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Level of Exposure of Populations to Atmospheric Pollution in Southern Benin

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Abstract

This study focuses on monitoring the exposure of populations in South Benin to atmospheric pollution. Thirteen (13) monitoring points were identified where the Air quality measurements were taken using autonomous electronic devices called "Air Quality Monitor". Calibrated and turned on, the measuring device automatically determines the concentrations of carbon dioxide CO_2, Total Organic Compounds, methanal (HCHO), particulate matter $PM_{2.5}$ and PM_{10}, temperature in degrees Fahrenheit and relative humidity (RH). Per site, air pollution levels are recorded for 5 minutes every 30 minutes from 7 a.m. to 6 p.m. After the analyses, it appears that the carbon dioxide CO_2 contents vary from 400 to 1444 ppm with an average of 486.80 ± 184.3 ppm, the daily contents of Total Volatile Organic Compounds from 0.01 to 6 .91 mg/m^3 with a daily average of 0.36 ± 0.65 mg/m^3, aldehydes from 0.005 to 3 mg/m^3 with an average of 0.05 ± 0.17 mg/m^3, for particulate matter of diameters less than or equal to 2.5 µm ($PM_{2.5}$) pollution levels vary between 5 and 173.8 µg/m^3 with an average of 21.5 ± 17.62 µg/m^3. On the other hand, for PM_{10}, the contents vary from 5 to 449.6 µg/m^3 with an average of 28.17 ± 31.74 µg/m^3, the Air Quality Index (AQI) varies from 0, 3 to 243 with an average of 39 ± 33.16. From the results observed, it appears that the south-western part of South Benin is heavily polluted by CO_2, Total Volatile Organic Compounds, PM_{10} and especially $PM_{2.5}$ with the city of Cotonou at its head, in particular the Red Star crossroads, the Toyota crossroads and the crossroads after the friendship stadium. The impacts of this pollution could be significant on sensitive people such as the elderly, newborns and patients with acute and chronic respiratory illnesses.

Keywords

Ambient Air Quality, Southern Benin, Cotonou, Atmospheric Pollution

1. Introduction

One of the facets of the impact of anthropogenic activities on the living environment is atmospheric pollution which has become one of the major socio-economic problems characterized by health, ecological and economic nuisances throughout the world. The WHO considers air pollution to be the second cause of reduced lifespan [1]. According to her, this form of pollution causes around 7 million premature deaths each year worldwide. In 2019, approximately 37% of premature deaths linked to outdoor air pollution were due to ischemic heart disease and stroke, 18% to chronic obstructive pulmonary disease, 23% to acute lower respiratory tract infections, and 11% to respiratory tract cancers. Cardiorespiratory disorders linked to air pollution constitute the leading cause of mortality, but the impacts are as numerous as the pollutants are varied [2]. The fight against air pollution is currently one of the major concerns of the international community. Indeed, several international conferences including those of Stockholm in 1972, Rio de Janeiro in 1992, Kyoto in 1997, the Johannesburg summit in 2002, and the Conference of the Parties each year have dealt with and are dealing with this problem. Thus, in large cities in Europe, Asia, and North America, networks for monitoring air quality and monitoring noise pollution are installed with the aim of informing public authorities and the population in real time of the different levels of pollution. But in low- and middle-income countries these provisions are struggling to take off despite these international conventions.

According to a report by the United Nations Economic Commission for Africa (ECA), air pollution in sub-Saharan Africa causes significant economic costs, particularly in terms of health costs related to respiratory, cardiovascular and neurological diseases ([3] [4]). Thus, [5] [6] [7] [8] showed that air pollution is the second cause of mortality per year in West Africa after malaria, water-borne diseases and/or malnutrition. However, despite these findings, air quality monitoring networks are almost non-existent [9].

Like other countries in the world, Benin is not immune to noise and atmospheric pollution. Regarding atmospheric pollution, several factors are at the root of this phenomenon, among which we can cite the rapid growth of cities, the rapid development of motorcycle taxis commonly called zémidjan, the explosion of the second-hand vehicle sector, poor road infrastructure in cities. To this list we cannot fail to add the illicit sale of adulterated fuels, from which no locality in Benin escapes, and the poor state of the automobile fleet [10]. This pollution was characterized by the persistent presence of an opaque mixture of smoke, dust and humidity on the main arteries and at major intersections in city centers during rush hours [11]. Added to this was also the installation of a few industrial units in the middle of the city [12]. For several decades this phenomenon has taken root and is growing, particularly in the main cities of Benin, particularly Cotonou and its suburbs [13]. The bill risked being heavy to pay in environmental and health terms if nothing was done. The cost of air pollution in the city of Cotonou alone was worth 1.2% of the GDP of the entire country [14]. Land transport according to the FOCON/ABF firm (2000) was responsible for 93% of particulate matter, 50% of SO_2, 88% of nitrogen oxides NO_x, 98% of hydrocarbons (HC) and 99% of carbon oxides CO and CO_2 in ambient air. However, in Benin, Law No. 2019-40 of November 7, 2019 revising Law No. 90-32 of December 11, 1990 establishing the Constitution of the Republic of Benin elevates environmental protection to constitutional status. Despite the panoply of institutional and legal provisions and the efforts made by the various governments in protecting the environment, the living environment in Benin continues to be degraded due to poverty, incivility, ignorance and illiteracy ([15] [16]). It is in this context that we chose to work on the theme.

2. Materials and Methods

2.1. Study Zone

Figure 1 shows the map of the sampling sites.

2.2. Methodology for Measuring Concentrations of Atmospheric Pollutants for Monitoring Air Quality

Before the measurement campaigns took place, a prospective visit was carried out on the road sections during which 13 sites were identified for monitoring including 9 hot spots and 4 points in the background areas. **Table 1** presents the list of ten (13) measurement sites, their location and their characteristics (heavy traffic lane paved or not).

Air quality measurements were taken using autonomous electronic devices called "Air Quality Monitor", powered by a lithium battery or by connection to the mains, via a transformer. The device is calibrated for 4 hours at first start-up in ambient air. Once turned on, the measuring device automatically determines the concentrations of carbon dioxide CO_2, total organic compounds (TVOC), methanal (CH_2O), particulate matter with diameters of 2.5 µm and 10 µm denoted $PM_{2.5}$ and PM_{10}, the temperature in degrees Fahrenheit (˚F = 1˚C × 1.8 + 32) and the hygrometry (Relative humidity H%) of the ambient air. Recordings were carried out for an entire day at each measurement site in 30-minute intervals. Measurements generally start at 7 a.m. and end at 6 p.m. with 24 measurements per site. In cases of delay, the measurement is extended beyond 6 p.m. to compensate for the delay. Units of measurement are parts per million air particles (ppm) or micrograms per cubic meter. These different parameters provide information, alone or combined, on the quality of ambient air.

Table 1. Ambient air quality measurement sites in southern Benin.

Codes	Names of air quality measurement sites	Geographic coordinates
S1	Carrefour Sèmè-Kpodji	N: 06˚22'86" E: 002˚37'23"
S2	Carrefour Ekpè	N: 06˚22'37" E: 002˚32'75"
S3	Carrefour Yagbantè (Aglangandan)	N: 06˚22'96" E: 002˚30'39"
S4	Von du Delegate Zogbo	N: 06˚23'65" E: 002˚23'50"
S5	Carrefour Togoudo (Godomey)	N: 06˚24'03" E: 002˚20'49"
S6	Carrefour Tankpè (Calavi)	N: 06˚25'45" E: 002˚19'22"
S7	Bypass intersection (Tori Bossito)	N: 06˚30'14" E: 002˚08'57"
S8	Houègboh (Bopa)	N: 06˚38'00" E: 001˚58'47"
S9	Wangbo village Davè (Ouinga)	N: 06˚35'44" E: 001˚49'28"
S10	Athiémé border bridge	N: 06˚34'02" E: 01˚39'52"
S11	Red Star Crossroads	N: 06˚22'17" E: 2˚24'35"
S12	Carrefour Cica Toyota	N: 06˚22'37" E: 02˚23'83"
S13	Carrefour Agla-Friendship Stadium	N: 06˚34'02" E: 06˚23'68"

Source: This study.

2.3. Data Processing

The processing methods cover all the operations applied to the data to bring them as close as possible to the nominal terrain. These are descriptive statistics techniques which make it possible to achieve inferential statistics and spatial type processing.

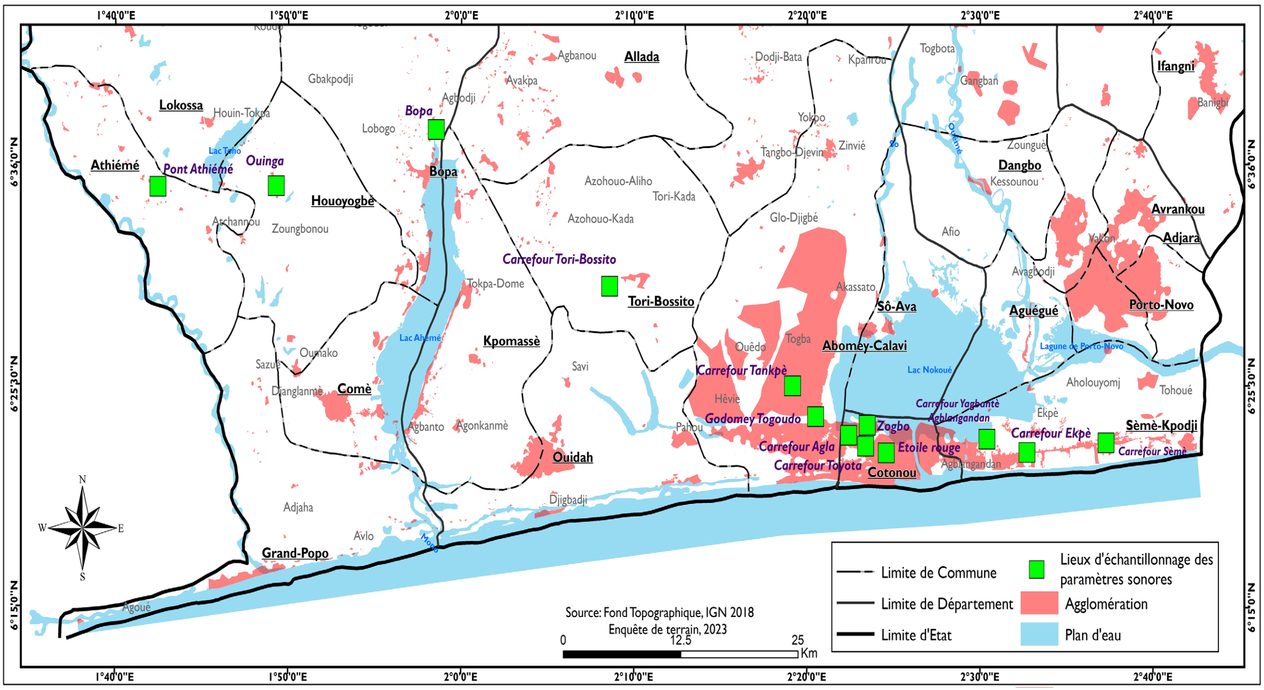

Figure 1. Mapping of the zonation of sampling sites in southern Benin (Source: This study).

2.3.1. Calculation and Use of the Coefficient of Variation % CV

Mathematically, the expression for the coefficient of variation is given by:

$$\%\,\mathrm{CV} = \left(\sigma i / \chi i\right) * 100$$

With σi and χi respectively the standard deviation and the arithmetic mean of the modalities taken by the random variable studied. The coefficient of variation (% CV) shows the degree of homogeneity of the measurements.

- If CV < 2%, the measurements are very homogeneous and the experience is reproducible;
- If 2% < CV < 30%, the measurements are homogeneous;
- If CV > 30%, the measurements are heterogeneous and therefore the experience for our case is not reproducible.

2.3.2. Principal Component Analysis

Principal component analysis (PCA) is one of the most common multivariate analysis methods. It is applied to quantitative data with the aim of finding dependencies between variables in order to reduce their number by grouping them on factorial axes. Whatever the criterion retained, it is important that the eigenvalues of the axes retained restore a "good proportion" of the analysis, that is to say that the sum of the inertia explained by each of the axes represents a significant part of total inertia. As part of this study, the relative criterion was used to determine the number of components (axes). The most interesting points are generally those which are quite close to one of the axes, and quite far from the origin. These points are well correlated with this axis and are the explanatory points for the axis: These are the most "speaking" points; their "true distance" from the origin is well represented on the factorial plane.

2.3.3. Assessment of Air Quality

To assess air quality, we used Table 2 which presents the guide values for assessing air quality based on the limit values of the World Health Organization (WHO) and regulations. Beninese. These values are defined by the manufacturer of the mobile air pollutant measurement monitor

3. Results and Discussion

3.1. Presentation of Ambient Air Pollution Results (Table 3)

- **Air pollution levels at site 1**

From the analysis of the data, we note that the coefficients of variation % CV of CO_2, HCHO aldehydes, and temperature are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative of the series. On the other hand, all other air quality monitoring parameters take variable values during the day. Therefore only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for the parameters with the guide values for

Table 2. Guide values for assessing air quality.

Air quality	Carbon dioxide (CO_2) in ppm	TVOC (mg/m^3)	HCHO (mg/m^3)	Fine particles ($PM_{2.5}$) in $\mu g/m^3$	Particulate matter (PM_{10}) in $\mu g/m^3$	AQI
Good	400 - 600	0 - 0.3	0 - 0.1	0 - 50	0 - 54	0 - 50
Moderate	651 - 1500	0.3 - 1.0		16 - 40	55 - 154	51 - 100
Unhealty for sensitive group	1501 - 2000	1.0 - 3.0	>0.1 mg/m^3	41 - 65	155 - 254	101 - 150
Unhealty	2001 - 2500	3.0 - 10.0		66 - 150	255 - 354	151 - 200
Very unhealty	2501 - 5000	>10.0		151 - 250	355 - 424	201 - 300
Hazardous	5001 - 15,000			251 - 500	425 - 604	301 - 500

Source: Present study.

Table 3. Presentation of average air contamination values at site 1.

	Sèmè crossroads: S1							
	CO_2 (ppm)	**TVOC (mg/m^3)**	**HCOH (mg/m^3)**	**$PM_{2.5}$ (mg/m^3)**	**PM_{10} (mg/m^3)**	**T˚F**	**RH (%)**	**AQI**
Average	408.33	0.21	0.03	13.88	17.21	77.04	65.38	21.42
Standard deviation	28.23	0.19	0.00	7.76	9.46	6.51	21.44	7.82
% RESUME	6.91	88.37	13.90	55.96	54.97	8.45	32.79	36.53
Max	500	0.66	0.04	35	44	88	93	41
Min	400	0.03	0.02	5	6	64	16	10

Source: This study.

ambient air quality, we note that apart from TCOV and $PM_{2.5}$ whose daily values taken show an air quality ranging from good to moderate, all other parameters indicate good air condition. Table 4 presents the daily air pollution levels of site 2 (Ekpè).

- **Air pollution levels at site 2 (Ekpè)**

Table 4 presents the daily values taken by the air quality monitoring parameters at site 2. From the analysis of the data, we note that the coefficients of variation % CV are less than 30 except at the level of particulate matter and air quality index. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative of the series.

On the other hand, $PM_{2.5}$ and PM_{10} have variable values during the day, which impacts the air quality index. Therefore only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for the parameters with the guide values for ambient air quality, we note that site 2 is under the influence of $PM_{2.5}$, the maximum daily value of which indicates poor air quality. Apart from this single parameter, all other parameters indicate an air condition ranging from good to moderate. Site 2 overall has a moderate air quality index (Table 5).

Table 4. Presentation of average air contamination values at site 2.

	Carrefour Ekpè: S2							
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T˚F	RH (%)	AQI
Average	420.83	0.39	0.04	27.58	29.79	78.75	63.46	37.22
Standard deviation	41.49	0.11	0.01	20.20	15.40	8.04	6.65	11.36
% RESUME	9.86	27.18	22.29	73.22	51.70	10.21	10.48	30.52
Max	500	0.55	0.06	99	60	90	76	61
Min	400	0.11	0.03	8	5	60	44	0.3

Source: This study.

Table 5. Presentation of average air contamination values at site 3.

	Carrefour Yagbantè: S3							
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T˚F	RH (%)	AQI
Average	400	0.07	0.02	18.58	21.46	78.21	68.13	18.00
Standard deviation	0	0.07	0.01	12.50	16.67	5.41	10.41	8.29
% RESUME	0	91.55	23.93	67.28	77.70	6.92	15.29	46.05
Max	400	0.3	0.04	62	88	88	88	33
Min	400	0.03	0.02	5	7	70	46	7

Source: This study.

- **Air pollution levels at site 3 (Yagbante)**

From the analysis of the data, we note that the coefficients of variation % CV of the values taken by CO_2, aldehydes and relative humidity RH% are less than 30. On the other hand, at the level of the other parameters the coefficients of variation of the values observed are greater than 30. Which leads us to conclude that the daily values observed for these parameters are not homogeneous and that the averages are not representative of the series. On the other hand, $PM_{2.5}$ and PM_{10} have variable values during the day, which impacts the air quality index. Therefore only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for the parameters with the guide values for ambient air quality, we note that the site is subject to $PM_{2.5}$, the maximum daily value of which indicates severe atmospheric pollution. Apart from this single parameter, all other parameters indicate an air condition ranging from good to moderate. Site 3 overall has a moderate air quality index.

- **Air pollution levels at site 4 (Zogbo)**

Table 6 presents the daily average values taken by the air quality monitoring parameters at site 4. From the analysis of the data, we note that the coefficients of variation % CV are greater than 30 except at the level particulate matter and air quality index. Which leads us to conclude that the daily values observed for these parameters are not homogeneous and that the averages are not representative of the series. On the other hand, all the other parameters have homogeneous daily values. Consequently, only the maximum values will be used for decision-making in cases where the % CV are greater than 30. Thus, by comparing the values observed for the parameters to the ambient air quality guide values recorded in Table 1, we note the following:

- The average values of CO_2 and methane are shown in the green line of Table 1, revealing no anomaly for these parameters with regard to ambient air quality;
- For PM_{10}, although the observed values are not uniform, the maximum value is less than 54 μg/m^3, the upper limit of the values characterizing good air quality for this parameter;

Table 6. Presentation of average air contamination values at site 4.

	Vons Zogbo: S4							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚F	RH (%)	AQI
Average	400	0.21	0.03	25.83	28.88	81.46	64.13	42.67
Standard deviation	0	0.34	0.01	10.70	11.16	3.16	9.36	15.28
% RESUME	0	163.29	17.03	41.42	38.65	3.88	14.60	35.80
Max	400	1.35	0.04	45	47	88	91	80
Min	400	0.05	0.02	10	12	77	41	20

Source: This study.

- TCOV, $PM_{2.5}$ and the AQI air quality index have % CV correlation coefficients which are all greater than 30. The maximum values observed make TCOV and $PM_{2.5}$ say that the quality of air at this site 4 is bad for sensitive groups such as the elderly, newborns and people suffering from acute and chronic respiratory illnesses. On the other hand, on site 4 overall, the air quality index indicates moderate pollution.

- **Air pollution levels at site 5 (Red Star Crossroads)**

From the analysis of the data in **Table 7**, we note that only the coefficients of variation % CV of the CO_2 contents and the temperature are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative of the series. On the other hand, all other air quality monitoring parameters take variable values during the day. Therefore only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for each of the parameters to the guide values for ambient air quality we note that atmospheric pollution by CO_2 is not good but not yet alarming. Regarding TCOV, daily levels vary from 0.05 to 1.48 mg/m^3 with an average of 0.56 ± 0.37 mg/m^3. During the day, air pollution by TVOCs at the Red Star crossroads reaches critical values that are harmful to the health of sensitive groups such as the elderly, newborns and people with acute respiratory illnesses and/or chronicles. In terms of aldehydes, contamination levels vary between 0.01 and 0.99 mg/m^3 with an average of 0.11 ± 0.19 mg/m^3. Like TVOCs, atmospheric pollution at the Red Star crossroads by aldehydes is very worrying, especially for sensitive people. Regarding particle pollution, we note that the levels of contamination by $PM_{2.5}$ vary from 6.7 to 50.1 mg/m^3 with an average of 25.39 ± 15.44 mg/m^3. On the other hand, for PM_{10}, the contamination levels vary from 11.4 to 79 mg/m^3 with an average of 40.65 ± 23.87 mg/m^3. Unlike PM_{10}, daily air pollution by $PM_{2.5}$ is of great concern at the Red Star Crossroads for sensitive groups. Overall, the air quality index at the Red Star crossroads varies from 28 to 118 with an average of 72.36 ± 31.22. The values taken by the air quality index confirm the trends announced by each of the air quality monitoring parameters. These observations led us to determine the periods of peak air pollution on site 5 (Red Star).

Analysis of the data in **Table 8** reveals that air pollution at the Red Star increases gradually from 7 a.m. to 8 a.m. where it reaches its peak with an AQI air quality index of 112 characteristic of a state of pollution very harmful for sensitive people such as old people, new people, patients with acute and/or chronic respiratory illnesses. From 8 a.m. to 10 a.m. the AQI oscillates between 70 and 108 characterizing moderate to severe pollution for sensitive groups. A 2nd peak is reported at 2 p.m. with an AQI of 118. The third peak resumes from 5 p.m. to 6:30 p.m. with an AQI of 107. These three periods of the day constitute periods of high traffic to and in the city of Cotonou including one of the nerve centers is the Red Star crossroads, the convergence point of 5 major routes leading to and/or from the Red Star.

Table 7. Presentation of average air contamination values at site 5.

	Carrefour Etoile rouge: S5						
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	*T˚C*	*AQI*
Avg	**792.68**	**0.56**	**0.11**	**25.39**	**40.65**	**32.08**	**72.36**
Standard deviation	**202.91**	**0.37**	**0.19**	**15.44**	**23.87**	**2.66**	**31.22**
% RESUME	**25.60**	**67.20**	**144.91**	**60.80**	**58.71**	**8.30**	**43.15**
Max	**1233**	**1.48**	**0.99**	**50.1**	**79**	**37**	**118**
Min	**410**	**0.02**	**0.01**	**6.7**	**11.4**	**28**	**28**

Source: This study.

Table 8. Results of monitoring ambient air quality at the Red Star crossroads.

Hours of measurements	Air quality monitoring parameter at the Red Star intersection: S5						
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚C	AQI
7 h	670	0.61	0.089	36.1	60.1	28	46
7:30	610	0.617	0.099	39.8	64	28.2	96
8 h	1009	0.987	0.18	50.1	79	30.1	112
8:30	740	0.789	0.11	44.7	70.3	28.2	104
9 h	1050	1.035	0.174	46.5	73	29.6	108
9:30	906	0.515	0.078	15.1	25.3	30.7	70
10 am	1233	1482	0.157	43.4	68.6	31.3	108
10:30 a.m.	757	0.414	0.045	18.3	31	30.7	67
11 am	798	0.488	0.124	36.7	62.5	32.3	103
11:30 a.m.	946	0.655	0.156	9.08	15	33.1	43
12 p.m.	607	0.247	0.074	12.5	23.4	36.4	53
12:30 p.m.	810	0.253	0.024	6.8	12.7	36.5	28
1 p.m.	715	0.23	0.055	10.3	17.1	37	43
1:30 p.m.	700	0.303	0.074	10	17.9	36.2	44
2 p.m.	673	0.305	0.071	33.5	54.2	34.5	118
2:30 p.m.	563	0.227	0.051	6.7	11.4	34.1	42
3 p.m.	455	0.02	0.005	12	19	33.4	49
3:30 p.m.	410	0.233	0.064	7.2	11.6	32.3	29
4 p.m.	750	0.264	0.056	7.2	12.1	32.4	29
4:30 p.m.	954	0.907	0.14	14.8	24.4	31.8	56
5 p.m.	856	0.704	0.99	21.8	35.1	31.2	70

Continued

5:30 p.m.	679	0.264	0.037	45	68.9	32	107
6 p.m.	1156	1282	0.193	38	59.3	31.9	107
6:30 p.m.	989	0.882	0.174	38	59.3	31.9	107
7 p.m.	781	0.208	0.016	31.2	41.1	28.1	70

Source: This study.

- **Air pollution levels at site 6**

From the analysis of the data in **Table 9**, we note that only the coefficients of variation % CV of the CO_2 contents and the temperature are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative of the series. On the other hand, for all other air quality monitoring parameters, the coefficients of variation % CV ≥ 30. Consequently, only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for each of the parameters to the guide values for ambient air quality we note that atmospheric pollution by CO_2 is not good but not yet alarming. Regarding TCOV, daily levels vary from 0.01 to 1.97 mg/m^3 with an average of 0.46 ± 0.43 mg/m^3. During the day, air pollution by TVOCs at the Toyota intersection reaches critical values that are harmful to the health of sensitive groups such as the elderly, newborns and people with acute and/or chronic respiratory illnesses. In terms of aldehydes, contamination levels vary between 0.01 and 0.22 mg/m^3 with an average of 0.069 ± 0.05 mg/m^3. Like TVOCs, air pollution at the Toyota crossroads by aldehydes is very worrying, especially for sensitive people. Regarding particle pollution, we note that the levels of contamination by $PM_{2.5}$ vary from 10.6 to 89.2 mg/m^3 with an average of 24.20 ± 20.18 mg/m^3. On the other hand, for PM_{10}, the contamination levels vary from 17.8 to 122.7 mg/m^3 with an average of 38.84 ± 30.25 mg/m^3. Unlike PM_{10}, daily air pollution by $PM_{2.5}$ is of greater concern at the Toyota crossroads than at the Red Star for sensitive groups. Overall, the air quality index at the Toyota intersection varies from 45 to 158 with an average of 74.88 ± 32.22. The values taken by the air quality index are higher at the Toyota crossroads than at the Red Star. Exposure to $PM_{2.5}$ is more accentuated at the Toyota crossroads than at the Red Star. These observations led us to determine the periods of peak air pollution on this site 6. **Table 10** presents the results of daily monitoring of air pollution at the Toyota crossroads.

From the analysis of the information recorded in **Table 10**, we note that the air quality index increases from 118 to 7 a.m. to reach its maximum value of 158 at 8 a.m. From this moment the AQI begins to gradually decrease to reach, after a few fluctuations during the day, its minimum value of 45 at 4:30 p.m. We then deduce that the period of concern for air pollution on this site is located in the time slot going from 7 a.m. to 8 a.m. contrary to the observations at the Red Star crossroads. This particularity of location of atmospheric pollution in the morning at the Toyota crossroads can be explained by the fact that in the mornings,

Table 9. Presentation of average air contamination values at site 6.

	Carrefour Toyota: S6						
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	*T°C*	*AQI*
Avg	713.04	0.46	0.069	24.20	38.84	32.23	74.88
Standard deviation	210.84	0.43	0.05	20.18	30.25	2.98	32.22
%RESUME	29.5687643	93.92	78.82	83.39	77.87	9.23	43.03
Max	1444	1.97	0.22	89.2	122.7	38.2	158
Min	449	0.01	0.01	10.6	17.8	26.2	45

Source: This study.

Table 10. Results of daily monitoring of air pollution at the Toyota crossroads.

Measuring hours	Toyota Crossroads Air Quality Monitoring Parameters: S6						
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T°C	AQI
7 h	786	0.339	0.044	42.1	68.5	26.2	118
7:30	941	0.772	0.154	62.5	100.7	28.5	154
8 h	1444	1973	0.219	66.7	112.8	27.2	158
8:30	882	0.832	0.094	30.6	50.2	30.4	89
9 h	985	0.964	0.149	32.2	52.1	31	95
9:30	518	0.547	0.015	20.6	32.8	32.3	67
10 am	869	1.21	0.176	89.2	122.7	30.3	94
10:30 a.m.	688	0.472	0.079	11.9	19.2	33.9	55
11 am	759	0.23	0.059	11.9	17.8	33.9	122
11:30 a.m.	863	0.61	0.099	22.2	35.3	33.1	71
12 p.m.	700	0.452	0.032	13.7	20.9	37.9	52
12:30 p.m.	629	0.2342	0.044	13.1	21.3	32.1	53
1 p.m.	699	0.249	0.049	13.5	26.1	33.3	57
1:30 p.m.	586	0.02	0.02	14.2	23.1	31	53
2 p.m.	752	0.366	0.071	16.1	27.5	31.6	62
2:30 p.m.	556	0.203	0.031	20.2	33.4	34.8	86
3 p.m.	578	0.197	0.038	12.2	20.3	38.2	51
3:30 p.m.	587	0.584	0.095	13.8	21.6	35.2	54
4 p.m.	449	0.01	0.02	15.4	26.2	35.4	58
4:30 p.m.	544	0.093	0.016	10.6	19.5	34.1	45
5 p.m.	764	0.391	0.072	16.3	29.3	33.4	64
5:30 p.m.	610	0.389	0.077	15.6	24.4	31.5	54

Continued

6 p.m.	601	0.267	0.053	13.2	21.8	32.3	55
6:30 p.m.	542	0.141	0.026	11.5	18.2	29.2	52
7 p.m.	494	0.042	0.006	15.8	25.4	28.9	53

Source: This study.

road users who are mainly civil servants all wanting to go to the service on time create traffic jams and therefore ricochets a lot of emissions at the level of the exhausts of thermal vehicles. On the other hand, since the evening is no longer subject to a constraint of punctuality at the service, users vary their exit times from Cotonou to avoid traffic jams which has a positive impact on air quality.

- **Air pollution levels at site 7**

From the analysis of the data (**Table 11**), we note that the coefficients of variation % CV of CO_2 and temperature are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative series. On the other hand, all other air quality monitoring parameters have % CV greater than 30. Consequently, only the maximum values will be used for decision-making in these cases. Thus, by comparing the values observed for the parameters to the guide values for ambient air quality, we note that the pollution of ambient air by CO_2 emissions is moderate. On the other hand, the levels of air contamination by TCOV vary from 0.02 to 1.69 with an average of 0.69 ± 0.49 mg/m^3. These levels of ambient air contamination by TVOCs are of concern for sensitive groups. In terms of aldehydes, contamination levels vary from 0.005 to 0.211 mg/m^3. As with TVOCs, ambient air contamination levels with aldehydes are very harmful to sensitive groups. Regarding exposure levels to particulate matter, they vary from 9.6 to 173.8 ppm with an average of 30.06 ± 38.60 ppm for $PM_{2.5}$. Likewise for PM_{10}, the observed values oscillate between 15.3 and 449.6 ppm with a daily average of 65.26 ± 89.48 ppm. $PM_{2.5}$ and PM_{10} pollution are of great concern at the crossroads after the Friendship Stadium. Overall on this S7 site the air quality index varies from 36 to 243 with a daily average of 90.73 ± 57.61. These levels of ambient air contamination are very very dangerous for human health regardless of the person. These observations led us to determine the periods of peak air pollution on site 7. **Table 12** presents the results of daily monitoring of air pollution at the crossroads after the friendship stage.

From the analysis of the information recorded in **Table 12**, we note that the air quality index fluctuates in sawtooth patterns from 7 a.m. to 12 p.m. with large fluctuations. After this time slot the index drops drastically to oscillate between 41 and 63 for the rest of the day. We then deduce that the period of concern for air pollution on this site is in the time slot. This particularity of location of atmospheric pollution in the morning also at the crossroads after the friendship stage can be explained by the same justifications for the observation at the Toyota crossroads. **Table 13** presents the results of monitoring air pollution at the Togoudo crossroads (site 8).

Table 11. Presentation of the average values of air contamination at site 7.

	Crossroads after the friendship stage: S7						
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T˚C	*AQI*
Avg	804.32	0.69	0.08	39.06	65.26	33.58	90.72
Standard deviation	224.59	0.49	0.05	38.60	89.48	2.94	57.61
%RESUME	27.9225439	71.38	64.06	98,825	137.11	8.76	63.50
Max	1252	1.69	0.211	173.8	449.6	40.5	243
Min	466	0.02	0.005	9.6	15.3	26.2	36

Source: This study.

Table 12. Results of daily monitoring of air pollution at the crossroads after the friendship stage.

Measuring hours	Air quality monitoring parameters at the intersection after the friendship stage: S7						
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T˚C	*AQI*
7 h	768	0.313	0.075	62.5	103.6	26.2	156
7:30	813	0.42	0.077	173.8	449.6	29.5	209
8 h	466	0.118	0.01	67.2	98.1	31.3	153
8:30	799	0.421	0.064	70.8	110.1	31.2	130
9 h	516	0.331	0.183	116.3	135.2	32.6	152
9:30	749	0.555	0.088	27.5	43.4	35.3	61
10 am	467	0.42	0.107	32.9	48.8	33.8	83
10:30 a.m.	979	1.28	0.119	54.6	39.8	32.7	243
11 am	1226	1573	0.211	68.8	161.7	33.9	104
11:30 a.m.	959	0.959	0.066	10.5	15.3	35.6	36
12 p.m.	704	0.28	0.025	47.3	32.6	35.3	170
12:30 p.m.	649	0.27	0.038	17.8	32.5	32.9	61
1 p.m.	743	0.389	0.067	10.9	17.9	37.1	52
1:30 p.m.	665	0.359	0.041	27.5	46.5	36.9	52
2 p.m.	1252	1694	0.124	22	33.4	40.5	56
2:30 p.m.	1023	1402	0.118	13	18.2	36.5	44
3 p.m.	833	0.588	0.097	24.4	39.6	34.9	74
3:30 p.m.	498	0.146	0.005	30.4	47.5	35.7	63
4 p.m.	550	0.928	0.174	10	15.8	33.2	41

Continued

4:30 p.m.	890	1321	0.082	22.1	24.8	34.8	56
5 p.m.	946	0.744	0.12	9.6	20.6	32.3	56
5:30 p.m.	809	0.501	0.083	14.6	24.8	33.7	56
6 p.m.	657	0.02	0.02	14.6	24.8	32.3	56
6:30 p.m.	1032	0.904	0.02	14.6	24.8	32.3	56
7 p.m.	1115	1383	0.073	12.9	22.1	29	48

Source: This study.

Table 13. Presentation of average air contamination values at site 8.

	Carrefour Togoudo: S8							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T°F	RH (%)	AQI
Average	400.57	0.26	0.03	32.17	34.57	82.74	61.61	44.70
Standard deviation	1.53	0.14	0.01	10.91	12.15	3.73	6.90	14.02
%RESUME	0.38	53.30	14.68	33.91	35.14	4.51	11.20	31.36
Max	405	0.68	0.04	58	63	88	78	67
Min	400	0.12	0.03	18	19	77	43	24

Source: This study.

- **Air pollution levels at site 8**

With regard to the analysis of the data contained in Table 13, we see that the coefficients of variation % CV of the values taken by CO_2, aldehydes, temperature and relative humidity are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the means are representative of the series. On the other hand, TCOV, $PM_{2.5}$ and PM_{10} and the AQI air quality index have variable values during the day. Consequently, only the maximum values taken by these parameters will be used for decision-making in these cases. Thus, by comparing the values observed for the parameters with the guide values for ambient air quality we note that site 5 is sometimes during the day subject to pollution by TCOV, $PM_{2.5}$ and PM_{10} whose daily value maximum reports moderate pollution at site 5.

- **Air pollution levels at site 9 (Tankpè)**

Table 14 presents the daily pollution levels of site 9. From the analysis of the data, we note that the coefficients of variation % CV of the daily CO_2 contents, temperature and relative humidity RH are less than 30. Which leads us to conclude that the daily values observed for these parameters are homogeneous and that the averages are representative of the series. On the other hand, TCOV, HCHO, AQI, $PM_{2.5}$ and PM_{10} have variable values during the hours of the day. Therefore only the maximum values will be used for decision-making in these

Table 14. Presentation of average air contamination values at site 9.

	Carrefour Tankpè: S9							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚F	RH (%)	AQI
Average	405.79	1.36	0.04	26.88	36.46	84.58	71.33	51.17
Standard deviation	1.14	1.82	0.03	13.23	21.84	5.91	9.30	14.32
%RESUME	0.28	134.08	74.24	49.23	59.89	6.99	13.04	27.98
Max	409	6.91	0.15	66	108	95	94	82
Min	404	0.05	0.02	12	16	75	60	22

Source: This study.

cases. Thus, by comparing the values observed for the parameters with the guide values for ambient air quality, we note that the averages of CO_2, temperature and relative humidity do not indicate any anomaly in terms of air quality. The air on site 9. On the other hand, the maximum value taken by PM_{10} indicates moderate pollution, while those observed at the level of TVOC, HCHO and $PM_{2.5}$ indicate severe pollution likely to impact sensitive people such as the elderly, newborns and patients with acute and chronic respiratory illnesses. The air quality index at site 9 indicates moderate pollution overall.

- **Air pollution levels at site 10**

Table 15 presents the daily values taken by the air quality monitoring parameters at site 10. From the analysis of the data, we note that only the values of CO_2, temperature and humidity relative are homogeneous. For these parameters, the daily averages are representative of the series and do not indicate atmospheric pollution. On the other hand, the values taken by the % CV reveal a dispersion of the measurements around the averages. Therefore only the maximum values will be used for decision-making in these cases. Thus, by comparing the observed values to the ambient air quality guide values we note that the pollution levels of site 7 by PM_{10} are moderate while those of TCOV and aldehydes are Severe. Overall, the air quality index indicates moderate air pollution.

- **Air pollution levels at site 11 (Bopa)**

Table 16 presents the results of monitoring air pollution at the Houègbah site in the commune of Bopa (Site 11).

Analysis of the data reveals that the measured values for CO_2, methane, temperature and relative humidity are homogeneous and do not reveal atmospheric pollution. On the other hand, TCOV, the AQI air quality index, $PM_{2.5}$ and PM_{10} have variable values during the day. Apart from $PM_{2.5}$ whose values signal moderate pollution, all other air quality monitoring parameters signal good air quality.

- **Air pollution levels at site 12**

Table 17 presents the results of air quality monitoring at site 12.

Table 15. Presentation of average air contamination values at site 10.

	Crossroads bypass (Tori Bossito): S10							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚F	RH (%)	AQI
Average	400.33	0.27	0.15	18.79	21.83	81.13	60.38	20.71
Standard deviation	1.09	0.58	0.61	7.45	10.58	3.37	7.10	12.17
%RESUME	0.27	212.85	394.33	39.67	48.47	4.15	11.76	58.76
Max	405	2.97	3	40	56	88	71	61
Min	400	0.07	0.02	8	9	77	43	11

Source: This study.

Table 16. The average air contamination values at site 11.

	Houègboh (Bopa): S11							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚F	RH (%)	AQI
Average	400	0.08	0.02	10.09	11.39	81.13	64.22	11.26
Standard deviation	0	0.02	0.01	4.69	4.69	1.79	6.58	4.09
%RESUME	0	30.15	20.61	46.49	41.15	2.21	10.24	36.34
Max	400	0.15	0.03	22	23	84	86	20
Min	400	0.04	0.02	5	5	77	53	4

Source: This study.

Table 17. The average air contamination values at site 12.

	Wangbo village Davè (Ouinga): S12							
	CO_2 (ppm)	TVOC (mg/m³)	HCOH (mg/m³)	$PM_{2.5}$ (mg/m³)	PM_{10} (mg/m³)	T˚F	RH (%)	AQI
Average	400.35	0.07	0.03	11.96	13.83	82.96	59.09	14.83
Standard deviation	1.19	0.03	0.01	4.17	4.96	3.24	6.00	5.49
%RESUME	0.30	42.96	18.63	34.89	35.88	3.91	10.15	37.04
Max	405	0.18	0.04	21	25	88	70	27
Min	400	0.04	0.02	7	7	78	41	8

Source: This study.

Analysis of the data reveals that the measured values for CO_2, methanal, temperature and relative humidity are homogeneous and the averages are representative of the series. These averages do not reveal atmospheric pollution on the site. On the other hand, TCOV, the AQI air quality index, $PM_{2.5}$ and PM_{10} have variable values during the day. Not all values taken by these air quality monitoring parameters indicate air pollution.

- **Air pollution levels at site 13**

Table 18 presents the results of air quality monitoring in Athiémé.

Analysis of the data reveals that all the measured values are homogeneous and the averages are representative of the series. None of these air quality monitoring parameters report air pollution.

3.2. Research of Key Parameters Influencing Air Quality on Each of the Sites Monitored

In the research, Principal Component Analysis was used to identify the different existing links between air quality monitoring parameters on the one hand and between air quality monitoring parameters on the other hand. Air and tracking points. The correlation matrix in Table 19 reveals how the monitored parameters are correlated.

Table 18. The average air contamination values at site 13.

	Athiémé border bridge: S13							
	CO_2 (ppm)	TVOC (mg/m^3)	HCOH (mg/m^3)	$PM_{2.5}$ (mg/m^3)	PM_{10} (mg/m^3)	T˚F	RH (%)	AQI
Average	400	0.06	0.03	9.10	10.60	77.55	64.85	13.20
Standard deviation	0	0.02	0.00	2.17	2.62	13.64	4.92	4.03
%RESUME	0	27.59	12.85	23.89	24.75	17.58	7.59	30.56
Max	400	0.1	0.03	14	16	84	74	21
Min	400	0.04	0.02	6	8	20	60	7

Source: This study.

Table 19. Correlation matrix.

CO_2	*1*							
TVOC	*0.054*	*1*						
HCOH	*−0.005*	*−0.011*	*1*					
$PM_{2.5}$	*0.041*	***0.141****	*0.017*	*1*				
PM_{10}	*0.073*	***0.211*****	*0.016*	***0.878*****	*1*			
T˚F	*−0.128*	***0.213*****	*−0.018*	*0.036*	*0.004*	*1*		
Relative humidity	***0.152****	*0.048*	*0.053*	*0.070*	*0.098*	***−0.209*****	*1*	
AQI	*0.111*	***0.377*****	*0.000*	***0.670*****	***0.705*****	***0.129****	*0.044*	*1*
	CO_2	TVOC	HCOH	$PM_{2.5}$	PM_{10}	T˚F	Humidity Relative	AQI

Source: This study. *Significant correlation at the 5% threshold. **Significant correlation at the 1% threshold.

From the analysis of the information in **Table 19**, it appears that CO_2 is positively correlated with relative humidity at the threshold of 5%. Thus, in conditions of high relative humidity, exposure to CO_2 becomes more significant with its corollaries of tearing headaches and suffocation in humans. This lack of links between the CO_2 levels and the levels of other ambient air quality monitoring parameters in southern Benin leads to the conclusion that the sources of CO_2 input into the ambient air at the measurement sites are not not exclusively road traffic. TCOV are significantly correlated with PM_{10}, temperature and the Air Quality Index at the 1% threshold and with $PM_{2.5}$ at the 5% threshold. In other words, the unburnt products coming out of chimneys and/or exhaust pipes impact the ambient air temperature due to their very high emission temperature. Likewise, these volatile organic compounds can be emitted in particulate form and/or adsorbed on inorganic particles which they coat. According to the Focon/ABF firm, 93% of particulate matter emissions, 98% of TCOV and 99% of CO_2 came from road transport in 2000. Aldehydes are not correlated with any of our ambient air quality monitoring parameters. This observation leads us to assume that aldehydes and TVOCs do not have the same emission sources. In other words, the aldehydes detected in the study presence, unlike TCOV which have a pyrolytic source, would come from other non-pyrolytic sources such as forests, industrial oxygenated organic solvents and others. Other authors recorded $PM_{2.5}$ contents of around 335.1 μg/m³ in 2016 in Cotonou [17] and 175.3 μg/m³ in Cotonou in 2017 [18]. The $PM_{2.5}$ contamination levels recorded by [18] are similar to our results and allow us to conclude that the evolution of $PM_{2.5}$ pollution in Cotonou remained stagnant from 2017 to 2023. However, during During this same period, the automobile fleet experienced an evolution. The data from [17] [18] and our results highlight the effectiveness of the different policies to combat air pollution in the large cities of Benin, implemented by the different successive governments at the head of the Beninese state. For [19] the TCOV contents vary from 0.15 μg/m³ to 0.17 μg/m³ during the days of the week, for aldehydes the contents vary from 0.05 μg/m³ to 0 .35 μg/m³. For Particulate Matter (PM), the average values are around 52.4 μg/m³ for PM_{10} and 45.7 μg/m³ for $PM_{2.5}$. Our values are much higher than those of [19]. These differences are due to the fact that our values were recorded at hot spots while those of [19] are recorded in background areas far from road traffic. [20] by measuring air quality in a community next to a technical landfill found a value for $PM_{2.5}$ of 75.5 ± 13.5 μg/m³, for PM_{10} 128.50 ± 28.50 μg/m³, for TCOV 2.67 ± 0.09 ppm, for HCHO 0.37 ± 0.02 ppm. The contamination levels found by these authors are also higher than ours. Similarly [21] working on indoor air quality across China found exposure levels to aldehydes varying between 94 μg/m³ and 163 μg/m³. These exposure levels are much lower than the values found by the present study. The explanation lies in the fact that our study focuses on outdoor exposure to atmospheric pollution while the study by [21] focuses on the indoor environment. The work of [9] in Côte d'Ivoire reported $PM_{2.5}$ contents of around 54.3 to 2018 μg/m³, PM_{10} contents of between 21.2 to 534.7 μg/m³ in Korogho compared to

28.8 to 113.4 µg/m³ for $PM_{2.5}$ and 38.1 to 160.4 µg/m³ for PM_{10} in Abidjan. If the maximum pollution levels in Korogho are higher than those found in southern Benin and in particular at the major intersections of Cotonou, our observed values are higher than those in Abidjan. Which leads us to conclude that the city of Cotonou is more polluted in particulate matter than the city of Abidjan. The work of [22] monitoring particulate matter in the city of Bamako in Mali reported contamination levels of 43 µg/m³ for $PM_{2.5}$ and 210 µg/m³ for PM_{10}. These levels are below our maximum values. Which leads us to conclude that the city of Cotonou is more polluted in particulate matter than the city of Abidjan. The work of [22] monitoring particulate matter in the city of Bamako in Mali reported contamination levels of 43 µg/m³ for $PM_{2.5}$ and 210 µg/m³ for PM_{10}. These levels are below our maximum values. Which leads us to conclude that the city of Cotonou is more polluted in particulate matter than the city of Abidjan. The work of [22] monitoring particulate matter in the city of Bamako in Mali reported contamination levels of 43 µg/m³ for $PM_{2.5}$ and 210 µg/m³ for PM_{10}. These levels are below our maximum values.

4. Conclusion

The methodology adopted allowed us to identify the levels of exposure of populations in southern Benin to atmospheric pollution. The localities affected by atmospheric pollution in South Benin are located in the south-western part of Benin headed by the city of Cotonou which is heavily polluted by CO_2, Total Volatile Organic Compounds (TCOV), PM_{10} and especially $PM_{2.5}$. These levels of pollution in the city of Cotonou are likely to impact sensitive people such as the elderly, newborns and patients with acute and chronic respiratory illnesses. The most polluted intersections in the city of Cotonou are the Red Star intersection, the Toyota intersection and the intersection after the Friendship Stadium. The South-East part is very less polluted. The Tori-Bossito intersection is the site most polluted by aldehydes. The main source of this pollutant in non-urban areas would be the surrounding forests. As a perspective, we plan to expand the study area, establish a database on air pollution which we will update.

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Conflicts of Interest

The authors declare no conflict of interest.

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