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LOW-COST MONITORING OF AIR QUALITY IN HIGH-TRAFFIC URBAN AREAS OF PANAMA: A PRELIMINARY ASSESSMENT

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ABSTRACT

This study presents the results of atmospheric pollutant monitoring for PM_{10}, PM2.5, NO_2, and O_3 in two of the most densely populated areas of Panama. Data were collected using a low-cost Aeroqual 500 series device, which, given the limited air quality monitoring infrastructure in the country, serves as a practical tool for generating valuable information to raise awareness among citizens and local authorities. The levels of PM_{10}, PM2.5, and NO_2 were relatively low, whereas O_3 concentrations exceeded the thresholds established by organizations such as the USEPA (for comparative purposes only). The most critical sites identified include the Gran Estación de San Miguelito, where PM_{10} levels reached up to 34 µg/m^3, likely influenced by its location at the intersection of major traffic arteries (Transístmica and Tocumen). The UTP-Site 2 Tocumen University Extension, situated near a highway, recorded the highest $PM_{2.5}$ levels at 10 µg/m^3. Regarding NO_2, the highest concentrations were observed in Plaza Princesa de Gales, Panama Norte, but remained relatively low (39 ppb). Similarly, O_3 levels were elevated in Plaza Princesa de Gales, with observed values ranging from 0.066 to 122 ppm. Standard deviations suggest moderate variability in PM_{10}, PM2.5, and O_3 measurements, whereas NO_2 levels exhibited significant fluctuations. These findings underscore the considerable contribution of vehicular emissions to urban air pollution in Panama, particularly concerning the high O_3 levels. Further in-depth studies are needed to better understand these trends and their implications for air quality management.

Keywords: Atmospheric Pollutants, Low-Cost Monitoring, High-Traffic Urban Areas, Air Quality

1. INTRODUCTION

Air quality has become an increasing concern across various sectors due to its potential impact on human health, ecosystems, and infrastructure. The vast body of technical information available on a global scale highlights the need to address this issue by leveraging successful case studies and best practices.

Urban areas are particularly vulnerable to pollutants such as particulate matter (PM10 and PM2.5), nitrogen dioxide (NO_2), and ozone (O_3), among others, primarily originating from vehicular emissions and industrial activities Abuelgasim & Farahat, (2020); Agudelo-Castañeda et al. (2020); Aziz et al. (2020); Cannistraro et al. (2016); Haque & Singh (2017); Inchaouh et al. (2018); Li et al. (2020). The World Health Organization (WHO) reports that 99% of the global population lives in areas where air pollution levels exceed its recommended guidelines World Health Organization. (2021), Global Air Quality Guidelines (2021).

In Panama, data from the National Institute of Statistics and Census (INEC) indicate that as of the 2021 census, there were 896,092 registered vehicles in the country, with 72% (649,452 vehicles) concentrated in Panama Province (Instituto Nacional de Estadística y Censo (INEC), n.d.). Unlike industrialized nations, Panama's economy is primarily based on logistics, trade, and services, making vehicular emissions the main source of air pollution. Additionally, the high density of buildings in urban areas may act as a barrier to pollutant dispersion, exacerbating air quality issues.

According to INEC, Panama has a population of 4,337,406 inhabitants, a total land area of 74,472.7 km^2, and a population density of 58.2 inhabitants per km^2. The province of Panama, home to 1,675,796 people (38.6% of the national population), contains two highly populated districts: Panama City, the capital, with 1,220,958 inhabitants and a density of 596.9 inhabitants per km^2, and San Miguelito, with 384,806 inhabitants and a much higher density of 7,715.3 inhabitants per km^2. These districts represent two of the most densely populated areas in the country and, consequently, are among the most affected by air pollution.

Although international air quality guidelines exist, their implementation requires substantial financial and technical resources. For Panama, this represents a significant challenge, further exacerbated by historical delays in the development and investment in science and technology. Despite these challenges, the country recently adopted the WHO Air Quality Guidelines through Resolution No. 21 of January 24, 2023 Resolución N° 021-24 de enero de 2023-Guías Global De Calidad Del Aire-World Health Organization. (n.d.). While this is a positive step toward improving air quality management, the adoption remains partial, as it lacks compliance goals, does not encompass all recommended pollutants and limits, and, most importantly, faces critical infrastructure deficiencies for effective implementation.

To address these limitations, the use of low-cost air quality monitoring technologies has been proposed as a viable alternative in Panama. These technologies are gaining international recognition and support from institutions such as the United States Environmental Protection Agency (USEPA), which has promoted their use as a tool to raise awareness among citizens, local authorities, and businesses Brilli et al. (2020) , Morawska et al. (2018), Murray et al. (2024), Prakash et al. (2021), Van Poppel et al. (2023), Williams et al. (2019), Yatkin & Signorini. (n.d.).The USEPA has also conducted studies to evaluate the performance of low-cost air quality sensors and has integrated them into community-driven monitoring initiatives Air Sensor Guidebook. (2014).

Panama currently participates in initiatives such as the Purple Air Real-Time Interactive Map, supported by the USEPA, which monitors PM2.5 concentrations using low-cost sensors. At present, there are two operational monitoring sites in the country Purple Air. (n.d.). Additionally, as part of institutional projects, Aeroqual 500 series equipment and sensors have been acquired to contribute to short-term air quality monitoring efforts in Panama. This initiative aims to encourage society to recognize air quality management as a fundamental citizen's right Project IDDS22-055. (n.d.).

This study aims to present the results of PM10, PM2.5, NO_2 and O_3 measurements using low-cost Aeroqual 500 series equipment, at selected sites within the Panama City metropolitan area. This initiative serves as an initial step towards obtaining real, albeit localized or preliminary data that can motivate national authorities to invest in the basic infrastructure needed for comprehensive air quality studies. The selected sites are characterized by high vehicular traffic and dense building structures, which may act as barriers to pollutant dispersion and, consequently, contribute to environmental and health impacts.

2. MATERIALS AND METHODS

2.1. LOCATION OF PANAMA

The Republic of Panama is located between 7°12'07" and 9°38'46" north latitude and 77°09'24" and 83°03'07" west longitude. It is bordered to the north by the Caribbean Sea, to the east by Colombia, to the south by the Pacific Ocean, and to the west by Costa Rica Instituto Nacional de Estadística y Censo (INEC). (n.d.), Figure 1 presents a map of Panama.

Figure 1

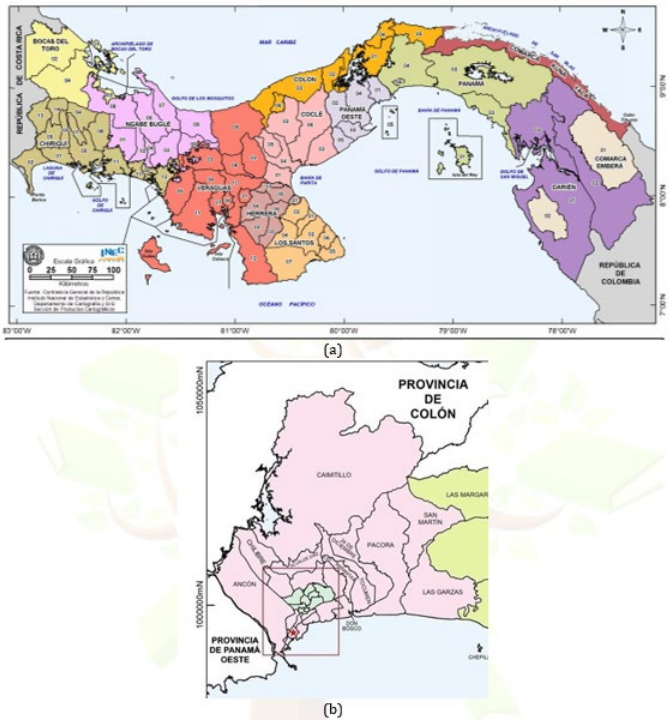

Figure 1 (a) Map of the Republic of Panama. The Zones Identified as 04 Correspond to the San Miguelito Special District and 06 to Panama City, (b) an Enlarged Image of both Sites: Zone 06 in Light Blue and in a Box, and Zone 04, in the Vicinity of Zone 06 and in Purple Instituto Nacional de Estadística y Censo (INEC). (n.d.).

2.2. STUDY SITES

Eight monitoring sites were selected, seven in Panama City (Capital District) and one in the Special District of San Miguelito. These sites were chosen based on their high vehicular traffic, high population density, and large concentration of buildings. Table 1 presents the identification and Global Positioning System (GPS) coordinates of the sites, while Figure 2 displays a Google Earth image showing their locations.

Table 1

Table 1 Identification and Location of Monitoring Sites

Identification	Description	District	Geographical coordinates
S1	UTP-Site 1 Tocumen University Extension	Panama City	9.06854, -79.40578
S2	UTP-Site 2 Tocumen University Extension	Panama City	9.05629, -79.40484
S3	Princess of Wales Square, Panama North	Panama City	9.08683, -79.52959
S4	The Great Station of San Miguelito	San Miguelito	9.03002, -79.50648
S5	UTP-Central Campus - Building #3	Panama City	9.02383, -79.53173
S6	-Interception of the Ricardo J. Alfaro and Transistmica roads	Panama City	8.98849, -79.53323
S7	Belisario Porras Park	Panama City	8.9699, -79.53637
S8	5 de mayo square	Panama City	8.96055, -79.54089

Figure 2

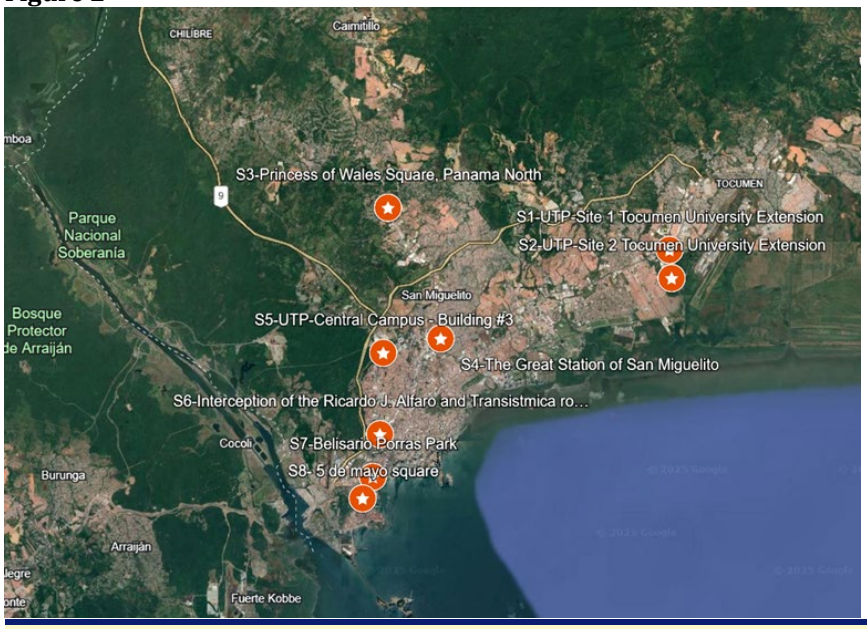

Figure 2 Google Earth View of the Location of the Eight (8) Monitoring Sites

2.3. MONITORING EQUIPMENT

The following air pollutants were measured: particulate matter smaller than 10 micrometers in diameter (PM_{10}), particulate matter smaller than 2.5 micrometers in diameter (PM2.5), nitrogen dioxide (NO_2), and ozone (O_3).

These measurements were conducted using a low-cost air quality monitoring device, the AEROQUAL Series 500, manufactured by Specto Technology, equipped with the aforementioned sensors, which were properly calibrated Aeroqual Series 200/300/500 User Guide. (n.d.), Table 2 presents their technical specifications, and Figure 3 shows some of the sensors used. The measurement frequency for each pollutant was one reading per minute, with a total monitoring duration ranging from 30 to 60 minutes

Table 2

Table 2 Technical Data of PM2.5, PM10, NO2 y O3 Sensors

Sensor	Sensor type	Measuring range	Detection limit	Resolution	Precision
$PM_{2.5}$/ PM_{10}	LPC[1]	0.001 a 1.000 mg/m³ (1 a 1000 µg/m³)	0.001 mg/m³ (1 µg /m³)	0.01 mg/m³ (1 µg/m³)	±0.005 mg/m³ + 15%
NO_2	GSE[2]	0 a 1 ppm	0.005 ppm (5 ppb)	0.001 ppm	<±0.02 ppm 0-0.2 ppm <±10% 0.2-1 ppm
O_3	GSE[2]	0 - 10 ppm	0.01	0.01	<±0.01ppm + 7.5%

1) Laser Particle Counter User Guide, n.d.) 2) Gas Sensitive Electrochemical (Aeroqual Series 200/300/500

Figure 3

Figure 3 Aeroqual 500 Series Measuring Equipment and Sensors Manufactured by Specto Technology Aeroqual Series 200/300/500 User Guide. (n.d.)

In Panama, local representatives for these devices provide support in training, verification, and periodic calibration. The measurements were conducted following the manufacturer's guidelines and international standards Aeroqual Series 200/300/500 User Guide. (n.d.); Metodología para la Validación de Datos de Sensores de Bajo Costo, Suplementarios e Informativos No Reglamentarios. (n.d.), Figure 4 displays an image of the Aeroqual equipment and the weather station in the field.

The data were stored in the memory of the Aeroqual device, extracted using the Aeroqual S500 V6.6 software, and processed in the laboratory.

Access was obtained to a portable Davis Vantage Pro2 weather station, equipped with a temperature sensor with an uncertainty of ±0.1 ºC, operating within a range of 0 ºC to 60 ºC, and a relative humidity sensor with an uncertainty of ±3 %, measuring relative humidity between 1 % and 100 %. The study sites are relatively close to each other and have similar average temperature and relative humidity ranges, with an average temperature of 30.4 ± 1.2 ºC and an average relative humidity of 63.3 ± 7.5 %. Therefore, meteorological variations were not considered in this study.

Figure 4

Figure 4 Aeroqual 500 Series Measuring Equipment and Weather Station

3. RESULTS AND DISCUSSIONS

In order to gain an understanding of the obtained pollutant levels, and solely for comparative purposes, Resolution No. 21 of January 24, 2023 Resolución N° 021-24 de enero de 2023-Guías Global De Calidad Del Aire-World Health Organization. (n.d.) were used.

3.1. MEASUREMENT OF PM10 AND PM2.5

Table 3 and, Table 4 present the results of PM10 and PM2.5 for the eight (8) evaluated sites, while Figure 5 and Figure 6 display these data in graphical form.

Table 3

Table 3 PM10 Results (µg/m3) of the Evaluated sites

Site	Average	Maximum	Minimum	Desvest
UTP-Site 1 Tocumen University Extension	14	21	2	1.5
UTP-Site 2 Tocumen University Extension	30	55	20	4.6
Princess of Wales Square, Panama North	8	12	6	0.8
The Great Station of San Miguelito	34	42	23	1.3
UTP-Central Campus - Building #3	14	18	9	1.7
Interception of the Ricardo J. Alfaro and Transistmica roads	29	52	22	1.2
Belisario Porras Park	31	39	26	0.7
5 de mayo square	29	46	18	5.9

The average PM_{10} values across the eight evaluated sites show relatively low levels (8–34 µg/m^3) compared to the limit of 75 µg/m^3 established in Resolution No. 21 (for a 24-hour period). The site with the highest concentration is The Great Station of San Miguelito, with 34 µg/m^3, which aligns with the fact that this district has the highest population density in the country. It is followed by Belisario Porras Park (31 µg/m^3) and UTP-Site 2 Tocumen University Extension (30 µg/m^3), both of which are high-traffic areas. The latter site recorded the highest value among all measurements, reaching 55 µg/m^3, due to its proximity to a major highway. Princess of Wales Square is located in an area slightly removed from the center of Panama City, with fewer buildings. The UTP-Central Campus site, despite being near a high-traffic road, has a high density of trees and buildings in its surroundings, which act as a barrier, limiting the flow of air and pollutants into the monitoring site. The deviations of the sites were low except for the 5 de mayo square site, which showed greater variability

Figure 5

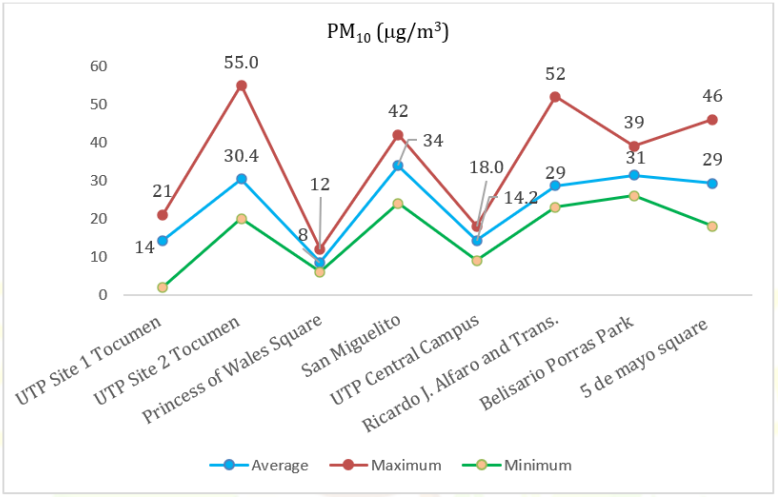

Figure 5 Results of PM10 (µg/m3) of the Evaluated Sites

The average PM2.5 levels at the eight evaluated sites are considered relatively low, ranging from 3.4 to 10 µg/m^3 (compared to Resolution No. 21, which sets a 24-hour limit of 37.5 µg/m^3). The site with the highest concentration is UTP – Site 2 - Tocumen University Extension with 10 µg/m^3, followed by 5 de mayo square,

Belisario Porras Park and The Great Station of San Miguelito with 8 µg/m3. In UTP – Site 2 the highest value of all measurements was observed with 30 µg/m3. The deviations of the sites were low except for the UTP – Site 2 site, which showed greater variability

Table 4

Table 4 PM2.5 Results (µg/m3) of the Evaluated sites

Site	Average	Maximum	Minimum	Desvest
UTP-Site 1 Tocumen University Extension	4	6	1	1.5
UTP-Site 2 Tocumen University Extension	10	30	8	4.6
Princess of Wales Square, Panama North	3	6	2	1.4
The Great Station of San Miguelito	8	13	6	1.4
UTP-Central Campus - Building #3	6	7	4	0.6
Interception of the Ricardo J. Alfaro and Transistmica roads	7	11	5	1.3
Belisario Porras Park	8	9	7	0.7
5 de mayo square	8	10	6	1

Figure 6

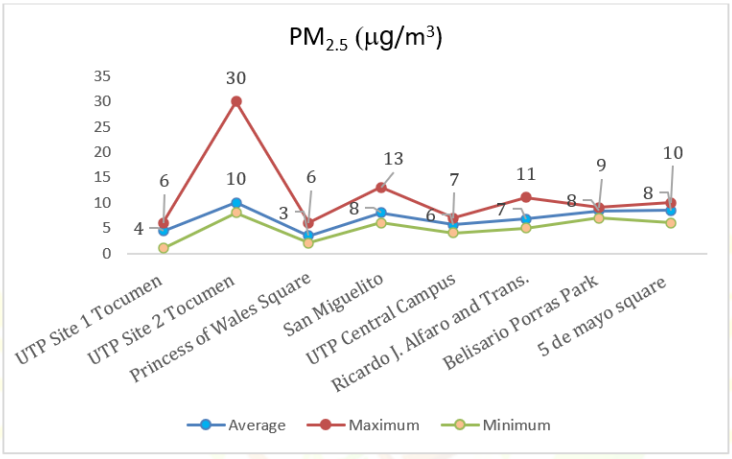

Figure 6 Results of (PM2.5 (µg/m3) of the Evaluated Sites

3.2. MEASUREMENT OF NO_2

Table 5 present the results of the pollutant NO_2 for the eight (8) evaluated sites, while Figure 7 display these data in graphical form.

As for NO2, average levels are considered low, in the range of 9 to 39 ppb (with respect to the USEPA limit of 100 ppb in 1 hour), with the highest average value observed at Princess of Wales site with 39 ppb. The highest value of all measurements was observed at Ricardo J. Alfaro with 66 ppb. In this case, the measurements at the evaluated sites showed high variation, reflecting high standard deviations, with the exception of the UTP-Central Campus - Building #3 site.

Table 5

Table 5 NO2 Results (ppb) of the Evaluated Sites

Site	Average	Maximum	Minimum	Desvest
UTP-Site 1 Tocumen University Extension	9	51	0	17
UTP-Site 2 Tocumen University Extension	23	42	1	11
Princess of Wales Square, Panama North	39	60	27	10

The Great Station of San Miguelito	9	33	0	10
UTP-Central Campus - Building #3	0.2	5	0	1.1
Interception of the Ricardo J. Alfaro and Transistmica roads	27	66	0	18
Belisario Porras Park	10	39	0	10
5 de mayo square	15	32	0	9

Figure 7

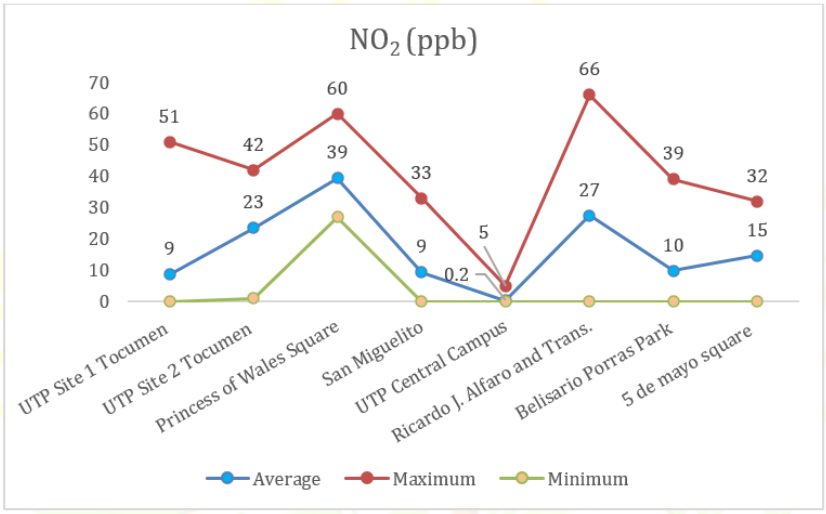

Figure 7 Results of NO2 (ppb) of the Evaluated Sites

These results reflect the direct influence of vehicular activity and, additionally, the barrier effect of natural elements such as the high presence of trees, which can help limit the airflow into certain areas, in this case, the UTP-Central Campus - Building #3 monitoring site.

3.3. MEASUREMENT OF O3

Table 6 present the results of the pollutants O_3 for the eight (8) evaluated sites, while Figure 8 display these data in graphical form.

Table 6

Table 6 O3 Results (ppm) of the Evaluated Sites

Site	Average	Maximum	Minimum	Desvest
UTP-Site 1 Tocumen University Extension	0.114	0.133	0.094	0.011
UTP-Site 2 Tocumen University Extension	0.117	0.136	0.102	0.011
Princess of Wales Square, Panama North	0.122	0.153	0.066	0.02
The Great Station of San Miguelito	0.099	0.157	0.015	0.039
UTP-Central Campus - Building #3	0.059	0.124	0	0.036
Interception of the Ricardo J. Alfaro and Transistmica roads	0.101	0.305	0.04	0.058
Belisario Porras Park	0.079	0.142	0.007	0.034
5 de mayo square	0.104	0.143	0	0.037

Figure 8

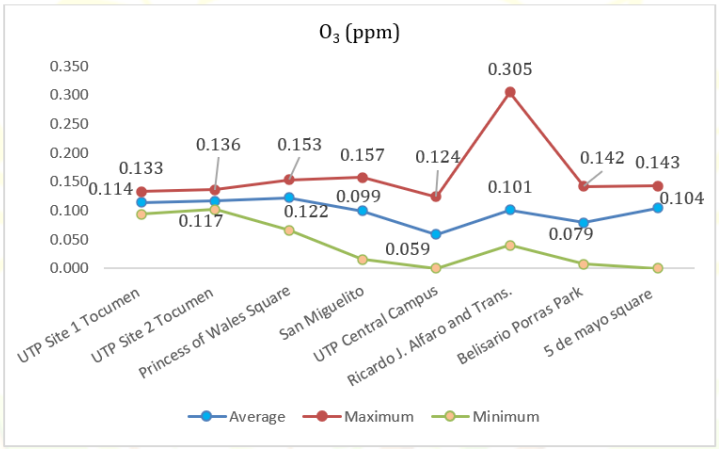

Figure 8 Results of O3 (ppm) of the Evaluated Sites

Regarding O3, all observed average values (0.059-0.122 ppm) are considered high (with respect to guidelines USEPA 0.070 ppm in 8 hours). The highest average value at Princess of Wales Belisario Porras Park site with 0.122 ppm, followed by UTP-Site 2 with 0.177 ppm. For this parameter, Interception of the Ricardo J. Alfaro and Transístmica) site had the highest value with 0.305 ppm. As in the case of NO_2, the lowest ozone value was observed at the Princesa de Gales site, reflecting the beneficial role of natural barriers, such as trees, in controlling air emissions. However, the observed ozone levels, despite being recorded over a short period, demonstrate the occurrence of well-known photochemical processes, which should be the focus of mitigation efforts.

3.4. COMPARISON WITH OTHER REFERENCES:

The present work is only introductory in nature, we can evaluate these results with respect to some references, from regions close to Panama, for example: in Barranquilla, Colombia where PM10 and PM2.5 levels higher than the present work have been found (PM10: 51.4-39.7 µg/m3; PM2.5: 18.1 -15.1 µg/m3) Duarte et al. (2022); Zona Cero. Vehículos y Motos: El Parque Automotor Que Circula En Barranquilla. Zona Cero (2023). Although the vehicle fleet in Panama (649,452, i.e. 72% in the area under study), is almost 4 times larger than in Barranquilla (173,889 vehicles and motorcycles) Duarte et al. (2022), however, the vehicle fleet can be considered relatively new, due to the facilities offered by local car sales brands, and may favor lower emissions of PM10 and PM2.5.

The WHO has air pollution maps for some parameters such as PM2.5 for various regions. In the case of Panama, it reported average levels of 11.89 µg/m3 (8.27-15.14), one of the lowest in the region, which is in accordance with the results obtained for the 8 sites evaluated Table 3, range of average values: 3.4 – 10 µg/m3) World Health Organization. (2021), Global Air Quality Guidelines (2021).

Regarding NO_2 levels, in areas of the Caribbean in Colombia, average values of 19.92 ± 11.50 µg/m^3 have been reported, with a maximum and minimum of 70.27 and 0.57 µg/m^3, respectively, where it has been correlated with high vehicular traffic. These values are consistent with the average levels observed in the present

work, which range between 9 and 39 ppb, and the maximum value of 66 μg/m^3 Agudelo-Castañeda et al. (2020).

In the case of O3, the high average concentration of O3 obtained (0.059-0.122 ppm or 118-244 μg/m^3), compared to the levels in Barranquilla (35.0-26.6 μg/m3), are mainly attributed to the high vehicular density and local photochemical processes in the environment of each evaluated site, and the influence of meteorological conditions and transport patterns in the study area is not ruled out, as observed in other studies Duarte et al. (2022). O3 levels of up to 200 μg/m3 have been observed in other areas, near the Mediterranean and during summer periods, which is consistent with the results obtained in this work.

4. CONCLUSIONS AND RECOMMENDATIONS

The present work is an initial effort of a group of researchers, whose interest is to contribute to the subject of air quality in Panama, with information obtained from low-cost equipment. The results represent preliminary and punctual data from the evaluated sites. All the selected sites are within an urban environment, and vehicular traffic can be considered as the main source of air pollution generation.

In this sense, the usefulness of the aeroqual sensor to estimate the presence of PM10, PM2.5 and NO2, in the evaluated sites was observed, at relatively low levels, and in the same order of magnitude as that observed in other references, such as those of Purpleair (PurpleAir, n.d.) and the WHO World Health Organization. (2021), Global Air Quality Guidelines (2021), for PM2.5 Agudelo-Castañeda et al. (2020).

Particularly noteworthy are the average levels of O3 observed in most of the sites evaluated, which can be considered high (compared to WHO guidelines), which suggest the existence of photochemical processes, and the presence of chemical precursors derived from high vehicular traffic.

An important aspect is that it is a preliminary evaluation, where it is evident that it is necessary to carry out evaluations with longer times. However, given that there are no air pollution measurement stations in Panama, we hope with this work, to incite greater efforts and support in the community and authorities, for the development of studies with greater solidity.

CONFLICT OF INTERESTS

None.

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