

Article

A Pilot Study with Low-Cost Sensors: Seasonal Variation of Particulate Matter Ratios and Their Relationship with Meteorological Conditions in Rio Grande, Brazil

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Abstract: (1) Background: This study investigated seasonal variations in particulate matter (PM) ratios ($PM_1/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and PM_1/PM_{10}) and their relationship with the meteorological conditions in Rio Grande, Brazil. (2) Methods: PM_1 , $PM_{2.5}$, and PM_{10} levels were collected using low-cost Gaia Air Quality Monitors, which measured PM concentrations at high temporal resolution. Meteorological variables, including atmospheric pressure, temperature, relative humidity, wind speed, and precipitation, were obtained from the National Institute of Meteorology (INMET). The data were analyzed through multiple linear regression to assess the influence of meteorological factors on PM ratios. (3) Results: The results show that the highest PM ratios occurred in winter, indicating a predominance of fine and ultrafine particles, while the lowest ratios were observed in spring and summer. Multiple linear regression analysis identified atmospheric pressure, wind speed, and maximum temperature as the key drivers of PM distribution. (4) Conclusions: This study highlights the importance of continuous monitoring of PM ratios, particularly PM_1 , which remains underexplored in Brazil. The findings underscore the need for targeted air quality policies emphasizing seasonal mitigation strategies and improved pollution control to minimize the health risks associated with fine and ultrafine PM exposure.

Keywords: particulate matter; air pollution; seasonality; meteorological influences; air quality monitoring

1. Introduction

Atmospheric pollutants, in both the short and long term, contribute to climate change, posing an ongoing threat to human health [1]. The exacerbation of the adverse effects on individuals as a result of these changes [2,3] creates an alarming scenario where, on average, 13 individuals die every minute due to exposure to these compounds [1]. While greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) are primarily associated with

climate change, other regulated pollutants—including ozone (O₃), carbon monoxide (CO), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), and particulate matter (PM₁₀ and PM_{2.5})—are critical due to their direct impacts on human health [4].

Particulate matter (PM) consists of a combination of solid particles and liquid droplets of varying sizes, such as PM₁₀ and PM_{2.5} [5], primarily formed by volatile organic compounds, nitrogen oxides, and sulfur dioxide. The major emission sources include vehicular activity, soil dust resuspension, industrial activity, and biomass burning [6]. Particulate matter significantly affects human health, causing respiratory diseases, oxidative stress, mortality, cardiovascular diseases [7–9], cerebrovascular conditions, and psychological disorders [10–12].

The presence of high levels of particulate matter (PM₁₀), along with other pollutants and elevated temperatures, leads to a significant increase in cardiovascular event (CVE) emergencies. Seasonality also plays a crucial role, particularly during autumn, when asthma-related emergencies are heightened due to increased concentrations of PM₁₀, PM_{2.5}, and NO_x in the atmosphere [2,3]. Smaller fractions of particulate matter such as PM_{2.5} raise concerns due to their ability to penetrate deeply into the lungs, potentially reaching the bloodstream and impacting cardiovascular and respiratory health. There is also growing evidence of their effects on brain health, including an increased risk of stroke, dementia, neurodevelopmental disorders, cognitive impairment, Parkinson's disease, depression, and other related conditions [10]. Numerous studies associate particle pollution exposure with various health issues, including premature death, heart attacks, aggravated asthma, and reduced lung function [13,14]. Ultrafine fractions (PM₁), on the other hand, remain little studied, although it is likely that the severity of PM_{2.5}'s impact is associated with a higher proportion of particles smaller than 1 µm in diameter [15].

A crucial metric for identifying the origin of particulate matter is the ratio between the particle concentrations [16–19]. These ratios are useful for characterizing pollution sources, as particles of different sizes originate from a diverse range of emission sources. Higher PM_{2.5}/PM₁₀ ratios indicate particulate pollution predominantly of anthropogenic origin, whereas lower ratios point to a greater contribution of coarse particles, often associated with natural sources [16,20]. Although some studies suggest that PM₁ is more strongly associated with certain diseases compared to PM_{2.5} and PM₁₀, research specifically focused on these ultrafine particles remains scarce [21], as does research exploring its contribution in relation to larger fractions.

Beyond the sources, atmospheric conditions exert a great influence on the dynamics of particulate matter, including the deposition, transport, or dispersion of pollutants [22]. However, the relationship between meteorological variables and the ratio between the different fractions of particulate matter is location-dependent [23], and knowledge of this is of fundamental importance to support pollution control strategies and mitigation policies.

Air pollution studies using data from automatic monitoring stations are difficult in regions with little air quality monitoring coverage, as is the case in Brazil. It is estimated that fewer than 2% of Brazilian municipalities have some type of air quality monitoring system [24], and for this reason, the use of low-cost sensors has gained importance in these locations. As an alternative, low-cost sensors, such as Gaia Air Quality Monitors, can be implemented in areas lacking monitoring stations. These devices can measure multiple pollutants and meteorological variables depending on the version of the equipment. Brazil has diverse sources of air pollutants, reflected in their composition and dynamics [5,16]. Furthermore, factors such as GDP, city size, and economic activities influence particulate matter ratios [25,26]. Rio Grande is a medium-sized municipality located in the extreme south of Brazil and is considered a hot spot for air pollution studies due to

its strong industrial complex dominated by fertilizer, petrochemical, chemical, and food industries [16].

Gaia Air Quality Monitors specifically utilize three redundant PMS5003 sensors, which are known for their higher accuracy and reliability compared to other particulate matter sensors commonly used in low-cost air quality monitoring devices [27]. The PMS5003 sensor is designed to measure particulate matter concentrations (PM_{10} , $PM_{2.5}$, and PM_{10}) with improved precision, making it a popular choice for research applications [28,29]. Its reliability is further supported by its use in scientific studies [30–33]. Additionally, the redundancy of three sensors in this monitor enhances data accuracy by cross-validating the measurements, reducing the likelihood of errors or outliers.

This study aims to evaluate the ratio between different sizes of particulate matter and its relationship with meteorological variables, while also considering seasonality as an important factor for investigation, in a medium-sized municipality influenced by an industrial complex in the extreme south of Brazil.

2. Materials and Methods

2.1. Study Area

The data collection was conducted in Rio Grande, a city in the state of Rio Grande do Sul, Brazil, with an approximate population of 191,900 inhabitants [34]. The city's primary economic activities include fishing, port activities, and the production of fertilizers and chemicals. Rio Grande features a significant maritime port, with major exports including agricultural and industrial products [35,36]. The Ar do Sul Project, an initiative by the Environmental Health Research Group at the Federal University of Rio Grande (FURG), aims to advance air quality research and monitoring in southern Brazil. The project focuses on understanding the impacts of air pollution on human health and the environment, particularly in regions with limited data, such as small and medium-sized cities [37]. The monitoring station is located at Miguel de Castro Moreira, Rio Grande, Immediate Geographic Region of Pelotas, Urban Agglomeration of the South, Rio Grande do Sul, South Region, 96211-694, Brazil. The distance between the monitoring station and the industrial hub is approximately 20 km, and the distance between the monitoring station and the weather monitor is approximately 21 km; this information and possible sources of pollution are provided in Figure 1. The data were collected between October 2023 and September 2024 and subsequently stratified by seasons. This period was selected because data collection began only in 2023, and entries that did not fully represent an entire preceding or subsequent season within the chosen timeframe were excluded from the study.

2.2. Data Collection

The data collection methodology involved the use of a singular low-cost and publicly accessible air pollutant monitoring equipment known as Gaia Air Quality Monitor Model A12, featuring three redundant PMS5003 sensors, developed by Earth Sensing Labs. Depending on the equipment version, the measurable parameters include O_3 , relative humidity (%), temperature ($^{\circ}C$), PM_{10} , $PM_{2.5}$, and PM_1 . In our specific case, the equipment did not possess O_3 sensors. This equipment uses light-scattering technology, with a laser operating at 680 nm with a detection limit of 300 nm, and a fan that blows air through it at 0.1 L min^{-1} [38]. The equipment makes reliable measurements and comes pre-assembled and pre-calibrated at the factory [39]. The publicly available data comprise daily medians, with pollutant measurements expressed in $\mu\text{g}/\text{m}^3$. Specific guidelines must be followed when installing the equipment: the monitoring station should be mounted at a minimum height of 1.5 m to prevent dust resuspension caused by human activity near the station, and

it must be located at least 10 m away from the nearest roadway, in line with the guidelines provided in the equipment manual. For this specific case, the data were collected at intervals ranging from 1 to 3 min, a configuration made possible through administrative access to the device. Public access to the low-cost sensor network can be found at the following website: waqi.info [40].

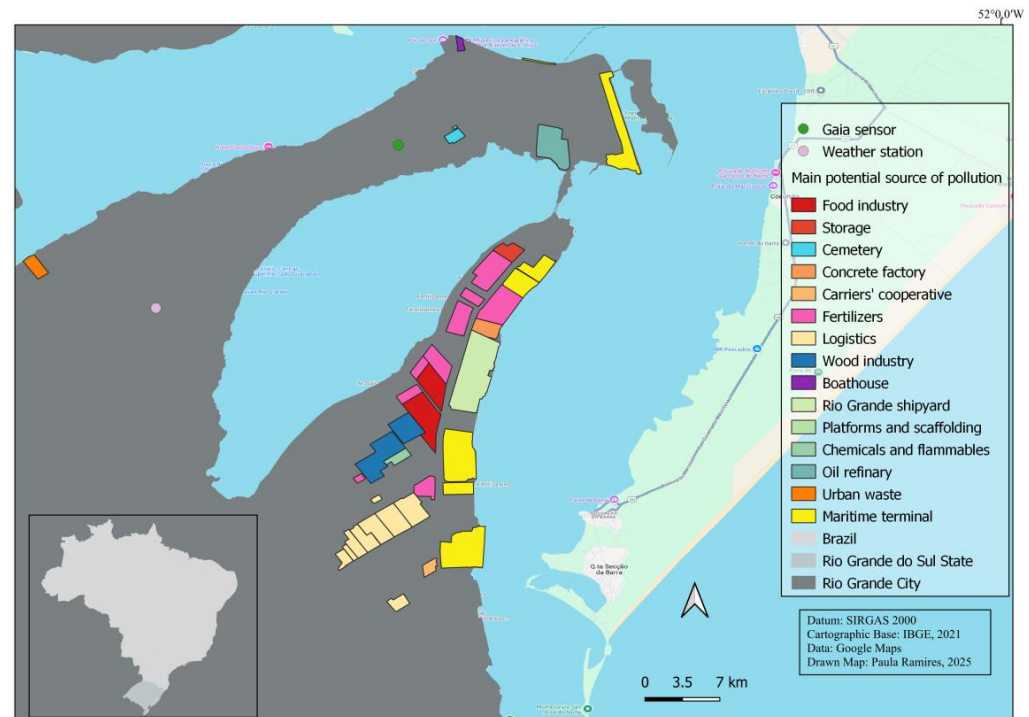


Figure 1. Location of the low-cost sensor, weather station, and main potential source of pollution.

Meteorological variables provided by the National Institute of Meteorology (INMET) platform were used because they are a reliable source of climate and weather information in Brazil. INMET operates a nationwide network of automatic weather stations, which collect and make available real-time and historical meteorological data. The variables included in this study were total precipitation (mm), average atmospheric pressure (Mb), average temperature (°C), maximum temperature (°C) (AUT), average relative humidity (%), and average wind speed (m/s). These parameters, recorded as daily averages, served as independent variables, and the particulate matter ratios PM_1/PM_{10} , $PM_1/PM_{2.5}$, and $PM_{2.5}/PM_{10}$ were analyzed as dependent variables for the multiple linear regression analysis present in this study.

2.3. Data Analysis

For each pollutant evaluated (PM_{10} , $PM_{2.5}$, and PM_1), the calculation of the ratios between respective pollutants ($PM_{2.5}/PM_{10}$, PM_1/PM_{10} , and $PM_1/PM_{2.5}$) was performed. These ratios range from 0 to 1, as particulate matter of smaller diameters (numerator) is always included within the larger diameter fractions (denominator). Consequently, readings resulting in a ratio greater than 1 were discarded, as were any cases of negative readings. After this analysis, the data were stratified across different seasons to capture the seasonal variations and understand the relationships between the seasons and the particulate matter levels.

To assess potential multicollinearity among the independent variables, we computed the variance inflation factor (VIF) for each predictor. None of the variables exhibited VIF values exceeding the critical threshold of 10, indicating that severe multicollinearity was not present in our dataset. The normality of the residuals was evaluated using the Shapiro–Wilk

test, as well as visual inspections of histograms and Q–Q plots. The results confirmed that the residuals followed an approximately normal distribution. Additionally, we assessed homoscedasticity (constant variance of errors) by examining residual plots against fitted values, which did not reveal any systematic patterns suggesting heteroscedasticity.

The initial data analysis was conducted using the Microsoft Office Excel spreadsheet software. For the association analysis, multiple linear regression was employed, with the dependent variables being the ratios PM_1/PM_{10} , $PM_{2.5}/PM_{10}$, and $PM_1/PM_{2.5}$ and the independent variables encompassing all of the meteorological data mentioned earlier. All analyses were performed using STATISTICA software, version 12.5, and the seasonal variation graph was created using GraphPad Prism 8 software.

3. Results

For each PM ratio, the total number of discarded readings—including those with ratios exceeding 1 and negative values—accounted for less than 10% of the total dataset. Specifically, discarded readings represented 9.05% for the $PM_{2.5}/PM_{10}$ ratio, 7.07% for $PM_1/PM_{2.5}$, and 6.26% for PM_1/PM_{10} . These relatively low percentages indicate a high level of data reliability and consistency across the measurements.

The R^2 values ranged from 0.26 to 0.71, indicating that the climatic determinants explained a moderate to substantial proportion of the PM variability. Additionally, the adjusted R^2 values ranged from -0.03 to 0.57, accounting for the number of predictors and providing a more robust assessment of model fit. All of these metrics are statistically significant.

The seasonal distribution of PM_1 , $PM_{2.5}$, and PM_{10} concentrations shown in Table 1 highlights notable variations across the year. Winter consistently exhibited the highest average concentrations for all particulate matter sizes, with PM_1 at $8.79 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ at $13.70 \mu\text{g}/\text{m}^3$, and PM_{10} at $15.82 \mu\text{g}/\text{m}^3$, accompanied by higher maximum values. Conversely, the lowest values were observed during spring and summer, particularly for PM_1 and PM_{10} , with summer showing the smallest average concentrations.

Table 1. Seasonal statistics for PM_1 , $PM_{2.5}$, and PM_{10} concentrations, including annual averages, standard deviations, and maximum and minimum values.

Season	Average ($\mu\text{g}/\text{m}^3$)	Standard Deviation ($\mu\text{g}/\text{m}^3$)	Maximum ($\mu\text{g}/\text{m}^3$)
PM_1			
Annual	5.66	4.87	402.97
Spring	3.88	2.91	125.24
Summer	3.25	2.27	118.00
Autumn	6.14	4.81	239.29
Winter	8.79	5.99	402.97
$PM_{2.5}$			
Annual	8.86	7.52	745.02
Spring	6.47	4.74	198.17
Summer	5.28	3.42	164.00
Autumn	9.17	7.24	400.69
Winter	13.70	9.47	745.02
PM_{10}			
Annual	10.22	8.71	861.86
Spring	7.56	5.23	210.75
Summer	6.11	3.61	177.56
Autumn	10.46	8.31	459.24
Winter	15.82	11.27	861.86

Figure 2 shows the proportions between different fractions of particulate matter ($PM_1/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and PM_1/PM_{10}) across the seasons, highlighting their annual and seasonal variability, with higher values in winter and lower values in spring, although the differences are slight. Higher ratios indicate a predominance of fine particles (PM_1 and $PM_{2.5}$) compared to coarse particles (PM_{10}).

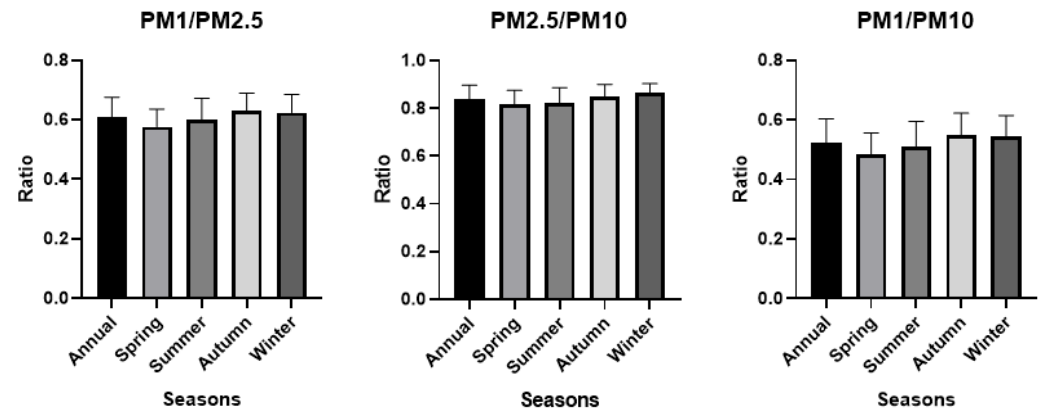


Figure 2. Seasonal variations in particulate matter ratios ($PM_1/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and PM_1/PM_{10}).

A multiple linear regression analysis was conducted to evaluate the influence of meteorological parameters on particulate matter (PM) ratios (PM_1/PM_{10} , $PM_1/PM_{2.5}$, and $PM_{2.5}/PM_{10}$). The independent variables included total precipitation (mm), average atmospheric pressure (Mb), average temperature ($^{\circ}C$), maximum temperature ($^{\circ}C$), average relative humidity (%), and average wind speed (m/s), as shown in Table 2.

Table 2. Multiple linear regression of each season and particulate matter ratio *.

Parameter	Annual	Spring	Summer	Autumn	Winter
$PM_1/PM_{2.5}$					
Total precipitation (mm)	$b = -0.072$ $p = 0.301$	$b = 0.162$ $p = 0.451$	$b = 0.070$ $p = 0.708$	$b = -0.179$ $p = 0.153$	$b = -0.029$ $p = 0.775$
Average atmospheric pressure (Mb)	$b = -0.334$ $p = <0.0001$	$b = -0.173$ $p = 0.513$	$b = 0.015$ $p = 0.942$	$b = -0.465$ $p = 0.001$	$b = -0.296$ $p = 0.014$
Average temperature ($^{\circ}C$)	$b = -2.125$ $p = 0.142$	$b = 0.859$ $p = 0.659$	$b = 0.853$ $p = 0.783$	$b = -3.933$ $p = 0.163$	$b = -3.368$ $p = 0.286$
Maximum temperature (AUT) ($^{\circ}C$)	$b = 0.488$ $p = 0.085$	$b = -0.231$ $p = 0.757$	$b = 0.401$ $p = 0.381$	$b = 0.432$ $p = 0.223$	$b = 0.696$ $p = 0.032$
Average relative humidity (%)	$b = -0.540$ $p = 0.290$	$b = 0.434$ $p = 0.688$	$b = -0.244$ $p = 0.922$	$b = -1.294$ $p = 0.268$	$b = -1.500$ $p = 0.263$
Average wind speed (m/s)	$b = -0.271$ $p = 0.003$	$b = 0.200$ $p = 0.680$	$b = -0.244$ $p = 0.209$	$b = -0.175$ $p = 0.198$	$b = -0.103$ $p = 0.580$
PM_1/PM_{10}					
Total precipitation (mm)	$b = -0.102$ $p = 0.134$	$b = 0.139$ $p = 0.483$	$b = -0.014$ $p = 0.927$	$b = -0.195$ $p = 0.100$	$b = -0.019$ $p = 0.851$
Average atmospheric pressure (Mb)	$b = -0.404$ $p = 0.0001$	$b = -0.173$ $p = 0.480$	$b = -0.074$ $p = 0.663$	$b = -0.553$ $p = <0.0001$	$b = -0.338$ $p = 0.006$
Average temperature ($^{\circ}C$)	$b = -2.322$ $p = 0.100$	$b = 1.553$ $p = 0.391$	$b = 0.294$ $p = 0.908$	$b = -3.968$ $p = 0.137$	$b = -3.025$ $p = 0.340$

Table 2. Cont.

Parameter	Annual	Spring	Summer	Autumn	Winter
Maximum temperature (AUT) (°C)	b = 0.858 p = 0.002	b = 0.460 p = 0.505	b = 0.733 p = 0.058	b = 0.729 p = 0.031	b = 0.836 p = 0.011
Average relative humidity (%)	b = −0.354 p = 0.476	b = 1.310 p = 0.197	b = 0.021 p = 0.992	b = −1.257 p = 0.254	b = −1.237 p = 0.358
Average wind speed (m/s)	b = −0.271 p = 0.002	b = 0.000 p = 0.999	b = −0.581 p = 0.004	b = −0.190 p = 0.139	b = −0.073 p = 0.696
PM _{2.5} /PM ₁₀					
Total precipitation (mm)	b = −0.138 p = 0.036	b = −0.004 p = 0.975	b = −0.197 p = 0.222	b = −0.211 p = 0.065	b = −0.014 p = 0.907
Average atmospheric pressure (Mb)	b = −0.370 p = <0.0001	b = −0.179 p = 0.295	b = −0.232 p = 0.195	b = −0.572 p = <0.0001	b = −0.271 p = 0.046
Average temperature (°C)	b = −1.473 p = 0.278	b = 2.143 p = 0.097	b = −0.385 p = 0.883	b = −1.893 p = 0.456	b = −0.885 p = 0.804
Maximum temperature (AUT) (°C)	b = 1.534 p = 0.0001	b = 1.801 p = 0.001	b = 0.941 p = 0.021	b = 1.403 p = <0.0001	b = 0.957 p = 0.010
Average relative humidity (%)	b = 0.495 p = 0.302	b = 2.580 p = 0.001	b = 0.752 p = 0.723	b = −0.215 p = 0.838	b = 0.140 p = 0.926
Average wind speed (m/s)	b = −0.137 p = 0.102	b = −0.345 p = 0.274	b = −0.244 p = 0.209	b = −0.109 p = 0.373	b = 0.002 p = 0.993

* Significant values ($p < 0.05$) are highlighted in bold.

4. Discussion

In the city of Rio Grande, the ratios between different particulate matter fractions (PM₁/PM_{2.5}, PM_{2.5}/PM₁₀, and PM₁/PM₁₀) exhibited slight variation throughout the year, with a higher proportion of smaller-diameter particles during the colder months. The average PM_{2.5}/PM₁₀ ratio was 0.84, indicating a strong anthropogenic contribution to particulate matter. When analyzing the PM₁/PM₁₀ ratio, it was observed that the proportion of ultrafine particles in the PM exceeded 50% on an annual average and in all seasons, except for spring. High PM ratios, particularly PM_{2.5}/PM₁₀, are often associated with the predominance of fine particulate matter originating from anthropogenic sources, such as combustion processes and industrial emissions [16,41,42]. This result suggests significant contributions from human activities to air pollution, which may have profound health implications [13,43,44].

Fine particles, such as PM_{2.5} and PM₁, can penetrate deep into the respiratory system and enter the bloodstream, exacerbating conditions such as cardiovascular diseases, respiratory disorders, and neurodegenerative diseases [45–48]. A study conducted by Tavella et al. (2023) [49] in the city of Recife, a Brazilian metropolis located in the state of Pernambuco and an important industrial hub housing various sectors, including automotive, pharmaceutical, textile, software, shipbuilding, and oil-refining industries, showed that the daily average PM_{2.5}/PM₁₀ ratio in the years 2020, 2021, and 2022 was 0.52 ± 0.08 , 0.58 ± 0.03 , and 0.58 ± 0.02 , respectively, indicating a relative predominance of fine particulate matter in the PM₁₀ composition. This increase in the PM_{2.5}/PM₁₀ ratio over the years suggests possible changes in emission sources and local conditions, and the impacts of restrictions imposed by the COVID-19 pandemic.

In the study by Espinzona-Guillen et al. (2024) [50] in the Lima-Callao metropolitan region, the ratio between fine and total particulate matter was analyzed from 2015 to 2019, revealing regional differences in emission sources. In downtown Lima, the ratio was higher (0.55), indicating a predominance of vehicular emissions, whereas in the southern

region, it was lower (0.27), suggesting a greater contribution from the resuspension of coarse particles.

On the other hand, the investigation of PM ratios involving ultrafine particles (PM_1) remains significantly underexplored in the scientific literature. While numerous studies have focused on $PM_{2.5}$ and PM_{10} , research specifically targeting the PM_1 ratio—despite its critical implications for human health—is still scarce. This gap is particularly notable given the unique behavior and higher toxicity of ultrafine particles, which can penetrate more deeply into the respiratory system and even enter the bloodstream. The limited availability of data and studies on PM_1 ratios underscores the need for further research in this area, especially in regions with sparse air quality monitoring, such as Brazil. The study by Theodosi et al. (2011) [51], conducted in the Greater Athens region, analyzed the contributions of local and regional sources to fine particulate matter, with measurements of PM_1 , $PM_{2.5}$, and PM_{10} between 2005 and 2006 in urban, suburban, and regional background areas. It was observed that, in winter, local sources were more significant for PM_1 , while in summer, regional sources predominated, with organic matter and elemental carbon being the main components of this fine fraction.

Meanwhile, in the study by Giugliano et al. (2005) [52], multiple monitoring campaigns in Milan investigated PM_1 , $PM_{2.5}$, and PM_{10} at different urban locations with varying levels of traffic exposure. The analyses revealed seasonal and spatial variations in particulate matter concentrations, influenced by both primary emissions and secondary aerosol formation, with up to 75% of $PM_{2.5}$ in winter and 40% in summer being of secondary origin. Both studies highlight the importance of PM_1 , which is often overlooked, and the need for specific strategies to mitigate its formation and dispersion in the atmosphere.

Seasonal variations in PM ratios, although subtle, may reflect changes in atmospheric conditions and emission sources, such as increased biomass burning or vehicular emissions during specific periods. Similar to the present study, Fan et al. (2021) [53] investigated the $PM_{2.5}/PM_{10}$ ratio at different locations in China and found higher ratio values during winter and lower ones during spring, although the ratios in the Chinese study were consistently lower than those observed in the current study. The authors emphasize that colder months tend to have greater atmospheric stagnation, whereas in spring, sandstorms can occur, leading to the suspension of coarser particles.

Understanding local scenarios is essential when studying particulate matter ratios. A study conducted in Bahrain yielded results that contrast sharply with those of the present study. The authors concluded that the $PM_{2.5}/PM_{10}$ ratio was low (0.31), revealing a strong contribution from natural sources to the PM. They also found that the lowest ratios occurred in winter, while the highest values were observed in the warmer months. Finally, in contrast to the present study, temperature was found to be negatively correlated with the $PM_{2.5}/PM_{10}$ ratio, which was attributed to high temperatures and windy conditions [54]. We believe that these findings highlight the influence of the local climatic characteristics of the city, which experiences a humid subtropical climate. This climate is particularly susceptible to thermal inversions, a phenomenon that may provide a plausible explanation for the observed seasonal variations.

In the present study, the main meteorological variables associated with the PM ratios were the atmospheric pressure and the daily maximum temperature. The analysis revealed a negative association between the daily mean atmospheric pressure and all of the particulate matter ratios ($PM_1/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and PM_1/PM_{10}), suggesting that high-pressure conditions reduce the proportion of smaller particles. This can be attributed to atmospheric subsidence, which limits vertical mixing and intensifies pollutant stagnation [55,56].

The temperature also influenced the particulate matter ratios. The daily maximum temperature had a positive effect on the $PM_{2.5}/PM_{10}$ and PM_1/PM_{10} ratios, indicating that higher temperatures are associated with a greater fraction of fine and ultrafine particles. This finding contrasts with several published studies [46,50,57,58] from different parts of the world but aligns with a study conducted in a tropical Brazilian metropolis [16]. A plausible explanation in this case is that thermal processes enhance the secondary formation of fine particles while also aiding in the dispersion of larger particles [59]. Additionally, it is important to note that all seasons and the annual period showed a positive association between $PM_{2.5}/PM_{10}$ and the daily maximum temperature ($^{\circ}C$), indicating that higher heat peaks result in higher ratios, meaning that a larger proportion of the PM consists of fine particulate matter.

Finally, the wind speed played a crucial role in the particulate matter dispersion. Higher average wind speeds were associated with lower $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratios, likely due to the increased dispersion of smaller particles to more distant areas, reducing their local concentration [60].

In addition to investigating particulate matter ratios using low-cost sensors in an unprecedented manner, the present study sheds light on the ultrafine particles present in PM. Although there are no recommended maximum limits for PM_1 , it is known that exposure to low levels of $PM_{2.5}$ (below $5 \mu g/m^3$ annual average) can compromise health [61]. This may occur due to both the chemical composition of PM and the predominant presence of ultrafine particles within $PM_{2.5}$. In the present study, the $PM_1/PM_{2.5}$ ratio was similar to that found in Milan, Italy [62], as well as in western China and Mongolia, but lower than the ratios observed in industrialized China [63].

PM_1 has been identified as a better indicator of vehicular emissions than $PM_{2.5}$ [64], and studies have shown a strong association between this PM fraction and numerous diseases [65–67]. The collection of PM_1 data through low-cost sensors has also been utilized in studies across different contexts [68,69]. However, in Brazil, studies addressing PM_1 quantification remain scarce. A study conducted in the metropolitan region of Porto Alegre concluded that the PM_1 levels ranged between 12.8 and $15.2 \mu g/m^3$, with higher concentrations in winter than in summer and a strong anthropogenic contribution from road traffic, combustion processes, and industrial activities [69]. To the best of our knowledge, this is the first study in Brazil to investigate PM_1 within the context of particulate matter relationships.

The predominance of high ultrafine particle ratios in $PM_1/PM_{2.5}$ and PM_1/PM_{10} during certain times of the year reinforces the need for more detailed monitoring of this fraction, particularly given its health impacts. The lack of PM_1 data in Brazil also highlights the urgency of public policies aimed at controlling this fraction, as well as improving monitoring networks to better assess the risks associated with prolonged exposure to fine and ultrafine particles. This pattern is consistent with findings from other industrial cities, as highlighted in several studies. For example, Xu et al. (2017) [70] observed similar trends in Wuhan, China, where industrial activities contributed to elevated $PM_{2.5}/PM_{10}$ ratios. Similarly, Bamola et al. (2024) [23] and Spandana et al. (2021) [71] reported higher PM ratios in industrial and urban areas, underscoring the influence of anthropogenic sources. In Rio Grande, the city's industrial and port activities—key drivers of the local economy, as reported by the Brazilian Institute of Geography and Statistics (IBGE)—likely contribute to the observed PM ratios. These findings collectively emphasize the importance of addressing industrial emissions in urban air quality management strategies.

The results of this study underscore the need for more robust and adaptive public policies for air quality control, considering the seasonal variations and meteorological conditions that directly influence particulate matter concentrations. The identification of higher

$PM_1/PM_{2.5}$ and $PM_{2.5}/PM_{10}$ ratios during autumn and winter indicates that these periods are particularly critical for public health, requiring heightened surveillance and specific mitigation measures. The implementation of continuous monitoring programs, combined with the use of low-cost sensors for real-time measurements, can provide essential data for more informed and effective decision-making.

Furthermore, green infrastructure strategies, such as increasing urban tree cover, not only improve air quality but also provide additional benefits, such as reducing urban heat islands and enhancing community well-being. Policies restricting the use of fossil fuels, incentives for electric transport, and improvements in industrial processes are essential to reducing emissions, particularly during months with higher fine-particle concentrations. The adoption of integrated actions, such as awareness campaigns, the development of clean technologies, and the strengthening of environmental monitoring networks, are essential steps toward achieving cleaner and safer air for all.

Despite the relevant findings, this study has some limitations that should be considered. The use of low-cost sensors, although widely recognized as a viable alternative for air pollutant monitoring, may present variations in data accuracy compared to reference-grade equipment. Additionally, data for September were removed from the analyses due to a series of wildfire events, which could have interfered with the seasonal behavior of spring. Moreover, the analysis was conducted in a single location, which may limit the generalization of the results to other regions with different meteorological characteristics and pollution sources. Another limitation is that the equipment has a detection limit of 300 nm, which excludes a portion of the readings, particularly those relevant to the collection of ultrafine and fine particulate matter. Furthermore, it was not possible to perform a chemical characterization of the pollutants, which could have provided more precise information about specific emission sources. Future studies should expand the spatial and temporal scope of the analysis, incorporate advanced calibration methods for the sensors used, and include investigations into the health impacts of PM_1 exposure to achieve a more comprehensive understanding of air pollution and its consequences.

5. Conclusions

This study analyzed the ratios between different fractions of particulate matter and their relationship with meteorological variables, highlighting that factors such as atmospheric pressure, temperature, and precipitation influence particle distribution. The $PM_1/PM_{2.5}$, $PM_{2.5}/PM_{10}$, and PM_1/PM_{10} ratios were higher in autumn and winter, indicating a greater concentration of fine particles during these periods, possibly due to reduced atmospheric dispersion and the increased influence of anthropogenic sources. These findings underscore the need for seasonal strategies to mitigate air pollution, including continuous monitoring, emission control, and investments in green infrastructure. Furthermore, the scarcity of studies on PM_1 in Brazil reinforces the importance of future investigations into its composition and health impacts. As such, this research provides valuable insights that will inform future studies and the ongoing development of air quality monitoring infrastructure in the region.

This study highlights significant seasonal variations in particulate matter ratios in Rio Grande, Brazil, where its results have shown high PM ratios overall, calling attention to the need for targeted monitoring and control. Although current Brazilian regulations, such as the CONAMA resolutions, do not establish specific limits for PM_1 , the growing evidence of its health impacts calls for proactive measures. We recommend expanding air quality monitoring networks to include PM_1 , which would provide critical data to inform future regulatory frameworks. Public awareness campaigns can further educate communities about the risks of ultrafine particles and promote behavioral changes. Aligning these efforts

with climate change mitigation strategies, such as promoting renewable energy, can simultaneously reduce particulate emissions and address broader environmental challenges. These recommendations aim to bridge the gap in current regulations and provide a foundation for improving air quality and public health in Brazil.

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