Revista Brasileira de Geografia Física v.16, n.6 (2023) 3168-3188.

Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage: https://periodicos.ufpe.br/revistas/rbgfe

Analysis of Air Quality in the Metropolitan Region of Recife, Pernambuco

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Artigo submetido em 17/06/2023 e aceito em 19/11/2023

A B S T R A C T
Atmospheric pollution is a global issue that results in the degradation of natural resources, modification of environmental cycles, and the deterioration of public health and well-being. However, air quality monitoring in Brazil, especially in the North and Northeast regions, remains inadequate, making it challenging to address the problem and underscoring the need for research in this area. Accordingly, this study aimed to analyze the air quality in part of the Metropolitan Region of Recife, in Pernambuco, using data from five monitoring stations from 2017 to 2021. The study employed criteria set by environmental agencies, federal legislation, and meteorological variables for representativeness. It was observed that only 557,921 (50.92%) of the hourly concentrations over the five-year period were available for analysis, and of these, 507,383 were considered representative. Pollutant behavior varied throughout the week, with the highest variability rate recorded for NO_2 (46.33%) at the CPRH station and the lowest for O_3 (1.66%) at the Gaibu station. Despite the majority of concentrations falling below the levels established by legislation, there were 221 days when emission criteria were not met, resulting in moderate (98.19%), poor (0.45%), very poor (0.91%), and extremely poor (0.45%) air quality. An analysis of wind patterns indicated that these cases may be associated with port, industrial, commercial, and recreational activities. Thus, air quality varies depending on the activities conducted in each area, highlighting the need for monitoring and regulation.
Keywords: Atmospheric pollution; Monitoring station; Air quality index

Análise da Qualidade do Ar na Região Metropolitana do Recife, Pernambuco

R E S U M O
A poluição atmosférica é uma problemática mundial que resulta na degradação dos recursos naturais, modificação dos ciclos ambientais e precarização da saúde e do bem-estar da população. No entanto, o monitoramento da qualidade do ar no Brasil, principalmente nas regiões Norte e Nordeste, ainda é precário, dificultando o enfrentamento do problema e evidenciando a necessidade de estudos na área. Dessa forma, este estudo teve como objetivo analisar a qualidade do ar de parte da Região Metropolitana do Recife, em Pernambuco, através de cinco estações de monitoramento no período de 2017 a 2021. Para isso, utilizou-se de critérios de representatividade de órgãos ambientais, legislação federal e variáveis meteorológicas. A partir disso, foi observado que apenas 557.921 (50,92%) das concentrações horárias nos cinco anos de estudo estavam disponíveis para consulta e destas, 507.383 puderam ser consideradas representativas. O comportamento dos poluentes ao longo da semana variou, com maior taxa de variabilidade registrada pelo NO_2 (46,33%) na Estação CPRH e menor pelo O_3 (1,66%) na Estação Gaibu. Apesar da maioria das concentrações apresentarem valores abaixo dos estabelecidos em legislação, houve 221 dias nos quais os critérios de emissão não foram atendidos, resultando em qualidade do ar moderada (98,19%), ruim (0,45%), muito ruim (0,91%) e péssima (0,45%). Ao analisar o regime dos ventos, observou-se que esses casos podem estar associados às movimentações portuárias, industriais, comerciais e de lazer. Assim, a qualidade do ar irá variar de acordo com as atividades desenvolvidas em cada local, evidenciando a necessidade de monitoramento e fiscalização.
Palavras-chave: Poluição atmosférica; Estação de monitoramento; Índice da qualidade do ar

Introduction

The primary sources of environmental pollution arise from anthropogenic activities, with vehicular emissions and industrial processes being the most common contributors to air pollution in large cities (Seibert et al., 2022). Exposure to these pollutants can vary among different socio-economic and age groups (Requia et al., 2021), and the inequality in environmental quality among populations negatively impacts the equity between health and the environment, serving as a determining factor (Requia et al., 2022).

The concentration of industries in a single area can accelerate the depletion of natural resources, leading to a high degree of environmental degradation if improvement measures are not implemented. Additionally, pollutant behavior varies depending on atmospheric circulation and wind patterns, which can exacerbate air quality issues due to prior local pollution (Hao et al., 2022).

Among the major industrial processes contributing to atmospheric degradation, the petrochemical industry stands out due to its numerous associated risks, often requiring stringent control standards. Due to the diverse processes involved in this type of industry, pollutants such as particulate matter (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2) and volatile organic compounds (VOCs) can be emitted (Lin et al., 2021). Among these elements, sulfur dioxide (SO_2) is a particularly significant pollutant from this activity (Chen et al., 2018). In addition, NO_x and VOCs deserve special attention, as they not only have intrinsic health implications but also play a crucial role in the photochemical reaction responsible for the formation of the secondary pollutant ozone (O_3). Furthermore, the constituents of VOCs are essential, as they can contribute to either more intense or milder O_3 formation (Guo et al., 2022a; Mu et al., 2023).

However, it is important to note that while the petrochemical industry has the potential to be a major source of atmospheric degradation, other nearby emitting sources can also play a significant role in this issue (Chen et al., 2018), such as industries clustered in industrial and port complexes. Estimates of port emissions indicate that ship maneuvers during loading or unloading and docking, due to high vessel traffic, can generate substantial amounts of PM_{10}. Additionally, the need for continuous energy generation during the lengthy loading and unloading process causes pollutants to accumulate in the same area for many hours, impacting air quality (Kwon, 2022).

In Pernambuco, the transportation of products arriving at or departing from ports is carried out by trucks using the road network. The primary trucks used are heavy-duty vehicles fueled by diesel, which are among the largest contributors to air pollution in port activities (Park, 2022). These vehicles release significant amounts of $PM_{2.5}$, CO_2, NO_x (Zhang et al., 2021), and SO_2, characteristic of diesel vehicles (Oliveira et al., 2019). Besides the mentioned operations, ships themselves are also sources of pollutants, emitting substantial quantities of SO_2 along with PM and NO_x (Toscano et al., 2021; Zhou et al., 2022).

In the Governador Eraldo Gueiros Industrial Port Complex, better known as the Suape Industrial Port Complex (SIPC) in Pernambuco, some industries use natural gas as fuel, such as thermal power and chemical industries producing polyethylene thermoplastic polymers. Others, like food industries producing margarine and vegetable oil refining, use liquefied petroleum gas (LPG) as a combustion source. Emission rates of PM, SO_2, NO_x, and CO from these specific point sources are low, possibly due to the efficiency of the fuel combustion process. Additionally, concentrations are estimated to decrease as one moves away from the emission source due to wind action (Nunes, 2017).

The United Nations Environment Programme highlights that air pollution is responsible for approximately 7 million deaths, with 90% of the world's population breathing air with pollutant levels exceeding the limits set by the World Health Organization (WHO) (United Nations [UN], 2021). The consequences of exposure to air pollutants can be felt in the short, medium, and long term, with a growing link to hospitalization and mortality rates. Studies indicate that exposure to air pollutants can increase the incidence of respiratory diseases in children (Liao et al., 2020) and that these pollutants can contribute to the spread of viral particles and an increase in mortality rates (Ho et al., 2021; Maleki et al., 2021).

Another extensively discussed aspect over the decades is the influence of air pollution on climate change and environmental imbalance. High levels of pollutant emissions directly affect the greenhouse effect, disrupting natural Earth cycles and influencing weather patterns. Changes in climate patterns, such as temperature rise, precipitation events, and alterations in wind speed, can impact pollutant concentration levels (Coelho et al., 2021), closing the cycle of impacts.

Differences in meteorological conditions and activities between Brazilian regions affect air quality differently (Coker et al., 2022; Requia et al., 2023; Rocha & Sant'Anna, 2022; Will et al., 2022). Additionally, geographic and topographic factors can also play a role, with coastal and more open areas benefiting from pollutant dispersion (Hu et al., 2021), while locations with physical barriers hinder dispersion and are more susceptible to intense pollution episodes (Guo et al., 2022b). Given Brazil's vast size and diverse biomes and geographical features, differences in air quality are more evident. Therefore, the development of specific public policies for monitoring and controlling air quality in each locality can assist in prevention and mitigation of impacts, ensuring that each reality is adequately addressed (Castelhano et al., 2022).

The implementation of policies and actions, coupled with financial investment to improve air quality, results in significant gains (Han et al., 2022). Thus, it is essential that air quality monitoring is conducted to track pollutant concentrations and assist decision-making. For this purpose, it is indispensable that responsible environmental agencies disseminate information correctly and regularly, providing support to the government and enabling the population to protect themselves (Vormittag et al., 2021).

In Brazil, both air quality legislation and monitoring remain inadequate (Andreão et al., 2018), with only 1.7% of municipalities having monitoring stations (Requia et al., 2021), and their frequency is inconsistent (Requia et al., 2022). This situation is particularly prevalent in the Northern and Northeastern regions, where no states in the North have monitoring stations, and only three in the Northeast do (Institute of Energy and Environment [IEMA], 2023), despite the evident adverse effects of this problem. Across the country, only ten states and the Federal District have air quality monitoring stations, including Pernambuco. Some of these states provide real-time data, while others only provide annual reports (IEMA, 2021).

The scarcity of monitoring stations and data from the few existing stations hampers management and oversight, resulting in inefficient problem-solving. This issue underscores the need for studies to be conducted to contribute to monitoring, assist in the decision-making process for preventive and corrective measures, and promote environmental improvement and better quality of life, especially in areas with potential polluting activities, such as major urban and industrial centers.

Thus, this study aimed to analyze air quality by studying five air quality monitoring stations located in the Metropolitan Region of Recife (MRR), Pernambuco, from 2017 to 2021. The study involved an analysis of data representativeness, concentration value frequency, pollutant behavior over the days of the week, air quality characterization, instances of exceeding legal limits, and their relationship with meteorological aspects.

Material e methods

Study Area

Five automatic air quality monitoring stations were analyzed (Figure 1), located in the municipalities of Ipojuca and Cabo de Santo Agostinho. These areas have a humid tropical (Am) and hot and humid tropical (As) climate classification according to the Köppen system (Alvares et al., 2013). They are coastal areas and belong to the MRR in the state of Pernambuco.

The monitoring network is situated near the SIPC, state and federal highways, residential urban areas, mangrove areas, tourist beaches, and environmental protection zones. SIPC houses the Port of Suape and numerous industries involved in various sectors. Among the major enterprises located there are the Abreu e Lima Refinery, Petroquímica Suape, pharmaceutical, chemical, food, energy generation, logistics, and liquid and gaseous bulk industries.

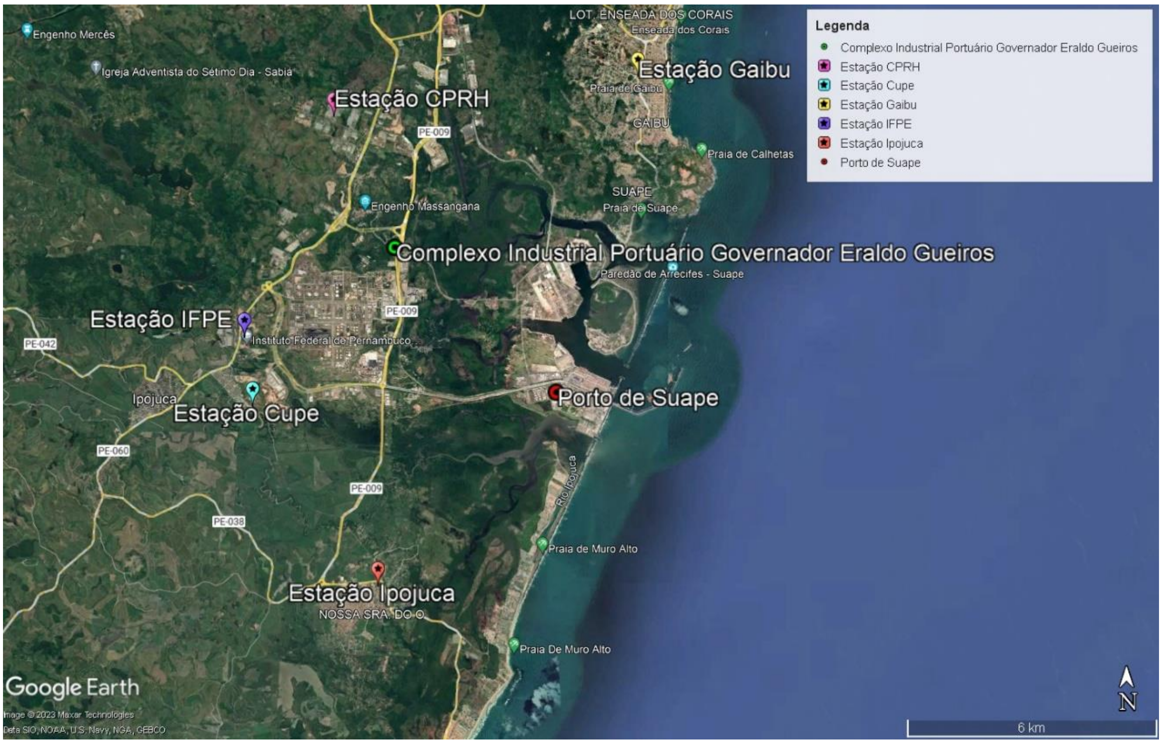


Figure 1. Location of Air Quality Monitoring Stations (Adapted from Google Earth, 2023)

In February 2023, the state had five active stations (CPRH, Cupe, IFPE, Ipojuca, and Suape) and one inactive (Gaibu). The monitoring network is financially supported by Petrobras as part of the environmental licensing requirement for the Abreu e Lima Refinery's operation, and the data are monitored online and in real-time by the State Environmental Agency (CPRH) to ensure compliance with legal standards. Although not all information is available for public consultation, emissions of $PM_{2.5}$, PM_{10}, SO_2, O_3, CO, hydrogen sulfide (H_2S), ammonia (NH_3), non-methane hydrocarbons (NCH_4), methane (CH_4), total hydrocarbons (HCT), NO, NO_2, and NO_x are monitored (CPRH, 2023).

During the research, data for public consultation were published annually in the subsequent year on the IEMA Air Quality Platform. Except for the Suape Station, which was activated in 2022 and therefore did not have sufficient data available at the time of the research, all stations were analyzed, including Gaibu. Each station provides hourly average concentration values for five pollutants: CO, PM_{10}, NO_2, O_3, and SO_2. The research covered the years from 2017, the earliest available data, to 2021, the most recent data. The Gaibu Station was deactivated in 2020 when the Cupe Station began operations, resulting in a different analysis period for both (Chart 1).

Chart 1. Location and analysis period of the treated monitoring stations (CPRH, 2023)

Station	Status	Municipality	Geographical coordinates	Analysis period
CPRH	Active	Cabo de Santo Agostinho	8º 20’ 15,47” S 35º 1’ 19,82” W	2017 - 2021
Cupe	Active	Ipojuca	8º 23’ 58,56” S 35º 2’ 23,29” W	2020 - 2021
Gaibu	Inactive	Cabo de Santo Agostinho	8º 19’ 44,37” S 34º 57’ 22,66” W	2017 - 2020
IFPE	Active	Ipojuca	8º 23’ 5,45” S 35º 2’ 29,61” W	2017 - 2021
Ipojuca	Active	Ipojuca	8º 26’ 17,20” S 35º 0’ 45,43” W	2017 - 2021

Data Source and Treatment

Data on the analyzed pollutants are provided by CPRH to the IEMA Air Quality Platform (2023). CO concentrations are presented in parts per million (ppm), and concentrations of the other pollutants are in micrograms per cubic meter (µg/m³). The database released offers information from August 2017 to December 2021. However, there are several gaps in the presentation of data due to the lack of information for numerous hours, days, and months. Therefore, to ensure data quality, concentrations that had negative or zero values were disregarded, and the representativeness criterion (Chart 2) of the Environmental Company of the State of São Paulo (Cetesb, 2022) was used to assess the daily, monthly, and annual representativeness of available concentrations.

Chart 2. Criteria for representativeness (Cetesb, 2022)

Annual average	1/2 of the valid daily averages for the four-month periods January-April, May-August, and September-December
Monthly average	2/3 of the valid daily averages in the month
Daily average	2/3 of the valid hourly averages in the day

Based on the conducted analyses, a significant information gap was observed. For the study period, only 557,921 (50.92%) of the raw hourly concentrations were available, and after data cleaning and applying the mentioned criterion, there was a 9.06% reduction in the amount of information (Table 1).

Table 1. Number of available raw and representative hourly concentrations

Year	Raw concentrations	Representative concentrations
2017	68,960	64,466
2018	128,295	119,987
2019	114,016	103,838
2020	94,963	79,322
2021	151,687	139,770
Total	557,921	507,383

The monthly representativeness analysis also yielded flawed results. The worst case occurred for NO_2 at the IFPE Station in 2020, where only two months were considered relevant. There were no cases where all months could be considered representative, and the best scenarios occurred in 2021, where all stations had between two and five pollutants with 11 relevant months.

For the annual analysis of the five pollutants (Chart 3), most stations only met the Cetesb criterion in 2021. For five of these cases, 2018 could also be considered representative.

Chart 3. Annual pollutant representativeness by Station

	CO	MP_{10}	NO_2	O_3	SO_2
CPRH	2021	---	2021	2021	2021
Cupe	2021	2021	2021	2021	2021
Gaibu	---	---	---	---	2019
IFPE	2021	2018	2018 and 2021	2018 and 2021	2018 and 2021
Ipojuca	2021	2021	2021	2018 and 2021	2018 and 2021

Based on the observed representativeness, the air quality for each pollutant at each station and each year was examined, and whether concentrations exceeded the values established in the legislation for each day was assessed. The followed regulation (Table 2) was Conama Resolution No. 491 of 2018, which is used as a basis by CPRH to monitor and regulate emissions in Pernambuco. The standard used was the final standard (PF), as although the intermediate standard 1 (PI-1) came into effect upon the publication of the Resolution, and the other standards should be implemented subsequently, Conama did not set a final deadline for compliance. Furthermore, the values adopted in the PF are the same as those established by WHO in 2005. For

CO and O_3, an 8-hour rolling average is calculated, and the maximum value obtained in the day is analyzed according to the PF. For PM_{10} and SO_2, the daily arithmetic mean is considered. For NO_2, the hourly mean is used. The Air Quality Index (AQI) is dimensionless and classifies air quality into five categories, ranging from good, moderate, poor, very poor, and extremely poor (Table 3). These categories can also be dimensionally related to the average concentrations of each pollutant. Concentrations exceeding the PF were compared with meteorological factors to analyze the relationship between them.

Table 2. National air quality standards (Adapted from Conama Resolution No. 491 of 2018)

Pollutant	Reference period	PI-1	PI-2	PI-3	PF
CO (ppm)	8 hours	---	---	---	9
MP_{10} (µg/m³)	24 hours	120	100	75	50
NO_2 (µg/m³)	1 hour	260	240	220	200
O_3 (µg/m³)	8 hours	140	130	120	100
SO_2 (µg/m³)	24 hours	125	50	30	20

Table 3. Final emission Standard and Air Quality Index for CO, PM_{10}, NO_2, O_3, and SO_2 (Conama Resolution No. 491 of 2018)

		Mean concentrations				
Quality	Index	MP_{10} (in 24h)	O_3 (in 8h)	CO (in 8h)	NO_2 (in 1h)	SO_2 (in 24h)
Good	0 - 40	0 - 50	0 - 100	0 - 9	0 - 200	0 - 20
Moderate	41 - 80	> 50 - 100	> 100 - 130	> 9 - 11	> 200 - 240	> 20 - 40
Poor	81 - 120	> 100 - 150	> 130 - 160	> 11 - 13	> 240 - 320	> 40 - 365
Very poor	121 - 200	> 150 - 250	> 160 - 200	> 13 - 15	> 320 - 1130	> 365 - 800
Extremely poor	> 200	> 250	> 200	> 15	> 1130	> 800

The distribution of raw concentrations was analyzed using histograms. To better observe the frequency behavior of these data, the number of classes was standardized, as there is a large variability among concentration values for different pollutants.

The study also examined how average concentrations behave over the days of the week. Since the raw CO concentrations are mostly below 01 ppm, and those of SO_2 are below 10 µg/m³, the curves for these pollutants were not representative compared to other pollutants. Therefore, it was necessary to multiply the CO data by 100 and the SO_2 data by 10 to better observe the curves due to the large variability in the raw concentration values.

Meteorological information was obtained from ERA5-Land Reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) via the COPERNICUS platform, extracted from the latitude -8.38 and longitude -35.02 point. Data on temperature, dew point temperature, relative humidity, sea-level pressure, wind direction, and wind speed were extracted. Further information about the data can be found in the ECMWF documentation (2022).

Results and discussion

It was possible to observe that the majority of CO concentrations (Figure 2 a-e) are below 1 ppm and more frequently fall within the range of 0.2 to 0.7 ppm. The highest concentration values for this pollutant were more frequently found at the CPRH Station (Figure 2a), with several cases of hourly concentrations exceeding 0.8 ppm. These values were also observed at the Cupe and Ipojuca Stations (Figures 2b and 2e).

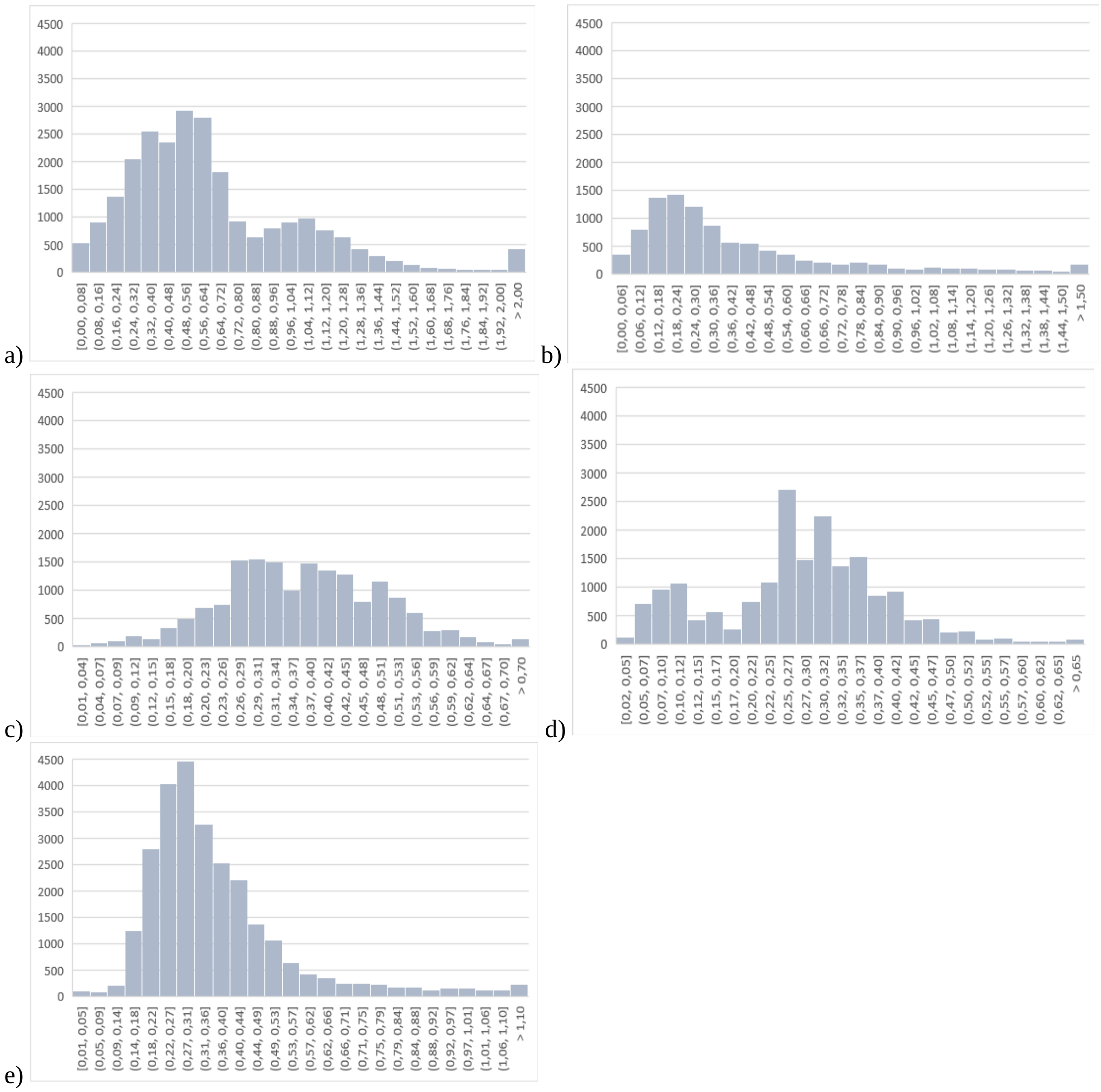


Figure 2. Histograms of hourly CO concentrations in ppm for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) stations from 2017 to 2021

Although PM_{10} (Figure 3 a-e) has higher quantities of concentrations with values below 35 µg/m³, this pollutant exhibits a considerable frequency of events with concentrations exceeding this value, especially at the Gaibu Station (Figure 3c). Higher concentrations can also be seen at the CPRH (Figure 3a), similar to CO, and IFPE (Figure 3d) Stations.

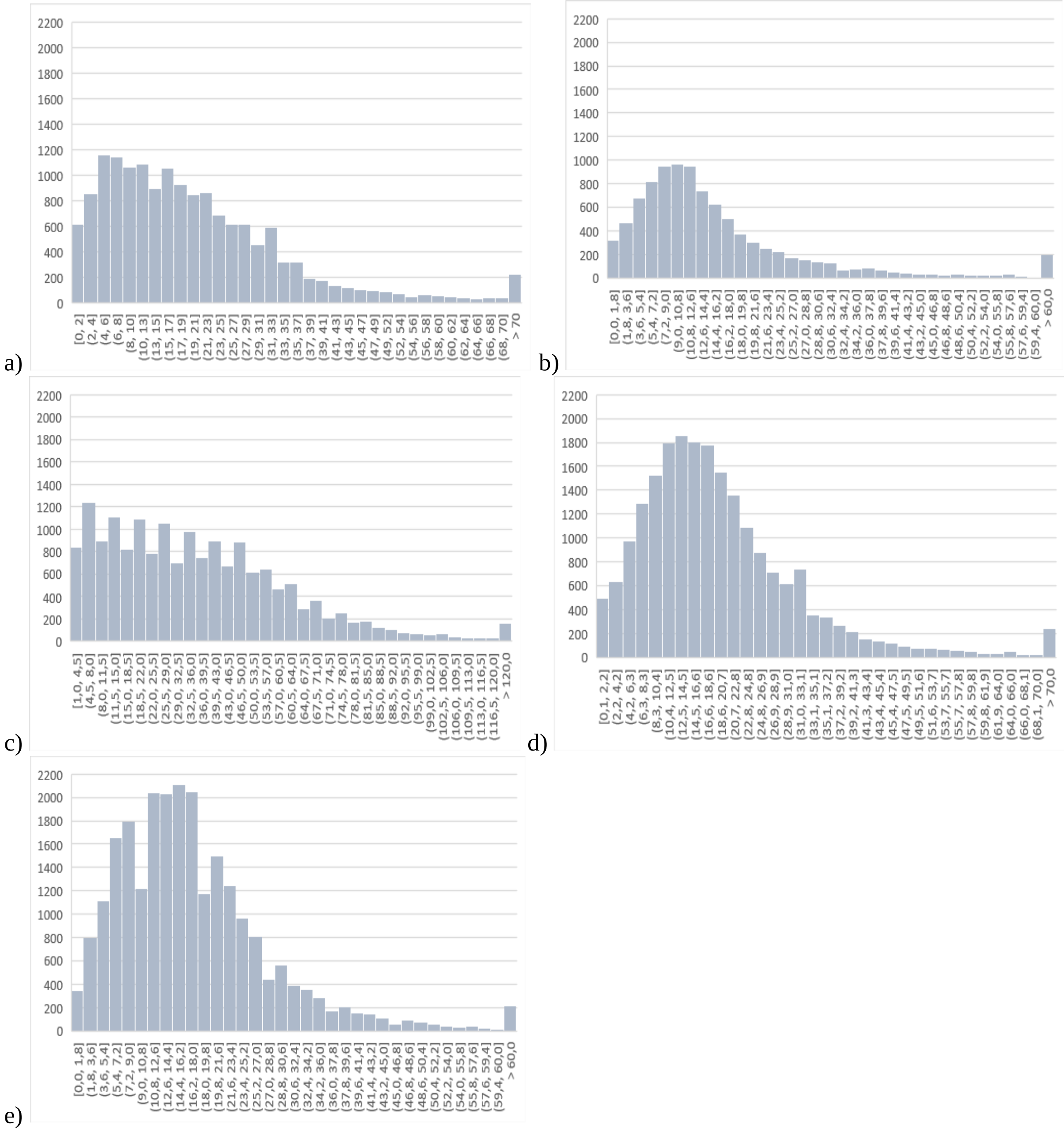


Figure 3. Histograms of hourly PM_{10} concentrations in µg/m³ for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) stations from 2017 to 2021

The distribution is more uniform for NO_2 (Figure 4 a-e), and despite hourly concentrations exceeding 20 µg/m³, the majority do not exceed this value. However, in cases where this value was exceeded, it occurred more frequently at the CPRH, Gaibu, and IFPE Stations (Figures 4a, 4c, and 4d), similar to MP_{10}.

a) b) c) d) e)

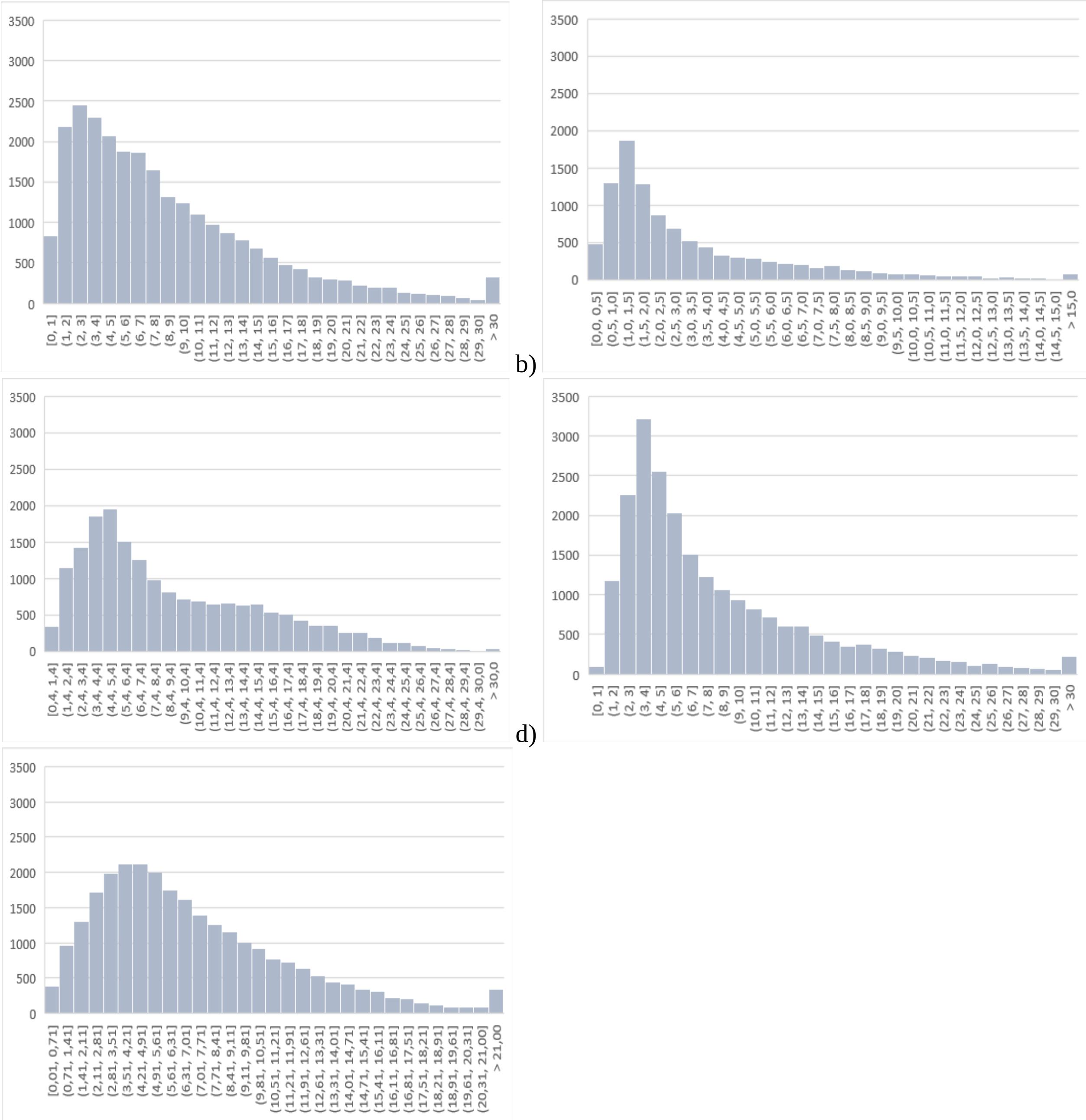


Figure 4. Histograms of hourly NO_2 concentrations in µg/m³ for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) stations from 2017 to 2021

Similar to NO_2, the O_3 histogram (Figure 5 a-e) shows some uniformity in the distribution, with most of the hourly concentrations below 60 µg/m³. Cases of concentrations above this value were more frequently observed at the Cupe and Ipojuca Stations (Figures 5b and 5e), similar to CO, and IFPE Station (Figure 5d), similar to MP_{10} and NO_2.

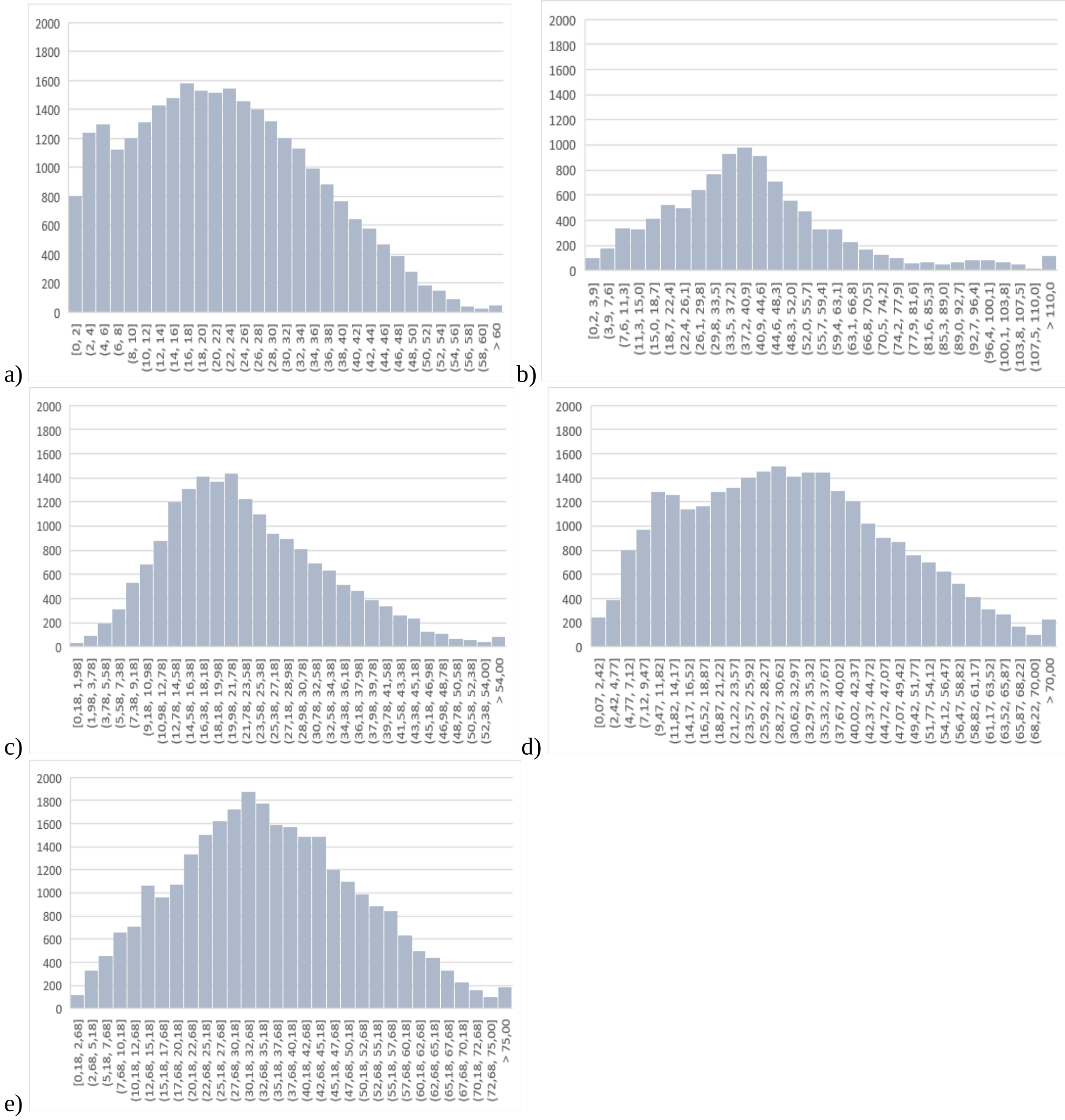


Figure 5. Histograms of hourly O_3 concentrations in µg/m³ for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) stations from 2017 to 2021

SO_2 (Figure 6 a-e), on the other hand, exhibits greater variability depending on the station. At the CPRH Station (Figure 6a), for example, the highest frequency is at concentrations below 6 µg/m³. At the Cupe Station (Figure 6b), there is a large number of values between 0.8 and 2.4 µg/m³ and 4.0 and 4.8 µg/m³. Beyond this range, concentrations drop, and uniformity occurs at approximately 9 to 18 µg/m³. The greatest stability of this pollutant can be observed at the Gaibu Station (Figure 6c). The highest concentrations were found at the Cupe and Ipojuca Stations (Figures 6b and 6e), similar to CO and O_3.

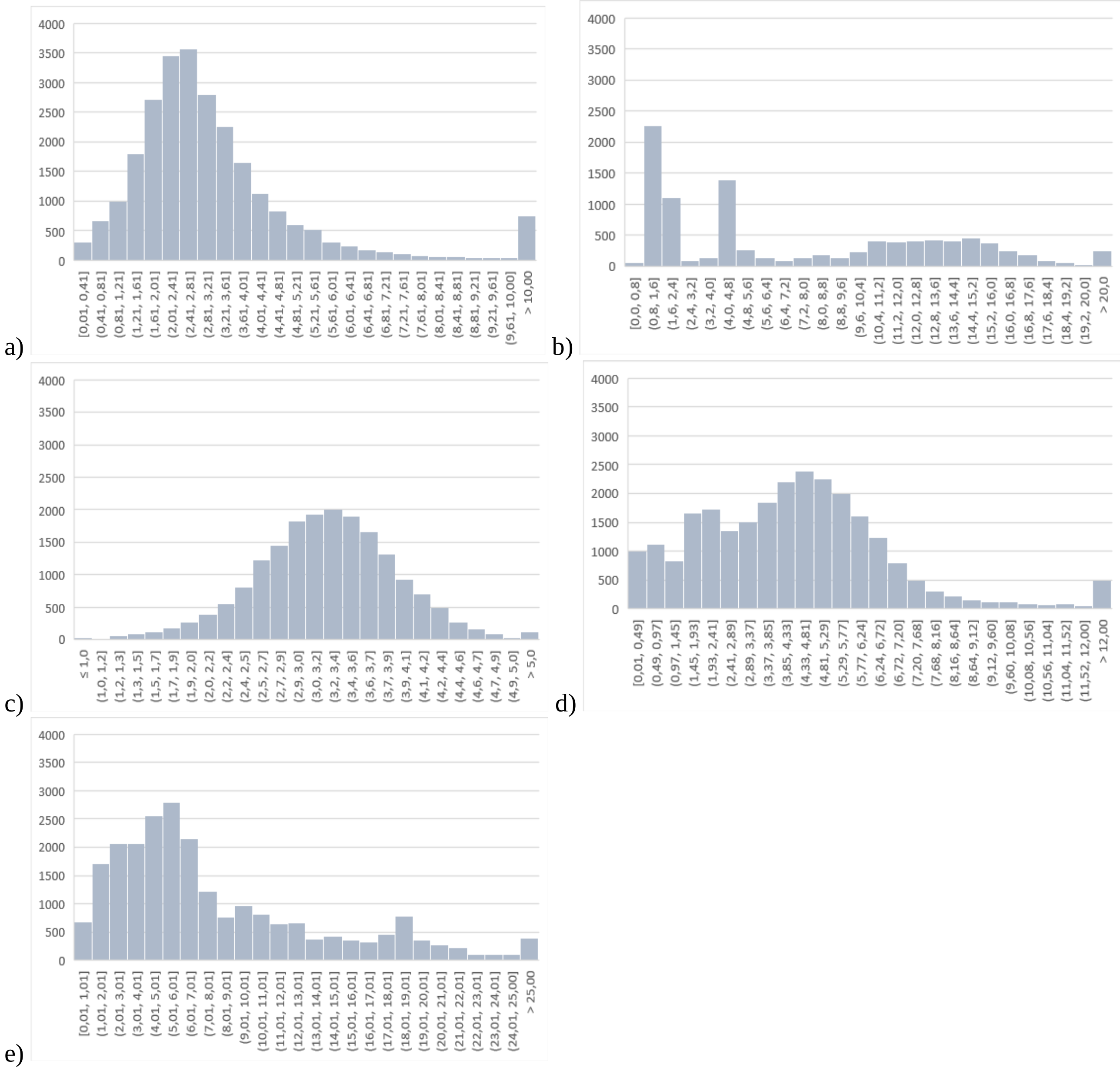


Figure 6. Histograms of hourly SO_2 concentrations in µg/m³ for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) stations from 2017 to 2021

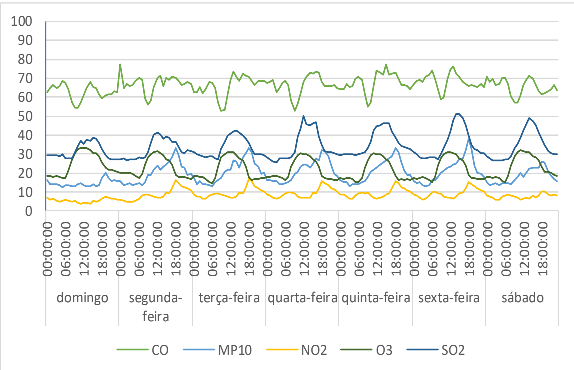
In the graphical representation of pollutants on the days of the week (Figure 7 a-e), in order for the curves to be more representative and variations could be better analyzed, the hourly concentrations of CO and SO_2 were multiplied by 100 and 10, respectively. The concentrations presented in Table 4 are in their original order of magnitude. From this information, it was observed that in the studied area, there is some variability in the behavior of pollutants between weekdays and weekends (Figure 7 a-e and Table 4). In all cases, the greatest variation, in terms of percentage, occurred at the CPRH Station (Figure 7a).

For CO, the largest difference was 0.056 ppm, with the highest average concentration observed on Friday and the lowest on Sunday. This difference corresponds to 8.32% of the overall average CO concentration at the CPRH Station, which was 0.661 ppm. The smallest difference (0.008 ppm) for this pollutant occurred at the Ipojuca Station (Figure 7e), corresponding to 2.12% of the overall average of 0.366 ppm. MP_{10} showed a larger difference of 6.906 µg/m³, with the highest average concentration on Friday and the lowest on Sunday, similar to CO. This difference represents 35.03% of the overall average MP_{10} concentration at the CPRH Station, which is 19.717 µg/m³. The smallest difference for this pollutant was 1.516 µg/m³ at the Cupe Station (Figure 7b), corresponding to 9.61% of 15.770 µg/m³.

NO_2, on the other hand, showed the most significant difference of all pollutants at 3.945

µg/m³, corresponding to 46.33% of the overall average of 8.514 µg/m³, with the highest average concentration recorded on Wednesday and the lowest on Sunday. This pollutant showed the smallest difference in average concentration of 0.570 µg/m³ at the Cupe Station (Figure 7b), corresponding to a decrease of 17.15% in the overall average concentration of 3.322 µg/m³. However, the smallest variability occurred at the Gaibu Station (Figure 7c), with a difference in average concentration of 0.980 µg/m³ and 10.62% of the overall average of 9.232 µg/m³. O_3 showed the largest difference in concentration at the Cupe Station (4.425 µg/m³, 10.67%) (Figure 7b). However, the highest rate was also observed at the CPRH Station (Figure 7a), as for all pollutants, with a difference in average concentration of 3.568 µg/m³, corresponding to 15.99% of the overall average of 22.307 µg/m³. This pollutant showed the highest average concentration on Sunday and the lowest on Thursday. Like NO_2, the lowest variability for ozone occurred at the Gaibu Station (Figure 7c), with a difference in average concentration of 0.383 µg/m³ and a corresponding rate of 1.66% of 23.041 µg/m³.

Finally, SO_2 showed behavior similar to O_3, with greater variability in average concentration at the Cupe Station (0.877 µg/m³, 11.44%) (Figure 7b) and a greater rate of decrease at the CPRH Station (Figure 7a), with a difference in average concentration of 0.436 µg/m³ and a corresponding rate of 12.91% of the overall average of 3.381 µg/m³. The highest average concentration occurred on Thursday and the lowest on Sunday. For the lowest variability of this pollutant, there was similarity with NO_2 and O_3, occurring at the Gaibu Station (Figure 7c), with a difference in average concentration of 0.086 µg/m³ and a drop rate of 2.64% of the overall average of 3.244 µg/m³.



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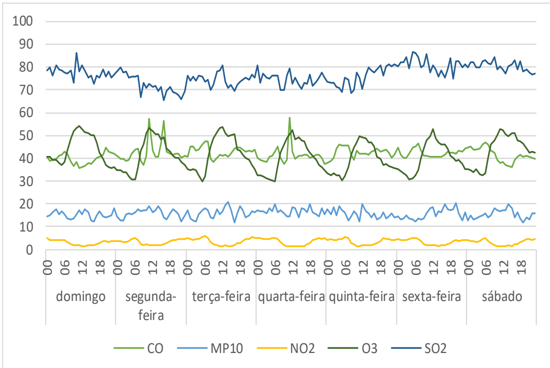

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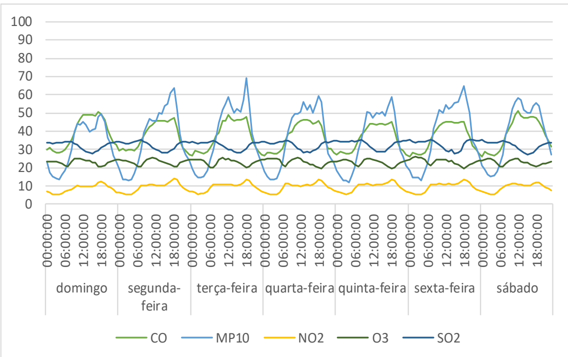

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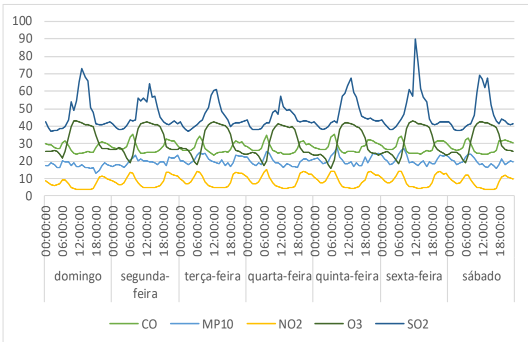

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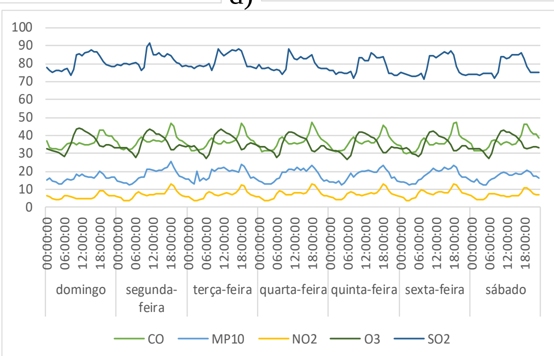


e)

Figure 7. Pollutant behavior across days of the week at CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) Stations from 2017 to 2021

Table 4. Average concentrations of CO (ppm), PM_{10} (µg/m³), NO_2 (µg/m³), O_3 (µg/m³), and SO_2 (µg/m³) during the days of the week at CPRH, Cupe, Gaibu, IFPE, and Ipojuca Stations from 2017 to 2021

	CO	MP_{10}	NO_2	O_3	SO_2
CPRH Station					
Sunday	0.626	14.565	5.497	24.615	3.144
Monday	0.672	20.451	8.791	22.609	3.262
Tuesday	0.658	20.946	9.412	21.651	3.328
Wednesday	0.663	21.165	9.442	21.539	3.420
Thursday	0.676	20.866	9.378	21.047	3.580
Friday	0.681	21.471	9.298	21.646	3.514
Saturday	0.655	18.213	7.683	23.047	3.412
Overall average	0.661	19.717	8.514	22.307	3.381
Cupe Station					
Sunday	0.398	15.250	3.017	43.842	7.765
Monday	0.426	15.815	3.246	41.392	7.221
Tuesday	0.431	16.031	3.587	41.998	7.452
Wednesday	0.413	16.766	3.477	40.056	7.468
Thursday	0.426	15.674	3.484	39.417	7.565
Friday	0.423	15.517	3.311	40.108	8.097
Saturday	0.415	15.358	3.125	43.437	8.029
Overall average	0.419	15.770	3.322	41.473	7.663
Gaibu Station					
Sunday	0.391	32.625	8.575	23.054	3.219
Monday	0.372	36.831	9.201	23.090	3.226
Tuesday	0.372	38.515	9.400	23.041	3.227
Wednesday	0.370	36.884	9.329	23.062	3.241
Thursday	0.361	35.216	9.442	22.884	3.296
Friday	0.369	39.395	9.556	23.267	3.289
Saturday	0.390	38.815	9.128	22.890	3.211
Overall average	0.375	36.924	9.232	23.041	3.244
IFPE Station					
Sunday	0.278	17.210	6.751	32.315	4.700
Monday	0.283	19.621	8.393	31.891	4.616
Tuesday	0.277	20.608	8.759	31.272	4.484
Wednesday	0.275	19.543	8.815	30.101	4.413
Thursday	0.284	20.828	9.012	29.847	4.713
Friday	0.280	20.859	8.783	31.053	4.895
Saturday	0.280	19.431	7.765	31.379	4.665
Overall average	0.280	19.721	8.327	31.125	4.641
Ipojuca Station					
Sunday	0.362	16.283	5.862	35.726	8.041
Monday	0.370	17.938	7.224	35.545	8.197
Tuesday	0.366	18.656	7.142	35.493	8.167
Wednesday	0.367	17.982	7.437	34.878	7.981
Thursday	0.364	17.678	7.354	34.046	7.809
Friday	0.363	17.751	7.832	34.626	7.827
Saturday	0.369	16.897	6.786	35.228	7.822
Overall average	0.366	17.594	7.084	35.078	7.975

It is possible that these results are linked to activities conducted near the monitoring network. On weekdays, for example, there is a significant flow of both large and small vehicles due to SIPC operations. On weekends, however, the flow is due to the tourist beaches located nearby, such as Muro Alto, Calhetas, Enseada dos Corais, and Porto de Galinhas, which may explain the low variability shown by CO. Regarding industries, they may have reduced or interrupted activities on weekends, which could explain the greater decrease in emissions of MP_{10} and NO_2. Another relevant point is that the Port operates without interruptions, operating 24 hours a day, every day of the year. This can favor the low decrease in SO_2 emissions, a pollutant characteristic of diesel-based combustion processes, such as ships and heavy vehicles transporting products arriving or departing from the Port, as in ports, the emission of this pollutant may be more related to shipping and port operations than other activities on-site (Song et al., 2022).

These indicators are similar to those observed in studies that indicate that in more urbanized areas, pollutant emissions are more prominent during weekdays (Monday to Friday) than on weekends (Saturday and Sunday) (Almeida et al., 2019; Castelhano & Pinto, 2022; Oliveira et al., 2019; Tsai et al., 2021; Zou et al., 2019). This phenomenon is referred to as the weekend effect, characterized by higher concentrations of most pollutants during weekdays, while O_3 exhibits emission peaks on weekends (Ceglinski et al., 2022). These variations may be related to the reduction in commercial and school activities on weekends, resulting in a lower flow of people leaving their homes during this period. As a result, vehicle emissions and activities that release pollutants into the environment are reduced, leading to lower levels of air pollution than on weekdays. On the other hand, when commercial and industrial activities are constant and uninterrupted, the emission of pollutants can also be constant. Furthermore, it is common for the population to seek cultural and leisure activities outside urban centers during weekends, often choosing nearby coastal areas, which can increase vehicular traffic (Ceglinski et al., 2022; Tavella et al., 2023). Thus, the behavior of the population and local economic activities has a significant influence on the pattern exhibited by pollutants. In other words, each location will exhibit characteristics consistent with the practices carried out.

In addition to local practices, wind patterns may influence how each station is affected by this dynamism. When analyzing wind direction data between 2017 and 2021, it was observed that the prevailing wind direction is mostly southeast, south-southeast, and east-southeast (29.91%, 22.05%, and 19.61%, respectively), with the highest intensity in the range of 3.4 to 5.1 m/s (Figure 8), patterns also verified by Nunes (2017) and indicating favorable pollutant dispersion in the area.

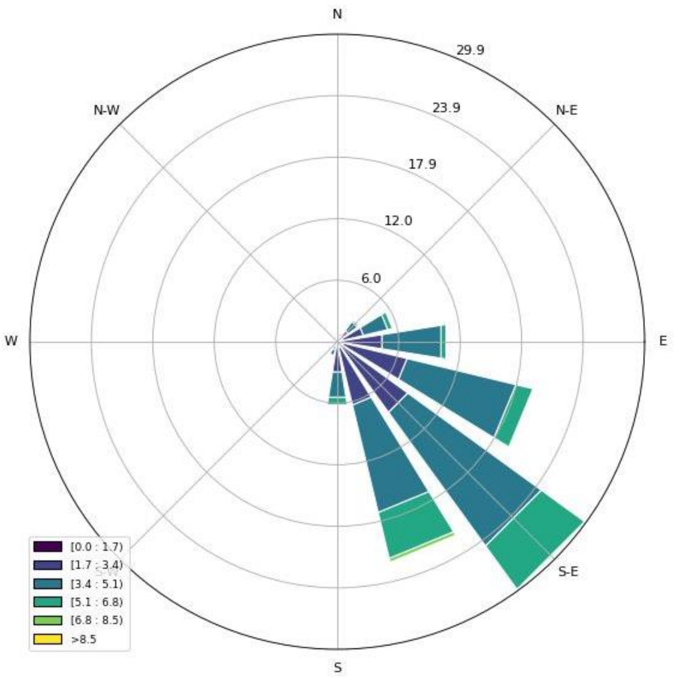


Figure 8. Relative wind frequencies from 2017 to 2021

According to the predominant wind direction observed at the CPRH, Gaibu, and IFPE Stations (Figures 9a, 9c, and 9d), most pollutants appear to originate from the SIPC area. For the

Cupe and Ipojuca Stations (Figures 9b and 9e), emissions may also have an additional influence from highways, urban areas, and the ocean.

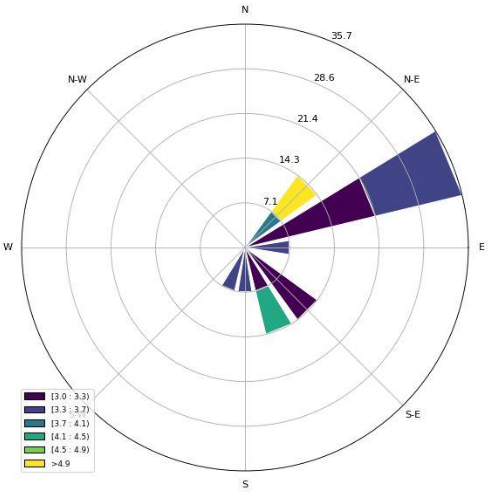
From representative data, cases in which the established legal limits were exceeded were calculated. For CO and O_3, the maximum daily average obtained was observed, calculated every 8 hours. For MP_{10} and SO_2, daily averages were considered. And for NO_2, hourly averages were considered. The adopted limit values were the PFs established by Resolution Conama No. 491/2018 (Table 2).

Following these criteria, 221 exceedance events were observed over the 5 years of analysis. During this period, CO exceeded the limits 3 times (1.36%); MP_{10}, 132 times (59.73%); NO_2, 1 time (0.45%); O_3, 26 times (11.76%); and SO_2, 59 times (26.70%). These cases occurred 11 times (4.98%) at the CPRH Station; 39 times (17.65%) at the Cupe Station; 110 times (49.77%) at the Gaibu Station; 16 times (7.24%) at the IFPE Station; and 45 times (20.36%) at the Ipojuca Station. In 2017, 16 (7.24%) of the 221 exceedance situations were observed; in 2018, 32 (14.48%); in 2019, 64 (28.96%); in 2020, 54 (24.43%); and in 2021, 55 (24.89%) of the situations were observed. In addition to the PF, some pollutants also exceeded intermediate standards, which are more lenient, such as MP_{10}, NO_2, and SO_2, the PI-3, and O_3, the PI-1.

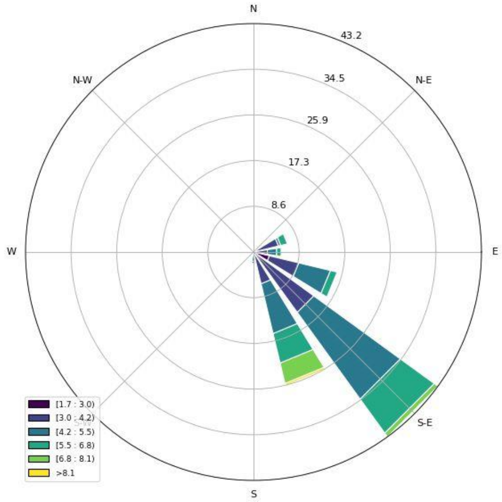
The highest exceedance values found for each of the pollutants on a daily basis were 20.31 ppm for CO on 06/07/2021; 99.59 µg/m³ for MP_{10} on 05/14/2019; 233.83 µg/m³ for NO_2 on 10/21/2017; 179.83 µg/m³ for O_3 on 10/31/2021; and 31.28 µg/m³ for SO_2 on 12/24/2021. According to the air quality criteria established by Resolution Conama No. 491/2018 based on PFs (Table 3), these days had extremely poor, moderate, moderate, very poor, and moderate air quality, respectively. Taking into account the 221 events in which concentrations exceeded the PFs, 98.19% had moderate air quality, 0.45% poor, 0.91% very poor, and 0.45% extremely poor. Extremely poor air quality implies worsening of various symptoms, such as dry cough, shortness of breath, and wheezing, with more severe effects on more vulnerable groups such as children, the elderly, and people with respiratory and heart diseases (Ministry of the Environment [MMA], 2019). Despite the legal instruments imposing emission limits, it is discussed that the established standards could be lower, so that the impacts are even smaller, especially on mortality rates. Thus, it is possible that there may be economic, environmental, and human health gains (Andreão & Albuquerque, 2021).

If all CO and O_3 moving averages are analyzed instead of just the daily maximum obtained, the total number of exceedance events increases from 221 to 412 events. Considering this scenario, wind directions were calculated for each station at times when the limits were exceeded. Thus, for these occasions, the predominant wind direction at the CPRH Station (Figure 9a) was east-northeast (35.7%); at the Cupe and Gaibu Stations (Figures 9b and 9c), southeast (43.2% and 37.0%, respectively); at IFPE Station (Figure 9d), east (25%), with a value close to that found for the northeast, east-northeast, east-southeast, and southeast directions (18.75% each); and at Ipojuca Station (Figure 9e), with a predominance of east-southeast (26.7%).

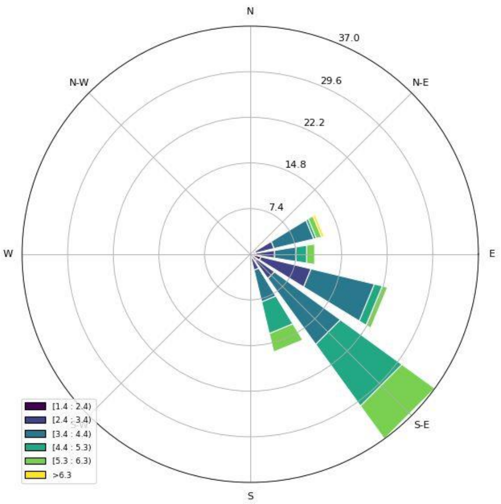
The main wind direction at the IFPE Station (Figure 9d) in cases of PF non-compliance coincides with the location of SIPC. The other directions observed for this station, which are equally distributed, are in the same direction as some SIPC industries, as well as urban areas, roads, and the ocean. In the other stations (Figures 9a, 9b, 9c, and 9e), exceedance events appear to be related to urbanized areas, highways, and beaches such as Muro Alto, Porto de Galinhas, Calhetas, Gaibu, and Enseada dos Corais. At the Cupe Station, O_3 was the pollutant that exceeded the PF the most (66.67%), and it was the only station in which the criterion for this pollutant was not met.



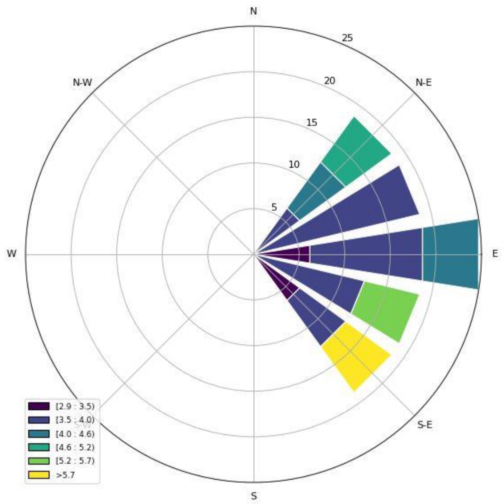
a)



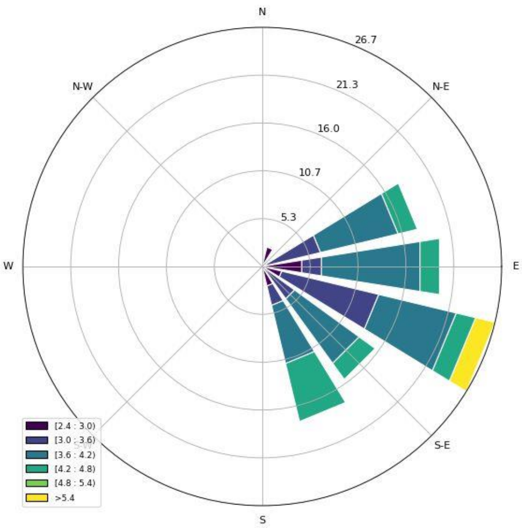
b)



c)



d)



e)

Figure 9. Wind rose diagrams for CPRH (a), Cupe (b), Gaibu (c), IFPE (d), and Ipojuca (e) Stations for cases of exceedance of limits from 2017 to 2021

It is possible that the high concentrations of O_3 observed may be related to vehicular exhaust and industrial sources, which can play a significant role in environmental contamination due to emissions of primary pollutants such as VOCs and NO_x (Zheng et al., 2023). Additionally, it may also be related to nitrogen oxide emissions from ships and port activities (Toscano et al., 2021; Song et al., 2022; Zhang et al., 2022; Zhou et al., 2022). This is because diesel engines are capable of emitting large quantities of NO_x (Deng et al., 2021), which can linger in the shipping traffic routes and influence O_3 formation (Sim et al., 2022). These hypotheses are consistent with the observed wind patterns (Figure 9b), which show winds originating from urban areas, highways, and the beach and ocean.

Conclusion

In Pernambuco, there are only six monitoring stations, with one of them being inactive and five operational, distributed across two of the 185 municipalities in the state. The newest of these stations, the Suape Station, was installed only in the year 2022. Furthermore, in the publicly available database, there is a significant lack of information. During the analyzed period, between the years 2017 and 2021, only 557,921 (50.92%) of the raw hourly concentrations were available, and out of these, 507,383 could be considered representative according to the criteria adopted by Cetesb, highlighting the data gap. Based on this information, the behavior of hourly concentrations of CO, MP_{10}, NO_2, O_3, and SO_2 at the CPRH, Cupe, Gaibu, IFPE, and Ipojuca Stations could be analyzed, and it was observed that most of these concentrations are below the levels necessary to exceed the limits established by legislation.

The performance of the studied pollutants throughout the days of the week (weekdays and weekends) exhibited considerable variability. The highest variation rates occurred at the CPRH Station for all pollutants, with NO_2 showing the most significant variation of 46.33%. In contrast, the lowest variation was 1.66% for O_3 at the Gaibu Station. Differences in pollutant concentrations throughout the days of the week may have been influenced by activities conducted near the monitoring network, whether commercial through the SIPC or recreational, owing to the beaches with a high influx of people during weekends. Regarding commercial emissions, the SIPC houses the Port of Suape and various industries, including petrochemical, pharmaceutical, chemical, food, energy generation, logistics, and bulk liquid and gas facilities. These enterprises can be significant sources of atmospheric pollution, with emissions occurring through both production and storage processes, as well as fuel combustion. Port activities such as ship maneuvering, docking, loading, unloading, and product transport can also emit significant quantities of contaminants. Although some of these industries may have reduced or interrupted operations during weekends, the Port operates continuously. Furthermore, there are several beaches near the facility that people visit for leisure during weekends, offsetting the vehicle traffic. Thus, the proximity of these activities to the monitoring network can influence the concentrations measured by the equipment.

Despite the majority of concentrations not exceeding the PF established by Resolution Conama No. 491 of 2018, 221 exceedance events occurred, resulting in moderate (98.19%), poor (0.45%), very poor (0.91%), and extremely poor (0.45%) air quality. The Gaibu Station had the highest number of exceedance events, with 110 cases (49.77%), all related to MP_{10}, and all with moderate air quality. The pollutant with the most significant number of exceedances was MP_{10}, which exceeded the limit 132 times (59.73%), all indicating moderate air quality. Based on the analysis of wind direction, it was observed that at the IFPE Station, most of the situations where legal criteria are violated have eastward winds (25%), where the SIPC is located, recognized as a significant source of pollutant emissions in the region. For the other stations, the predominant wind direction is associated with urban areas, highways, and beaches, and it may also be linked to emissions from ships arriving or departing from the Port of Suape.

Due to the distinct behavior of pollutants observed in relation to the activities conducted, there is a clear need to improve and expand the air quality monitoring network in both Pernambuco and nationally. Additionally, there is an emphasis on the necessity of maintaining and making data more widely available for future studies. In this way, all realities can be addressed, and preventive and mitigation measures can be taken to ensure environmental quality and the well-being of the population.

Acknowledgment

The current study was conducted with the support of the Coordination for the Improvement of

Higher Education Personnel (CAPES) - Financing Code 001, from Brazil.

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