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Impact of the meteorological variables and of restrictions to urban mobility associated with the COVID-19 pandemic on the concentrations of particulate matter (PM_{10})

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A B S T R A C T

This study investigated the association of meteorological parameters with the different periods of urban mobility related to COVID-19, on the PM_{10} concentrations in a small town in Southern Brazil. The particulate matter was monitored during a two-year period from 2019 to 2021, which covered the pre-lockdown, lockdown, and relaxation time phases. The meteorological data and PM_{10} concentrations, monitored using a high-volume air sampler installed in the centre of the town, were implemented in a Generalized Additive Model (GAM) as predictive air pollutant concentration variables. The results indicated that the wind speed and direction did not affect the variation in PM_{10} concentrations. However, the seasons showed a significant influence, with greater PM_{10} concentrations in the winter, due to worse pollutant dispersion conditions. There was a mean reduction of 40% in the PM_{10} concentrations during the lockdown period, corroborating the efficacy of mobility restrictions on air quality. The study concluded that although rainfall and relative humidity interfered significantly with particulate matter concentrations, social mobility and seasons were also preponderant factors with respect to air quality improvements. The study also emphasized the importance of monitoring air pollution in small towns (with no air quality monitoring stations), where the impact of air pollutants on public health can also be significant.
Keywords: Atmospheric pollution, Generalized Additive Model (GAM), SARS-CoV-2, Temporal variability of air pollutants

Impacto das variáveis meteorológicas e das restrições à mobilidade urbana associadas à pandemia de COVID-19 nas concentrações de material particulado (PM10)

R E S U M O

Este estudo investigou a associação de parâmetros meteorológicos e os diferentes períodos de mobilidade urbana relacionados à COVID-19 nas concentrações de MP_{10} em uma cidade de pequeno porte no Sul do Brasil. O monitoramento do material particulado abrangeu um período de dois anos, de 2019 a 2021, que compreendeu as fases de pré-confinamento, confinamento ("lockdown") e período de relaxamento das restrições de mobilidade social. Os dados meteorológicos e as concentrações de MP_{10}, monitoradas com um amostrador de grandes volumes ("high vol") instalado na região central da cidade, foram implementadas em um Modelo Aditivo Generalizado (GAM) como variáveis preditoras das concentrações do poluente monitorado. Os resultados indicaram que a velocidade e a direção do vento não foram significativas na variação das concentrações de MP_{10}. As estações do ano influenciaram significativamente, com maiores concentrações de MP_{10} no inverno, devido às piores condições de dispersão de poluentes. Durante o período de confinamento social, observou-se uma redução média de 40% nas concentrações de MP_{10}, corroborando a eficácia das restrições de mobilidade na qualidade do ar. O estudo concluiu que, embora a precipitação e a umidade relativa interfiram significativamente nas concentrações de particulado, a mobilidade social e as estações do ano também foram fatores preponderantes na melhoria da qualidade do ar. O trabalho destacou ainda a importância de monitorar a poluição do ar

em cidades de pequeno porte (e sem estações de monitoramento de qualidade do ar), onde os impactos de poluentes do ar na saúde pública também podem ser significativos.
Palavras-chave: Modelo Aditivo Generalizado (MAG), Poluição atmosférica, SARS-CoV-2, Variabilidade temporal de poluentes atmosféricos

Introduction

The technical literature has reported the most variable respiratory, cardiac, pulmonary, and neurological problems, some types of cancer and even cognitive diseases, related to atmospheric pollutants (Zhao et al., 2016; Costa et al., 2020; WHO, 2021; Bodor et al., 2022; Odo et al., 2023; USEPA, 2023; Ard et al., 2024; Zhao, 2025). With respect to PM_{10} (inhalable particulates with aerodynamic diameters equal to or less than 10 µm), some studies even have mentioned that, for each increase of 10 µg m^{-3} in the PM_{10} concentration, there is a corresponding 0.6% increase in death rates for cardiovascular and respiratory diseases (Samoli et al., 2008; Zhao et al., 2016). Apart from the aspects directly related to health, some studies emphasize economic impacts resulting from the action of PM_{10} on the organism (Zhao et al., 2016; Giaccherini et al., 2021; Martins et al., 2024). These and other factors "qualify" PM_{10} as an indicator of atmospheric pollution (Zhao et al., 2016).

Particulate matters consist of a complex mixture of contaminants of different chemical (sulphate, nitrate, organic matter, ammonium, metals, etc.) and physical (mineral dust, fog, smoke, soot, resuspended dust, etc.) natures (WHO, 2013; CETESB, 2017). The nature and concentration of PM_{10} can vary a lot as a function of the anthropogenic sources (industries, agricultural practices, vehicles, biomass burning, etc.), and the relief characteristics and meteorological conditions of the monitored location. Parameters such as wind speed and direction, relative humidity, temperature, rainfall, etc. can exert a direct influence on the transport (propagation, sedimentation, etc.) of air pollutants (Wang and He, 2020; Maleki et al. 2021; McMullen et al. 2021). For example, knowledge of the predominant wind speed and direction in the region under evaluation, can be a determinant factor in determining the main sources of the monitored pollutant. Elminir (2005), monitoring PM_{10} in the metropolitan region of Cairo (Egypt) during the whole of 2002, showed that the source of the particulates could vary according to the wind speed: for low wind speeds, traffic was identified as the main factor responsible for high PM concentrations; but on the other hand, for high wind speeds, dust and sand from the desert impacted the PM concentrations monitored with greater intensity. This same study also concluded that just the wind (speed and direction) could not explain the pollutant concentrations observed alone, and that other meteorological parameters should be analysed concomitantly. Rainfall is another key parameter in the removal of PM from the air due to its "washing effect", and the tendency observed by most of the researchers was that the greater the rainfall intensity, the lower the PM concentrations observed (Ouyang et al., 2015; Zhou et al., 2020; Tian et al., 2021). Other studies indicated that the effect of rainfall in the removal of PM could also vary according to particle size (McMullen et al., 2021) and period (night and day) when the rainfall occurred (Wang and He, 2020), and even with atmospheric stability (Roldán-Henao et al., 2020).

For the same geographical location, the accumulation and dispersion conditions of these pollutants can vary greatly, temporally, and spatially (Unal et al., 2011; Chen et al., 2020; WHO, 2021). In addition, different meteorological parameters can influence the PM concentrations in the same region throughout the different seasons of the year. Yang et al. (2017), evaluating the relationship between the meteorological conditions and $PM_{2.5}$ concentrations in sixty-eight towns in China (between February 2013 and November 2014), showed that the relative humidity had a greater influence on the PM concentrations in the spring and summer, whereas the temperature and wind speed exerted a greater influence on the PM concentrations in the winter. This study also revealed that the same meteorological conditions could influence the $PM_{2.5}$ concentrations in differentiated ways in the various towns monitored.

The WHO (2021) guideline points out that one of the main gaps in the air quality management programmes is that most of the pollutant monitoring studies are restricted to large urban centres, to the detriment of smaller towns. In addition, since the influence of meteorological factors on the PM concentration can change considerably, temporally, and spatially, the influence of these factors on the PM_{10} dispersion and accumulation processes must be evaluated on a local scale, comparing the concentrations observed with the air quality standards.

Thus, this study evaluated the PM_{10} concentrations in different "meteorological scenarios" in a small town in the interior of Brazil, to identify the most favourable conditions to reduce these pollutants. A meteorological dataset made available by the weather forecasting agency was used for this purpose, allied to methods and statistical models compatible with weather phenomena. In addition to observing the relationship between the meteorological parameters (rainfall, relative humidity, etc.), the seasons and the PM_{10} concentrations, the study also aimed to verify the impact of the Covid-19 lockdown on the concentrations of this pollutant in three urban mobility periods: pre-lockdown (period before the pandemic), lockdown, and the vaccination phase in Brazil (relaxation time). Some studies indicated a reduction in the concentrations of PM during lockdown (Silver et al., 2020; Filonchyk et al., 2021; Millán-Martínez et al., 2022) or even a direct relationship between the number of COVID 19 cases and the concentrations of PM (Scapini et al., 2023). Thus, the methodology applied here constituted an important tool in the study of air quality tendencies (in locations with no air quality monitoring stations), applying a statistical analysis of the meteorological parameters to orientate government and regulatory bodies when making decisions concerning the best strategies to mitigate these pollutants.

Material and methods

Study area, PM_{10} sampling and meteorological data

The study took place in the city of Francisco Beltrão (FB), Paraná State (Brazil). FB has a total area of 757.2 Km^2, but only 5.3% of its territory is an urban area (the rest being rural). The town is 650m above sea level, and since it is in the south of Brazil, it has a moist, mesothermal sub-tropical climate (PMFB, 2023). The region evaluated presented no similar PM_{10} monitoring studies.

A PM_{10} high volume air sampler ("high vol", brand Energetica) was used to monitor the PM, installed in the cathedral tower in the centre of the town (26°04'44.7"S, 53°03'09.1"W; Figure 1). This location was chosen for ease of access, safety of the equipment and height from the ground (6m, within the interval predicted by CFR, 2024). The PM_{10} samples were collected between August 27th, 2019, and July 07th, 2021, always on weekdays, and each sample collected for 24 hours at a constant air flow rate of 1.13 m^3 min^{-1} (sampling parameters according to USEPA, 2011 and USEPA, 2012).

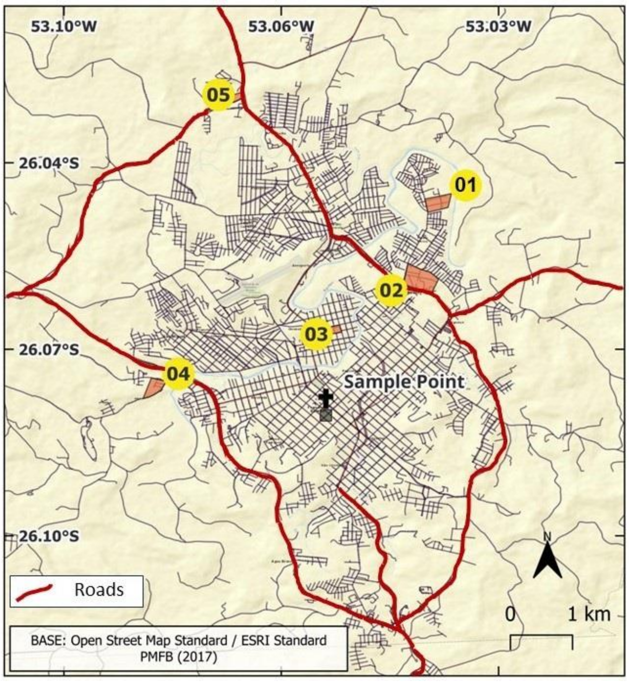

Figure 1. Location of the sampling point in relation to highways (red lines) and industrial districts (indicated by the numbers 1 to 5).

Glass fibre filters (brand GE) were used as the filtering material, with dimensions of 203 x 254 mm and filter area of 40.645 mm^2. Since it was a gravimetric method, each filter was weighed before and after the sampling period to determine the mass of PM_{10}. The PM_{10} concentration in the period sampled is the ratio between the mass of PM removed from the filter and the total standard volume of air sampled (V_{std}); V_{std} is the product between the average flow rate under reference conditions (Q_{std}, at 298K and 1 atm) and the sampling time (24h±15min) (USEPA, 2011). The calibration assays for Q_{std} were carried out with a flow rate transfer standard of the orifice type; calibration was performed every time the brushes or the starter motor of the high vol were substituted. The assay should result in a ratio between Q_r (flow rate under real conditions) versus d_{Hc} linear (differential manometric pressure).

The meteorological parameters used in the study (wind speed and direction, rainfall, relative humidity of the air, atmospheric pressure, and room temperature) were provided by the Paraná Meteorological System (SIMEPAR).

Pollution sources

Agriculture

The economy of FB is highly based on agriculture, and the soybean, corn and wheat harvesting areas (main cultures) occupy 42% of the total area of the municipality (IBGE, 2017). Figure 2 shows that these cultivated areas are well distributed around the town.

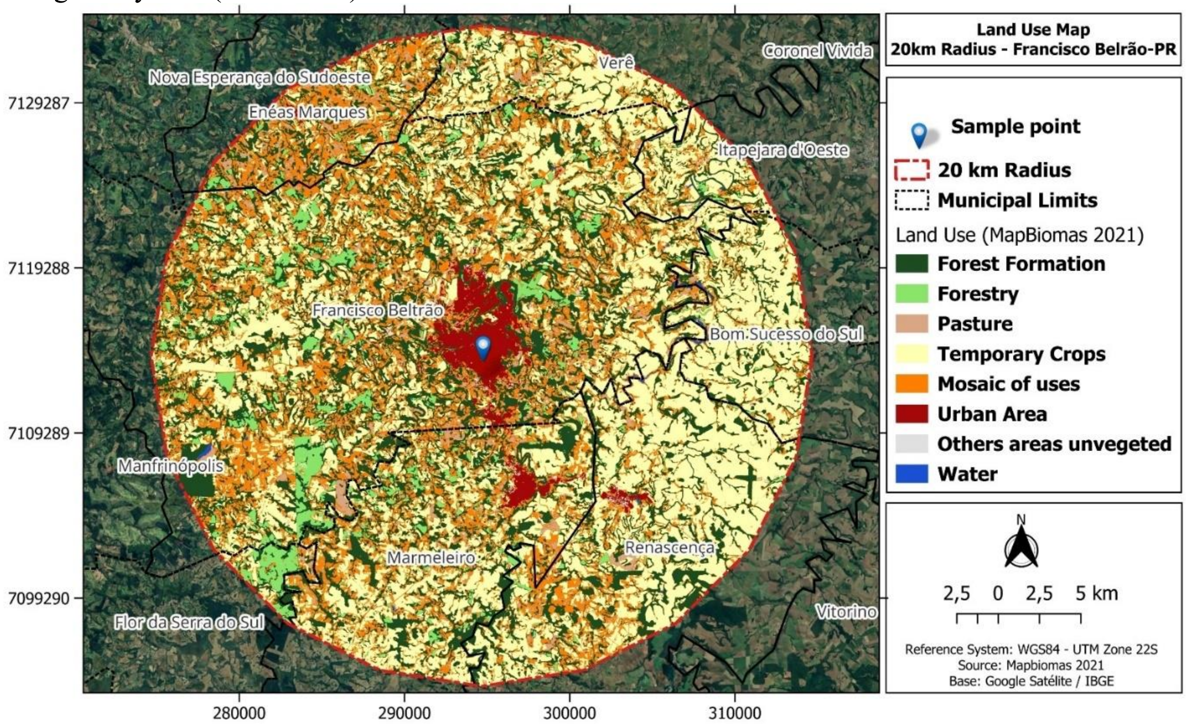

Figure 2. Map showing the land occupation in the FB municipality and surrounding areas (sampling point shown in blue in the centre).

Vehicle contributions

Although the vehicle fleet (total) of FB increased 7.2% between 2019 and 2021 (from 67,341 to 72,166), the proportions of road-based vehicles run on petrol and on diesel remained the same throughout the study (≈76% run on petrol and ≈14% on diesel) (values estimated from National Traffic Secretariat data – IBGE, 2022). Apart from local contributions, FB is surrounded by four state highways and two federal highways (Figure 1). It should be emphasized that highways are important sources of PM, be it from fuel combustion emissions (primary source) or even from the abrasion of tyres, brakes and the resuspension of PM already deposited on the soil (WHO, 2013; Giaccherini et al., 2021). All the highways in the region also served for the transport of agricultural produc7e, which could further potentize PM emissions during the transport of grains.

Stationary sources

Like the agricultural sector, the industrial sector (another essential activity) was also not totally paralyzed during lockdown, and hence its influence as a PM_{10} source during lockdown should also be considered. FB has five industrial districts, all with considerably diverse activities, elevated MP generation potential and located in the northern half of the urban area (Figure 1):

District (1): one metallurgical industry with a predominance of lumber mills and furniture factories;

District (2): marble factories, cement factories, metallurgical industry, aluminium industries, wood frame factories and lumberyards, etc.;

District (3): (the closest to the monitoring point) with a predominance of metallurgical and aluminium industries;

District (4): aluminium and furniture factories;

District (5): industrial zone furthest from the monitoring point with furniture and aluminium factories (PMFB, 2017).

Data analysis

The data collected during the monitoring period (total of 116 samplings) made up the matrix of variables for the present study. Three urban mobility periods were considered to delimit the pandemic period: pre-lockdown (period before March 20th 2020), lockdown (from March 2020 to the end of January 2021, when the vaccination phase started in Brazil), and the vaccination phase (from January 19th 2021 to July 07th 2021, period with a greater flexibility of the confinement rules in Brazil). Thus, PM_{10} monitoring did not include the "post-pandemic" period.

The climatic variables of rainfall intensity (classified according to the Weather and Climate Services Division, NCHM, 2024), relative humidity, wind direction, wind intensity (classified according to the "Beaufort Wind Scale", NWS, 2024) and the mean daily temperature, together with the seasons of the year and the pandemic period, were implemented in a Generalized Additive Model (GAM) as predictive variables of PM_{10} concentrations. The Akaike Information Criterion (AIC) was applied to determine the best fit of the model and the probabilistic distribution was determined according to the Poisson distribution. The Generalized Additive Model (GAM) is commonly used in the statistical modelling of data with a stochastic nature, as in the present case (Chen et al., 2020).

The one-way variance analysis (ANOVA) and the contrast with the means assured by the Fisher post-hoc test and Spearman correlation were implemented to evaluate the influence of the predictive variables on the PM_{10} concentrations in a univariate way, and the Student t test was used for orthogonal comparisons. Non-parametric tests (Kruskal-Wallis and Wilcoxon) were applied when the premises of homogeneity of the variances and normality of the residues were not met. The reliability of the tests was 95% and all the analyses were carried out using the RStudio version 2024.09.1.

Results and discussion

Data analysis of the PM_{10} according to the Brazilian and WHO regulations

Figure 3 shows the PM_{10} concentrations obtained during the two years of monitoring (total of 116 samplings). The data were compared with the limits recommended by the World Health Organization (WHO) Global Air Quality Guidelines (AQG) and by the Air Quality Standards (AQS) of the National Council for the Environment (CONAMA, a Brazilian Agency). Since all the samplings were for 24 hours, the data analysis was based on the concentrations of 100 µg m^{-3} (CONAMA, 2024) and 45 µg m^{-3} (WHO, 2021), the currently valid values corresponding to a short-term target (24 h).

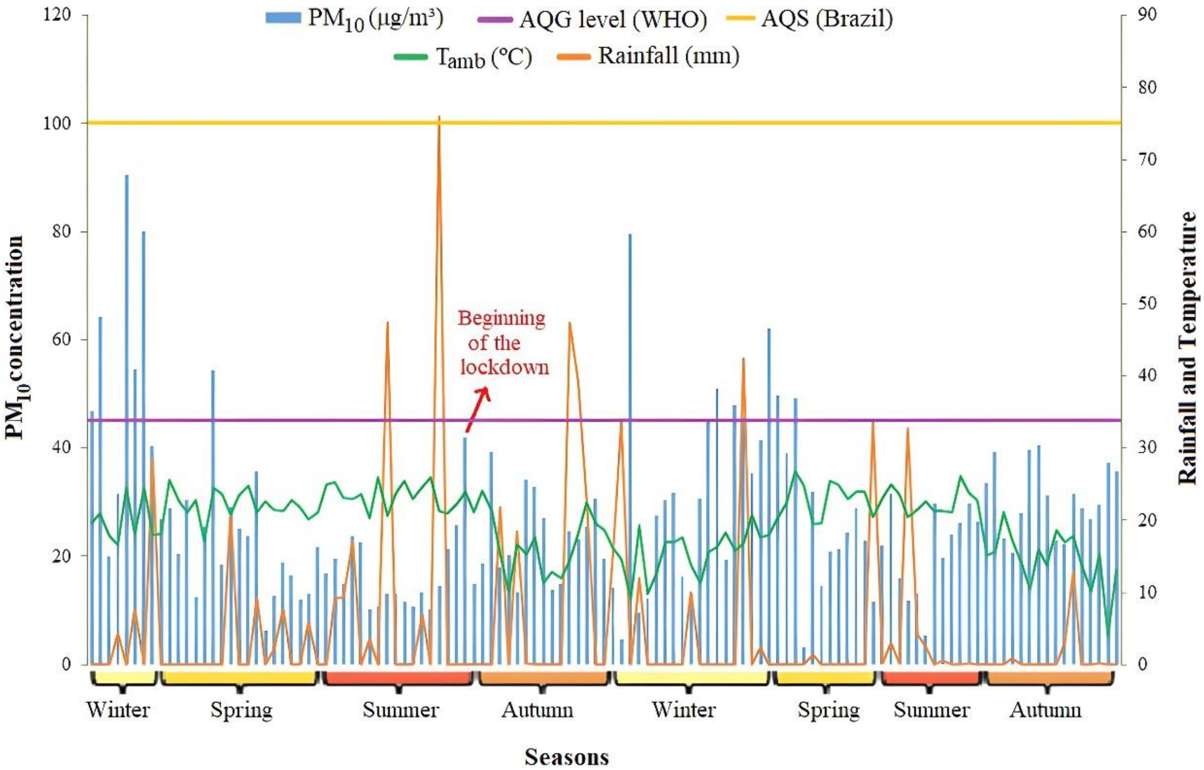

Figure 3. Plot of the PM_{10} concentrations (all campaigns) versus seasons and meteorological parameters.

Considering the Brazilian standards, no sampling showed a concentration above 100 µg m^{-3}. However, it is important to note that this is a temporary value ("interim target 2" of a total of four concentration levels). The final value will be 45 µg m^{-3} (CONAMA, 2024) in agreement with the WHO (2021) standards.

Since the limit recommended by WHO (PM_{10} Air Quality Guidelines) is 45 µg m^{-3} and can be exceeded up to four days a year, Figure 3 shows that, during the monitoring period, this concentration was exceeded twelve times, almost always in the winter and start of spring, periods with the lowest mean ambient temperatures. Nevertheless, even with lower mean temperatures in the autumn as well, there was no relationship between temperature (lower) and particulate concentration (above 45 µg m^{-3}) for this season. Also, in an individual analysis of the accumulated daily rainfall data and the respective PM_{10} concentration values, there was no clear relationship between the rainfall and particulate values, as frequently indicated in most of the studies published in the literature ("washing effect"). The largest rainfall values observed during the period monitored were 47.4 mm (Jan 01st, 2020), 76.0 mm (Feb 25th, 2020), 47.4 (Jun 04th, 2020), 39.2 (Jun 09th, 2020) and 42.4 mm (Aug 18th, 2020), corresponding to concentrations of 13.1, 14.5, 24.7, 23.1 and 45.4 µg m^{-3}, respectively. On the other hand, even with little or no rain for the greater part of the period, the PM_{10} concentrations varied from 3.2 to 64.2 µg m^{-3} on days with no rain (0.0 mm) and from 5.4 to 41.4 µg m^{-3} on days with rainfall varying from 0.2 to 2.5 mm. Thus, even though rainfall is one of the main mechanisms for removing PM from the air, no direct relationship was found between the PM_{10} concentration and the accumulated volume of rain when based only on a specific analysis of the data in Figure 3.

In addition, the effects of the pre-lockdown and lockdown mobility periods on the PM_{10} concentrations were also not clear. Even if the urban population of FB effectively adhered to the mobility restriction norms imposed by the government in an attempt to contain the proliferation of the SARS-CoV-2 virus, the highway transport, agricultural and even the industrial sectors (well distributed around the municipality as shown in Figures 1 and 2) did not stop completely during lockdown, which could justify the non-existence of a sharp fall in the PM_{10} concentrations as from the second half of March, 2020 (start of the lockdown period).

Thus, the relationship between the PM concentrations, meteorological parameters, seasons of the year and mobility periods will be analysed using the generalized additive model (GAM) in the next sections, since this model can investigate complex non-linear relationships between the predictive variables, such as meteorological factors, social mobility, and the response variable (PM_{10}). Studies such as that of Wood (2017) also highlight the efficacy of GAMs in the modelling of environmental data.

PM_{10} concentrations versus meteorological parameters and mobility restrictions

Seasons and temperature

A preliminary analysis grouping the data for environmental temperature, seasons of the year and mobility periods together showed a very weak correlation between these factors (r=-0.12; p=0.19). Thus, Figure 4 presents the relationship of the PM_{10} concentrations just with the seasons and temperature.

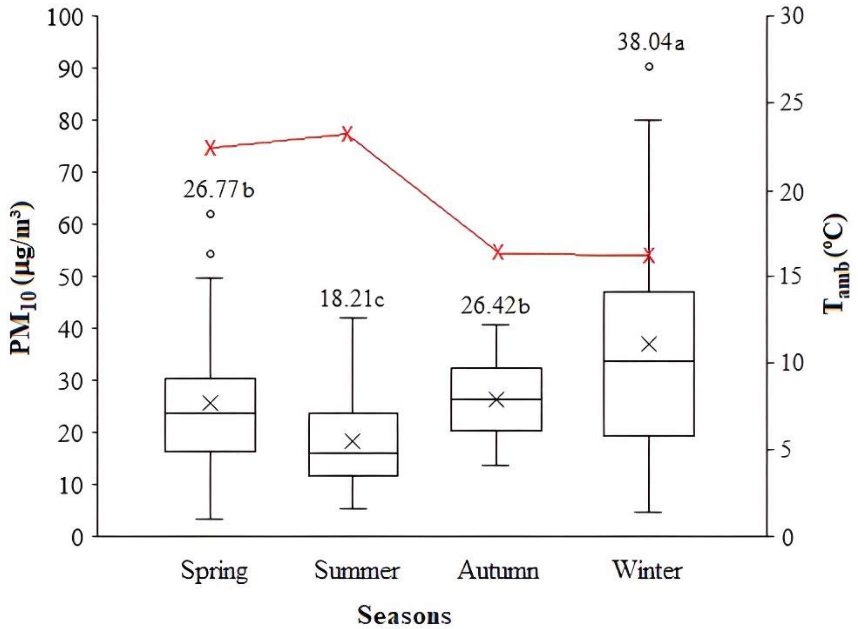

Figure 4. Boxplots and mean values (x) of the PM_{10} concentrations and temperatures observed during the four seasons. Means followed by the same letter (a,b,c) do not differ statistically according to the Fisher test at 5% significance.

Although the mean PM_{10} concentrations in the autumn and spring were practically the same (≈26.5 µg m^{-3}), the mean PM_{10} concentration in the winter was 109% higher than that verified in the summer (Figure 4). That is, lower temperatures (which occurred in the winter) corresponded to higher PM_{10} concentrations; whereas on the other hand, high temperatures (in the summer) were tied to lower PM_{10} concentrations. In the same way, Zhang et al. (2014) observed higher PM_{10} concentrations in the Chinese winter, followed by the autumn, spring and finally, the summer. Unal et al. (2011) also reported higher PM_{10} concentrations in the winter (30% higher, compared to the summer). In both these studies, the increase in anthropogenic emissions in the winter was mainly due to the use of fossil energy sources (mainly coal), used mostly to heat residential homes in the winter (Chen et al., 2020). Barmpadimos et al. (2011) attributed the higher PM_{10} concentrations in the winter to the use of log fires to heat residences, which is common in the south of Brazil. Apart from the emission source (wood burning), the higher PM concentrations at ground level during the winter could also be attributed to the worse conditions for the vertical dispersion of the pollutant observed in this season. That is, the greater thermal stability conditions found in the winter tend to make the vertical exchange of air masses (convection currents) difficult, observed with greater intensity in the summer (Unal et al., 2011; Liu et al., 2023).

Rain and relative air humidity

The rainfall observed during the period monitored was classified according to the Weather and Climate Services Division (NCHM) into three categories: Rainless and light rain (0 to 10 mm), moderate rain (11 to 30 mm) and heavy rain (31 to 70 mm).

During the almost two years of monitoring, moderate rain and heavy rain were only observed on 7.6% and 6.7%, respectively, of the PM_{10} sampling days, and on 66% of the sampling days there was no rain (0 mm). Figure 5 shows the relationship between rain, mobility period and the PM_{10} concentrations.

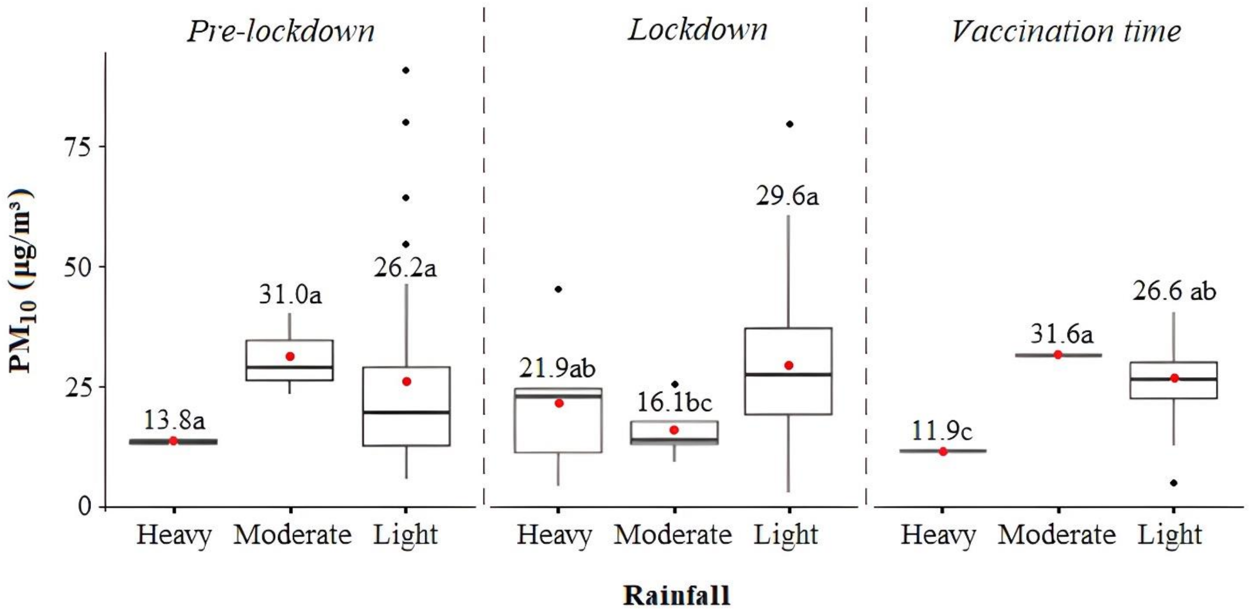

Figure 5. Boxplots and mean values (in red) of the PM_{10} concentrations during the different mobility periods and rainfall categories. Means followed by the same letter (a,b,c) do not differ statistically according to the Fisher test at 5% significance.

Figure 5 only shows that the lowest PM_{10} concentrations occurred exactly on the days with heavy rain (during the pre-lockdown and vaccination periods). However, the arrangement of the days according to rainfall and mobility period failed to show in a clear way the relationship between the volume of rain (or even the absence of rain, which corresponded to two thirds of the sampling days) and the pollutant concentrations. Thus Figure 6 only shows the relationship between the accumulated daily rainfall and the PM_{10} concentration.

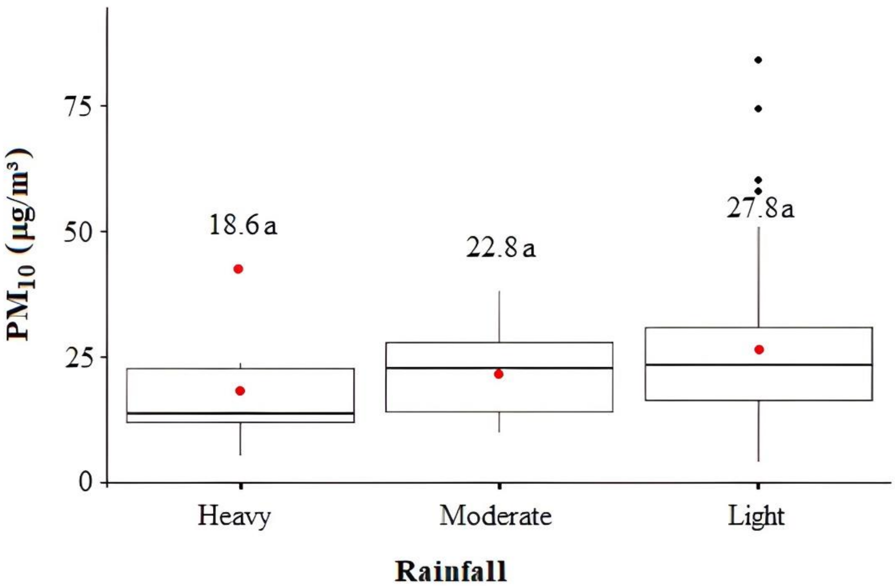

Figure 6. Boxplots and mean values (in red) of the PM_{10} concentrations for the three rainfall categories. Means followed by the same letter (a,b,c) do not differ statistically according to the Fisher test at 5% significance.

Independent of the mobility period, the mean PM_{10} values for the days with heavy rain, moderate rain and rainless/light rain were 18.6; 22.8 and 27.8 µg m^{-3}, respectively. Figure 6 also shows that the greatest PM_{10} concentrations during the two years monitored occurred exactly on the rainless days (0 mm): 62.2; 64.2; 79.7; 80 and 90.4 µg m^{-3}. In fact, the technical literature commonly reports a highly representative correlation between rainfall and the PM concentration (Ouyang et al., 2015; Gao et al., 2019; Wang and He, 2020). In general, the greater the concentration of raindrops during rainfall, the greater the collision between the raindrops and the particulates (Luan et al., 2019), favouring the scavenging effect on the PM_{10} concentrations. However, Gao et al. (2019) and Roldán-Henao et al. (2020) emphasize the fact that the particulate concentrations are not always reduced during rainfall episodes; this happening mainly as a function of external sources (long-range transport) which can contribute to the particulate concentration in the place being monitored (Kanniah et al., 2020). In fact, as already mentioned, even after the period of greatest urban mobility restriction (March 2020), some sectors of the local economy were not totally paralysed. Furthermore, apart from the daily accumulated rainfall (only rainfall data available in this study), other factors related to rainfall can also interfere directly in the PM concentrations, such as the frequency of rain (number of events per day), rainfall rate (rain volume per hour), duration of the rainfall and even the sizes of the raindrops and of the particulates (Quérel et al., 2014; Gao et al., 2019; Luan et al., 2019; McMullen et al., 2021), which were not evaluated here. Thus, although Figure 6 presents a clearer (and "clean") relationship of the PM concentrations *versus* rainfall as compared to Figure 5, uncertainties concerning the real proportion of the contribution of the daily accumulated rainfall on the PM concentrations ratify the need for a joint analysis of the influence of other meteorological parameters on the PM values. In the context of the present study, it is important to consider that heavy and moderate rain events correspond to less than 15% of the days monitored and that other factors (such as the air humidity) could influence the relationship between the concentrations of PM and rainfall (Zhou et al., 2020).

Figure 7 shows the relationship between the relative humidity (RH) of the air, the mobility period and the PM_{10} concentrations.

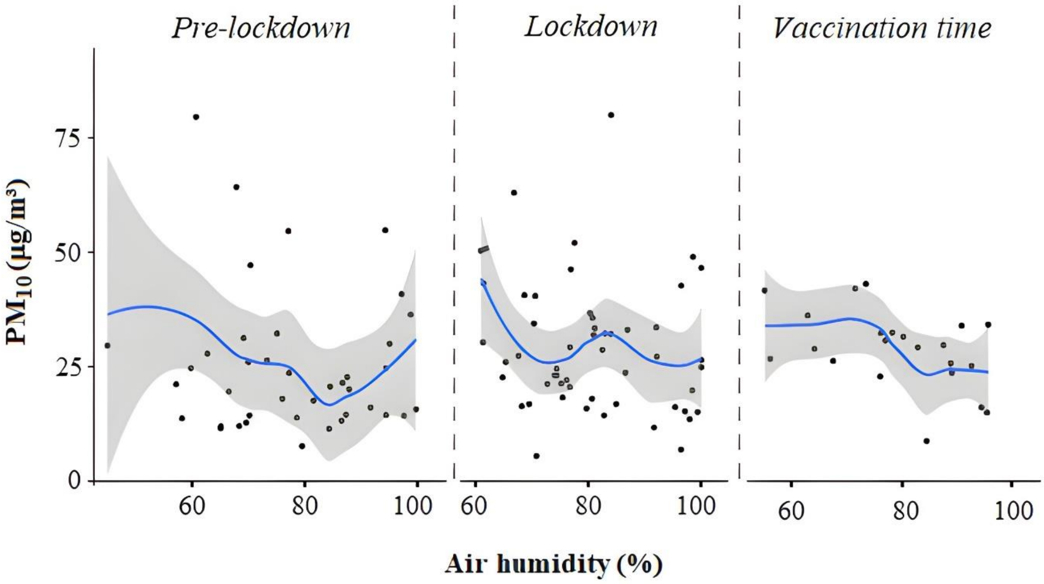

Figure 7. PM_{10} concentration tendencies as a function of the relative humidity of the air for the three social mobility periods: Before lockdown – r=-0.29, p=0.19, n=41; lockdown – r=-0.19, p=0.16, n=53; vaccination – r=-0.46, p=0.03, n=22.

Independent of the mobility period, there was a clear tendency to reduce the PM_{10} concentration with increase in RH, a tendency compatible with other studies (Zender-Świercz et al., 2024; Saqer et al., 2024). Although the relationship (inversely proportional) between the RH and PM_{10} can be influenced by various mechanisms, in short, the process can be explained by a combination (coalescence) between the particulates and the air humidity, with the subsequent sedimentation of these particulates in the atmosphere (Al-Jallad et al., 2013).

Wind (speed and direction)

The wind speed observed during the period monitored was classified according to the Beaufort Wind Scale (NWS, 2024) into two categories: "calm and light air" (wind speeds between 0 and ≈5.5 Km h^{-1}) and "light breeze" (≈5.6 to 11.3 Km h^{-1}). During the almost two years of monitoring, "calm and light air" and "light breeze" were observed, respectively, on 29% and 71% of the PM_{10} monitored days. Wind speeds above 11.3 Km h^{-1} (between 11.4 and 12.8), here classified as light breeze, were only registered on four days. Taking the conclusions of Elminir (2005) and Liu et al. (2023) as reference in relation to wind speeds and the probable sources of PM, the main sources of the PM_{10} concentrations obtained on calm and light air days could be vehicles circulating in the centre of the town, urban population activities, dust resuspension, civil construction, etc. On the other hand, since light breeze predominated during most of the period monitored, the greater part of the PM_{10} concentrations could be associated with agricultural activities and highway transport (both sources well distributed around the town) and even industrial activity (to the north of the sampling point). Thus, it was highly probable that the predominance of light breeze potentized the contribution of sources external to the central region of the town, where the sampling point was located (long-range transport).

Figure 8 shows the relationship between the wind speed and the PM_{10} concentrations.

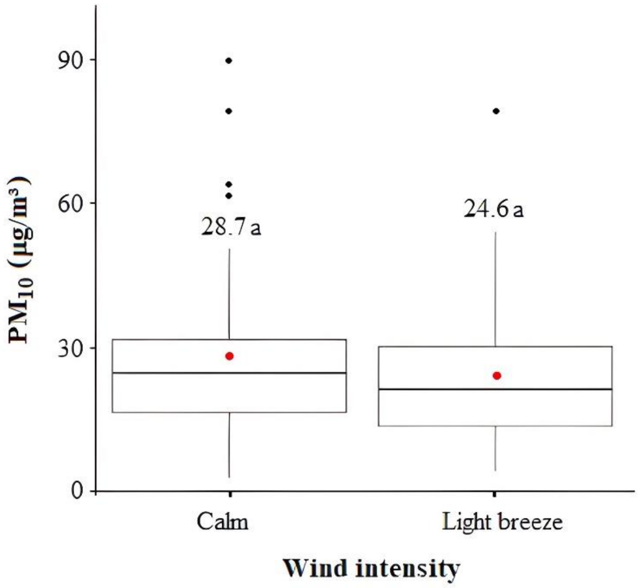

Figure 8. Boxplots and mean values (in red) of the PM_{10} concentrations in the predominant two wind speed categories. Means followed by the same letter (a,b,c) do not differ statistically according to the Fisher test at 5% significance.

A preliminary analysis of the grouped data for wind speed, seasons and mobility periods indicated a very weak correlation between these factors (r=-0.15; p=0.11). Even not considering the mobility period, Figure 8 shows that the PM_{10} concentrations also failed to differ statistically as a function of wind speed (according to the Fisher test at 5% significance). Thus, Figure 9 presents the relationship between the wind direction (considering a single speed), mobility period and the PM_{10} concentrations.

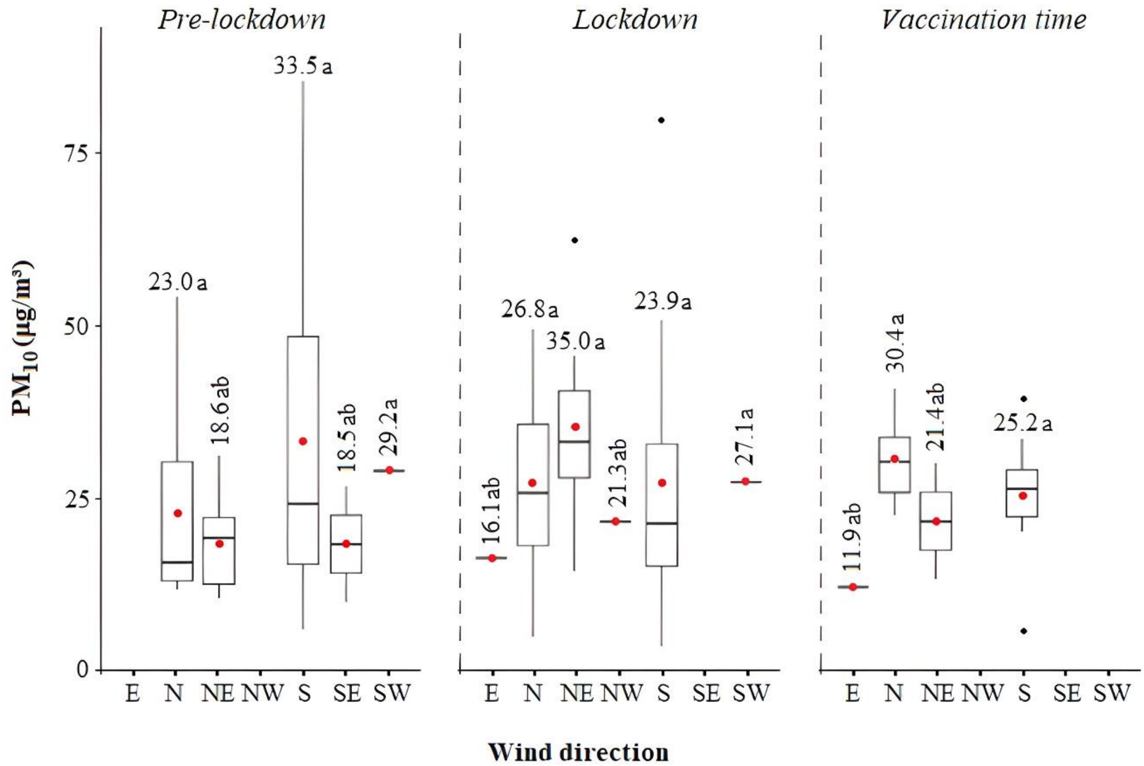

Figure 9. Boxplots and mean values (red points) of the PM_{10} concentrations during the different mobility periods and wind directions. Means followed by the same letter do not differ statistically according to the Fisher test at 5% significance.

Figure 9 shows that the mean PM_{10} concentrations remained stable during the three social mobility phases. Even in the pre-pandemic period, the PM_{10} concentrations were not higher than in the other periods, independent of the wind direction.

One of the main aspects related to the grouping of the pollutant concentration per wind direction is the possibility of identifying the origin (sources) of the pollutants. However, Figure 9 indicates that all the sources described in section "*Pollution sources*" could be contributing to the PM_{10} concentrations to a greater or smaller degree.

PM_{10} concentrations and mobility restrictions

Figure 10 shows the graphs (boxplots) related to the PM_{10} concentrations and the three urban mobility periods evaluated in this study.

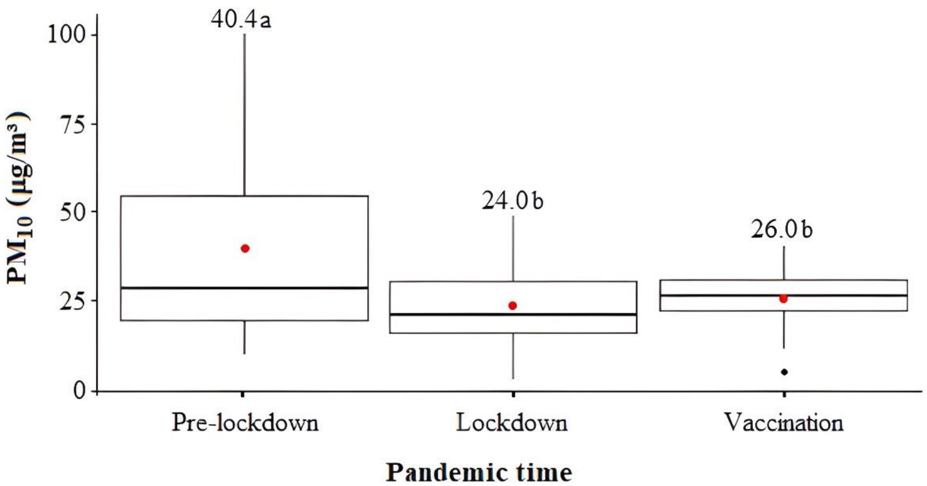

Figure 10. Boxplots and mean values (red points) of the PM_{10} concentrations during the different mobility periods. Means followed by the same letter (a,b) do not differ statistically according to the Fisher test at 5% significance.

The mean PM_{10} values for the pre-lockdown, lockdown and vaccination phase (relaxation period) were 40.0; 24.0 and 26.0 µg m^{-3}, respectively. That is, there was a mean reduction of 40% in the PM_{10} concentrations in the central urban area of FB during the pandemic period. As the vaccination procedure started and the confinement rules became more flexible, so there was a small increase in the mean PM_{10} concentrations, but still lower than the pre-pandemic concentration levels. As mentioned earlier, many PM_{10} sources could be located outside the urban limits of FB, such as the circulation of cargo vehicles on the highways in the region (in Brazil they are all run on diesel), resuspension of particulate material already deposited on the soil, secondary particle formation, biogenic emissions, etc. (Kanniah et al., 2020), which could have contributed to the fact that a greater difference between the pre-lockdown and lockdown periods was not observed. Nevertheless, based on the technical literature, this fall in the PM_{10} concentration between the pre-pandemic and lockdown periods could be highly representative when dealing with public health. Taking the ExternE Project of the European Commission as reference, for each increase of 1 µg m^{-3} in the PM_{10} concentration, the number of deaths related to this pollutant can increase by up to 0.06% (Zhao et al., 2016); hence, even in a small town with a population of less than 100,000 inhabitants, as in the case of FB) a reduction of 40% in the particulate concentration represents a significant fall in the mortality rate directly related to PM_{10} exposure. If one considers that these particles also include $PM_{2.5}$ (which reaches even further in the respiratory tract), the impact on health due to exposure to these pollutants could be even greater.

Various studies have considered the impact of lockdown on the PM (PM_{10} and/or $PM_{2.5}$) concentrations. Filonchyk et al. (2021) monitored the mean PM_{10} concentrations in five Polish towns between March and May 2020, and compared the data obtained with the mean concentrations of this pollutant in the same period for the years of 2018 and 2019. The authors observed that the concentrations varied greatly between the towns: from 19.2 µg m^{-3} in May 2019 to 43.1 µg m^{-3} in March 2018 in the town of Wroclaw; and from 23.3 µg m^{-3} in May 2019 to 69.8 µg m^{-3} in March 2018 in Krakow. Compared to the pandemic period, the reductions in the mean PM_{10} concentrations (in 2020 as compared to the 2018/2019 biennium) also showed considerable variation: from -4.3% to -39.6% in Wroclaw and from -4.8% to -47.3% in Krakow; the reductions observed have been attributed to the significant fall in the circulation of vehicles (transport sector) and crude oil/coal consumptions during the pandemic. Millán-Martínez et al. (2022) also observed a great variation in the mean PM_{10} concentrations in different regions in Spain during the lockdown period, as compared to the mean PM_{10} concentrations determined in the 2013 to 2016 (pre-lockdown) period. The authors monitored different sites (traffic, urban, industrial, rural, etc.) and obtained the greatest reductions in the traffic monitoring stations (between -23 and -41%). The monitoring stations located in the urban and urban-industrial regions also presented great reductions in the PM_{10} concentrations (-13 to -27% and -12 to -41%, respectively). Kanniah et al. (2020) also verified the variation in air pollutants (including PM_{10}) in various regions in Malaysia, covering urban, industrial, rural and suburban sites. The authors evaluated the behaviour of the mean PM_{10} concentrations in the period from 18th March to 30th April 2018, 2019 (pre-lockdown) and 2020 (lockdown) and observed a reduction in PM_{10} during the pandemic period in the four regions evaluated. In a comparison with the same period in 2018 and 2019, the largest falls during lockdown were observed in the urban and industrial areas. Mahato et al. (2020) also reported a significant improvement in the air quality during lockdown, with a more than 50% reduction in the PM_{10} and $PM_{2.5}$ concentrations compared to the same period in 2019; the authors also reported a strong relationship between the PM_{10} concentrations and gases such as NO_2 and SO_2 (both associated with acid deposition processes), ammonium and carbon dioxide. This and other studies which also verified the efficiency of urban mobility restrictions in the control of PM sources, made it clear that the direct comparison of values obtained in the present study with others reported in the literature is a very complicated task, due to the enormous variation between the different regions monitored: size of town and population, climate and local meteorological characteristics, industrialization degree (stationary sources), number of vehicles and fuel used (diesel, ethanol, petrol), quantity and nature of the power plants, energy matrix (for example, many countries still use coal as the main fuel for domestic heating), etc. Nevertheless, despite the specificities between the different studies, there was a common tendency to reduce the PM concentrations during the pandemic (lockdown).

General statistical analysis of the relationship between the mobility periods and meteorological parameters

Modelling of the PM_{10} concentrations based on the generalized additive model explained more than 50% of the variation observed in the PM_{10} levels (fitted R^2=0.59, p<0.01). The variables that most contributed to the behaviour of the PM were, in increasing order of significance: the seasons of the year, the period of social mobility nested in the seasons and the rainfall intensity. The nested factor allows one to explore how two or more variables interfere simultaneously in the response variable (PM_{10}). This experimental design made it possible to model the behaviour of the PM with greater efficiency, investigating in a reliable manner how the social mobility impacted the levels of pollution in the different seasons of the year. Secondary variables, such as the relative humidity and mean temperature, also had significant effects. However, the wind intensity and direction were not significant parameters (Table 1).

Table 1. Analysis of variance of the model coefficients GAM (R^2_{adj}=0.59, p<0.01).

Parameters	F	p
Intercept (constant)	21.95	0.00
Seasons	5.64	0.00
Pandemic time (seasons)	6.95	0.01
Rainfall	3.64	0.04
Relative air humidity	2.25	0.07
Mean temperature	2.58	0.08
Wind intensity	0.84	0.43
Wind direction	0.46	0.83

It is important to emphasize that the social mobility period only significantly impacted the PM_{10} concentration when nested in the seasons of the year. Before lockdown, the effect of the seasons was more pronounced, with statistically significantly differences between the winter (mean PM_{10}=54.46 µg m^{-3}) and summer (mean of 14.97 µg m^{-3}) (values considering the social mobility nested in the seasons of the year). During the social mobility restricted periods, such as lockdown and vaccination, no significant differences were observed in the PM_{10} concentrations, although the seasonal standard of a greater concentration in the winter than in the summer persisted.

Conclusions

- Influence of the mobility period and of the climatic variables on the PM_{10} concentrations: The study concluded that the mobility period, especially during the COVID-19 lockdown, had a significant influence on the reduction of the PM_{10} concentrations (mean reduction of 40%). The climate variables (such as rainfall and the relative humidity of the air) and the seasons of the year also played important roles. The PM_{10} concentrations were higher in the winter, attributed to the use of firewood for domestic heating and less favourable conditions for the dispersion of pollutants. The study also indicated that factors such as urban mobility, anthropogenic sources of PM (agriculture, transport, industries etc.) and climatic conditions should be considered in air quality management strategies.

- Use of additive models: The use of mixed additive models (GAM) in the study was efficient in correlating complex non-linear relationships between the meteorological and social variables and the PM_{10} concentrations. This model allowed for a detailed analysis of the simultaneous influences of multiple factors, especially the capacity of the GAMs to provide valuable insights into the dynamics of air pollution in specific scenarios. The modelist approach used was shown to be a robust tool to evaluate and forecast the conditions which favour the reduction of atmospheric pollutants.

- Considerations concerning the results in relation to Brazilian air quality legislation: The results revealed that, although the PM_{10} concentrations in FB decreased significantly during lockdown, in some moments they still exceeded the limits recommended by the World Health Organization (WHO), which are more restrictive than those of the current standards in Brazil (currently in the process of being aligned with the WHO standards). Thus, this study also shows the need for more rigorous policies and for continuous monitoring of the air quality standards, especially in small towns, nearly all of which do not have air monitoring stations.

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