urban planning and environmental policies may yield important co-benefits by lowering chronic disease burden and reducing population vulnerability to future respiratory epidemics.

Acknowledgements

This work was supported by the "Make Our Planet Great Again" (MOPGA) program through the *Make Air Quality Great Again* (MAQGA) project. The authors sincerely thank Mr. Subramanian Ramanchandran for supervising the $PM_{2.5}$ data collection and mobilizing resources through the MAQGA project, as well as Mr. Matthias Beekmann for establishing the scientific framework within the OSU-EFLUVE that enabled the implementation of the $PM_{2.5}$ measurement campaign.

The authors also thank the U.S. Embassy in Abidjan for providing access to reference BAM data. They are grateful to the researchers and technical staff of Félix Houphouët-Boigny University (Abidjan, Côte d'Ivoire) for their support in field deployment and equipment maintenance.

Finally, the authors acknowledge the Institut Pasteur de Côte d'Ivoire and the Institut National d'Hygiène Publique for providing high-quality COVID-19 data used in this study, and thank the OSU-EFLUVE and LISA (UPEC) for creating the scientific and institutional environment that made this work possible.

Conflicts of Interest

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

References

[1] Pearson, C.A., Van Schalkwyk, C., Foss, A.M., O'Reilly, K.M. and Pulliam, J.R. (2020) Projected Early Spread of COVID-19 in Africa through 1 June 2020. *Eurosurveillance*, **25**, Article ID: 2000543. https://doi.org/10.2807/1560-7917.es.2020.25.18.2000543

[2] Tcholi Idrissa, E., Hannadé Houma, I., Salifou Ibrahim, A., Halawen Mohamed, A., Ibrahim Maman Laminou, I. and Eric Omar, A. (2024) Influence des Paramètres Climatiques sur l'Incidence de la COVID-19 de Mars 2020 à Décembre 2022 dans la Région de Niamey au Niger. *European Scientific Journal*, *ESJ*, **20**, 20-40. https://doi.org/10.19044/esj.2024.v20n21p20

[3] Jenkins, G.S., Freire, S.M., Ogunro, T., Niang, D., Andrade, M., Drame, M.S., *et al.* (2023) COVID-19 New Cases and Environmental Factors during Wet and Dry Seasons in West and Southern Africa. *GeoHealth*, **7**, e2022GH000765. https://doi.org/10.1029/2022gh000765

[4] Ogunjo, S., Olaniyan, O., Olusegun, C.F., Kayode, F., Okoh, D. and Jenkins, G. (2022) The Role of Meteorological Variables and Aerosols in the Transmission of COVID-19 during Harmattan Season. *GeoHealth*, **6**, e2021GH000521. https://doi.org/10.1029/2021gh000521

[5] Yarber, A.Y., Jenkins, G.S., Singh, A. and Diokhane, A. (2023) Temporal Relationships between Saharan Dust Proxies, Climate, and Meningitis in Senegal. *GeoHealth*, **7**, e2021GH000574. https://doi.org/10.1029/2021gh000574

[6] Fawole, O.G., Yusuf, N., Sunmonu, L.A., Obafaye, A., Audu, D.K., Onuorah, L., *et al.* (2022) Impacts of COVID-19 Restrictions on Regional and Local Air Quality across Selected West African Cities. *GeoHealth*, **6**, e2022GH000597. https://doi.org/10.1029/2022gh000597

[7] Joshua, B.W., Fuwape, I., Rabiu, B., Pires, E.E.S., Sa'id, R.S., Ogunro, T.T., *et al.* (2023) The Impact of the First and Second Waves of COVID-19 Pandemic in Nigeria. *GeoHealth*, **7**, e2022GH000722. https://doi.org/10.1029/2022gh000722

[8] Ogunjo, S.T., Fuwape, I.A. and Rabiu, A.B. (2022) Predicting COVID-19 Cases from Atmospheric Parameters Using Machine Learning Approach. *GeoHealth*, **6**, e2021GH000509. https://doi.org/10.1029/2021gh000509

[9] Salyer, S.J., Maeda, J., Sembuche, S., Kebede, Y., Tshangela, A., Moussif, M., *et al.* (2021) The First and Second Waves of the COVID-19 Pandemic in Africa: A Cross-Sectional Study. *The Lancet*, **397**, 1265-1275. https://doi.org/10.1016/s0140-6736(21)00632-2

[10] Yassi, G.A. and Kambiré, B. (2021) Système de Santé et Risques Sanitaires En Côte

d'Ivoire: Abidjan Territoire de Relégation En Contexte de COVID-19. COVID-19, Santé-Environnement, Productivité Scientifique: Regards Sur La Période Du Confinement à l'Université Quisqueya. https://hal.science/hal-05001546

[11] WHO (2021) WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. World Health Organization.

[12] Domingo, J.L. and Rovira, J. (2020) Effects of Air Pollutants on the Transmission and Severity of Respiratory Viral Infections. *Environmental Research*, **187**, Article ID: 109650. https://doi.org/10.1016/j.envres.2020.109650

[13] Ciencewicki, J. and Jaspers, I. (2007) Air Pollution and Respiratory Viral Infection. *Inhalation Toxicology*, **19**, 1135-1146. https://doi.org/10.1080/08958370701665434

[14] Horne, B.D., Joy, E.A., Hofmann, M.G., Gesteland, P.H., Cannon, J.B., Lefler, J.S., *et al.* (2018) Short-Term Elevation of Fine Particulate Matter Air Pollution and Acute Lower Respiratory Infection. *American Journal of Respiratory and Critical Care Medicine*, **198**, 759-766. https://doi.org/10.1164/rccm.201709-1883oc

[15] Prata, D.N., Rodrigues, W. and Bermejo, P.H. (2020) Temperature Significantly Changes COVID-19 Transmission in (Sub)tropical Cities of Brazil. *Science of the Total Environment*, **729**, Article ID: 138862. https://doi.org/10.1016/j.scitotenv.2020.138862

[16] Fattorini, D. and Regoli, F. (2020) Role of the Chronic Air Pollution Levels in the Covid-19 Outbreak Risk in Italy. *Environmental Pollution*, **264**, Article ID: 114732. https://doi.org/10.1016/j.envpol.2020.114732

[17] Setti, L., Passarini, F., De Gennaro, G., Barbieri, P., Licen, S., Perrone, M.G., *et al.* (2020) Potential Role of Particulate Matter in the Spreading of COVID-19 in Northern Italy: First Observational Study Based on Initial Epidemic Diffusion. *BMJ Open*, **10**, e039338. https://doi.org/10.1136/bmjopen-2020-039338

[18] Tung, N.T., Cheng, P., Chi, K., Hsiao, T., Jones, T., BéruBé, K., *et al.* (2021) Particulate Matter and SARS-CoV-2: A Possible Model of COVID-19 Transmission. *Science of The Total Environment*, **750**, Article ID: 141532. https://doi.org/10.1016/j.scitotenv.2020.141532

[19] Wu, X., Nethery, R.C., Sabath, M.B., Braun, D. and Dominici, F. (2020) Air Pollution and COVID-19 Mortality in the United States: Strengths and Limitations of an Ecological Regression Analysis. *Science Advances*, **6**, eabd4049. https://doi.org/10.1126/sciadv.abd4049

[20] Frontera, A., Cianfanelli, L., Vlachos, K., Landoni, G. and Cremona, G. (2020) Severe Air Pollution Links to Higher Mortality in COVID-19 Patients: The "Double-Hit" Hypothesis. *Journal of Infection*, **81**, 255-259. https://doi.org/10.1016/j.jinf.2020.05.031

[21] Morawska, L. and Cao, J. (2020) Airborne Transmission of SARS-CoV-2: The World Should Face the Reality. *Environment International*, **139**, Article ID: 105730. https://doi.org/10.1016/j.envint.2020.105730

[22] INS (Institut Nationale de la Statistique) (2022) Recensement General de la Population et de l'Habitat 2021 RÉSULTATS GLOBAUX.

[23] Bahino, J., Giordano, M., Beekmann, M., Yoboué, V., Ochou, A., Galy-Lacaux, C., *et al.* (2024) Temporal Variability and Regional Influences of $PM_{2.5}$ in the West African Cities of Abidjan (Côte d'Ivoire) and Accra (Ghana). *Environmental Science: Atmospheres*, **4**, 468-487. https://doi.org/10.1039/d4ea00012a

[24] Milleliri, J.M., Coulibaly, D. and Lamontagne, F. (2021) La Covid-19 En Côte d'Ivoire

(Mars 2020-Avril 2021) Une Année Sous Le Sceau Du Coronavirus. *Médecine Tropicale et Santé Internationale*, **1**, 102.

[25] Prospero, J.M., Ginoux, P., Torres, O., Nicholson, S.E. and Gill, T.E. (2002) Environmental Characterization of Global Sources of Atmospheric Soil Dust Identified with the Nimbus 7 Total Ozone Mapping Spectrometer (Toms) Absorbing Aerosol Product. *Reviews of Geophysics*, **40**, 2-1-2-31. https://doi.org/10.1029/2000rg000095

[26] Woodby, B., Arnold, M.M. and Valacchi, G. (2020) SARS-CoV-2 Infection, COVID-19 Pathogenesis, and Exposure to Air Pollution: What Is the Connection? *Annals of the New York Academy of Sciences*, **1486**, 15-38. https://doi.org/10.1111/nyas.14512

[27] Chivé, C., Martín-Faivre, L., Michoud, V., Baeza-Squiban, A. and Garcia-Verdugo, I. (2025) Contribution of Ambient Airborne Particles on the Susceptibility to Respiratory Viral Infections. *Environmental Toxicology and Pharmacology*, **119**, Article ID: 104797. https://doi.org/10.1016/j.etap.2025.104797

[28] Zhu, Y., Xie, J., Huang, F. and Cao, L. (2020) Association between Short-Term Exposure to Air Pollution and COVID-19 Infection: Evidence from China. *Science of the Total Environment*, **727**, Article ID: 138704. https://doi.org/10.1016/j.scitotenv.2020.138704

[29] Conticini, E., Frediani, B. and Caro, D. (2020) Can Atmospheric Pollution Be Considered a Co-Factor in Extremely High Level of SARS-CoV-2 Lethality in Northern Italy? *Environmental Pollution*, **261**, Article ID: 114465. https://doi.org/10.1016/j.envpol.2020.114465

[30] Engelstaedter, S., Tegen, I. and Washington, R. (2006) North African Dust Emissions and Transport. *Earth-Science Reviews*, **79**, 73-100. https://doi.org/10.1016/j.earscirev.2006.06.004