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Positive matrix factorization used to identify $PM_{2.5}$ and PM_{10} sources in southern Brazilian cities

Fatoração matricial positiva utilizada para identificar as fontes de $MP_{2,5}$ e MP_{10} em cidades do Sul do Brasil

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ABSTRACT

Particulate matter (PM) is one of the main air pollutants found suspended in the atmosphere, and is composed of a mixture of chemical elements of natural and anthropogenic origin. Therefore, the objective of this study was to use the Positive Matrix Factorization (PMF) receptor model to identify the sources of $PM_{2.5}$ and PM_{10} concentrations, the data for which were collected and chemically quantified through secondary studies. The Enrichment Factor (EF) was calculated to analyze the degree of anthropogenic influence on the chemical enrichment of the particles. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) was used to identify the atmospheric transport of particles based on the trajectory of air masses. Emissions were identified as having primarily vehicular, industrial, and natural origins. The results confirm the chemical enrichment in the analyzed PM concentrations and indicate a strong relationship between the fine and coarse fractions. The identification of sources indicated that the presence of the metallic variables Ba, Cd, Cu, Pb, Cr, Ni and Zi in the PM are of anthropic origin, and present strong enrichment, while that of Fe and Mn are of natural origin, with a low degree of enrichment. The relevance of this research lies in its ability to provide precise technical support for air quality management. By identifying and quantifying human influence on atmospheric chemistry, the study offers fundamental data for the formulation of public policies to control emissions and mitigate risks to the respiratory health of the population.

Keywords: particulate matter; enrichment factor; air pollution.

RESUMO

O material particulado (MP) é um dos principais poluentes do ar, encontrado em suspensão na atmosfera, composto de uma mistura de elementos químicos de origem natural ou antrópica. Dessa forma, o objetivo do presente estudo foi usar o modelo receptor *Positive Matrix Factorization* (PMF) para identificar as fontes de concentrações de $MP_{2.5}$ e MP_{10}, cujos dados foram coletados e quantificados quimicamente por estudos secundários. O Fator de Enriquecimento (FE) foi calculado para analisar o grau de influência antrópica no enriquecimento químico das partículas. O *Hybrid Single-Particle Lagrangian Integrated Trajectory* (HYSPLIT) foi usado para identificar o transporte atmosférico das partículas com base na trajetória das massas de ar. Foi identificado que as emissões possuem origens principalmente veiculares, industriais e naturais. Os resultados encontrados ratificam o enriquecimento químico nas concentrações de MP analisadas e indicam forte relação entre as frações finas e grossas. A identificação de fontes revelou que as variáveis metálicas Ba, Cd, Cu, Pb, Cr, Ni e Zi presentes no MP são de origem antrópica e apresentam forte enriquecimento, enquanto Fe e Mn são de origem natural, com baixo grau de enriquecimento. A relevância desta pesquisa reside na sua capacidade de fornecer subsídios técnicos precisos para a gestão da qualidade do ar. Ao identificar e quantificar a influência humana na química atmosférica, o estudo oferece dados fundamentais para a formulação de políticas públicas de controle de emissões e para a mitigação de riscos à saúde respiratória da população.

Palavras-chave: material particulado; fator de enriquecimento; poluição do ar.

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Introduction

Particulate matter (PM) consists of an air pollutant classified according to the aerodynamic diameter (d_a) of particles. $PM_{2.5}$ corresponds to $d_a \leq 2.5$ µm, whereas PM_{10} encompasses particles with $d_a \leq 10$ µm (Seinfeld and Pandis, 2016). Notably, the smaller the particle, the longer it remains suspended and the greater the distance it can travel (Delikhoon et al., 2021).

PM size is also directly related to potential damages to the exposed population's health, since particles with a smaller aerodynamic diameter have a greater capacity to penetrate the respiratory system and may, in more severe cases and under prolonged exposure, contribute to the development of diseases like lung cancer (WHO, 2026). PM can originate from anthropogenic activities, such as industrial activities (Fadel et al., 2021) and vehicle emissions (Kumar et al., 2021; Nogarotto et al., 2022), or from natural processes like dust resuspension from the Earth's crust, volcanic emissions and forest fires (CETESB, 2025; Choi and Ying, 2025; Linda et al., 2025; Whitty et al., 2025). Importantly, both PM concentration and physicochemical composition can present high variability and complexity depending on its origin and associated emitting sources (Pozza et al., 2023).

Enrichment Factor (EF) calculation helps to determine whether the PM-constituting chemical species are of natural or anthropogenic origin (Gurgatz et al., 2025). EF is obtained by the ratio between the concentration of the chemical element of interest and the concentration of a reference element (or geogenic tracer), characterized by its high abundance and stability in the lithosphere. Commonly used reference elements include aluminum (Al), silicon (Si), iron (Fe), and titanium (Ti). High EF values indicate elemental enrichment, suggesting a significant contribution of anthropogenic sources to the PM composition (Elhadi et al., 2018).

Polluting sources can be identified using the Positive Matrix Factorization (PMF) receptor model, a mathematical tool capable of identifying sources that emit environmental pollutants by means of information collected by receptors (Alves et al., 2020). This model has been widely used to identify PM sources (Xu et al., 2023; Dai et al., 2024; Heo et al., 2025; Quang Le et al., 2025).

Assessing the trajectory of air pollutants can be achieved by using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, which determines the origin of air masses and simulates their trajectories by calculating them backwards in time as a function of climatic conditions and concentration of pollutants (Nogarotto et al., 2021; ARL, 2025; Mustaqiman et al., 2025).

Thus, this research sought to identify PM_{10} and $PM_{2.5}$ sources using PMF and analyze the degree of chemical enrichment in the particles by calculating EF. For analysis, PM data were retrieved from three studies conducted from 2013 to 2019—Alves et al. (2016), Pletsch (2019) and Alves et al. (2020)—in the municipalities of Campo Bom, Canela, Canoas, Gramado, and São Leopoldo, located in Rio Grande do Sul state, Brazil. These studies contain data from chemical analyses performed on PM samples, but did not investigate the possible polluting sources.

Methodology

Study area and influences

The study area includes five municipalities in Rio Grande do Sul, Brazil: Campo Bom (CB), Canela (CNL), Canoas (CNS), Gramado (GRA) and São Leopoldo (SL) (Figure 1). Importantly, no similar studies previously conducted in these cities were found in the literature.

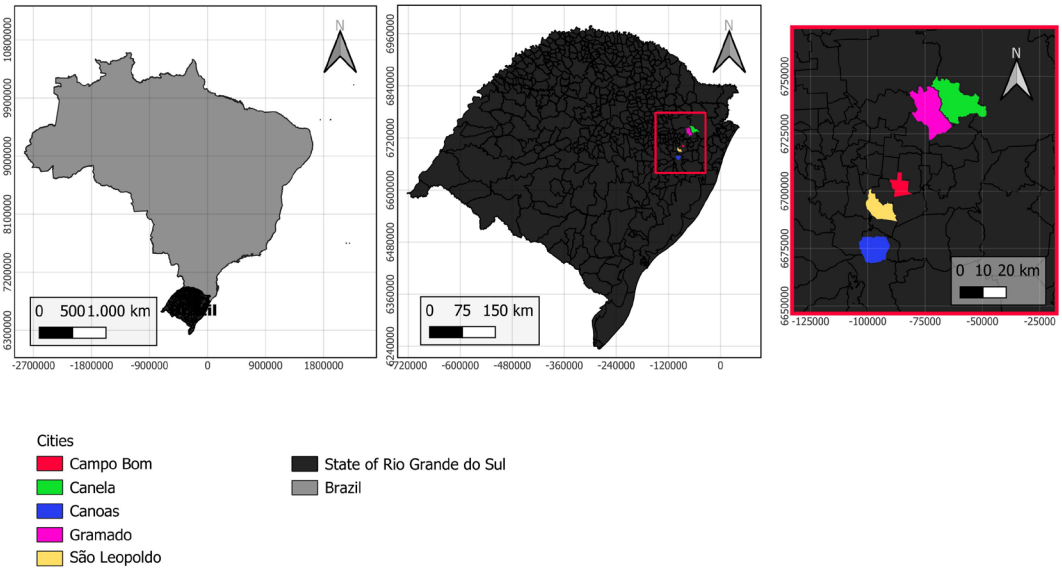


Figure 1 – Location of the Rio Grande do Sul (RS) municipalities where the study was conducted.

CB, CNS and SL make up the metropolitan region of Porto Alegre, and have an estimated 64,704, 359,554 and 225,669 inhabitants, respectively (IBGE, 2025). Sampling in CB was performed in a semi-urban area, with the influences highlighting the proximity of the collection equipment to BR-116 and to footwear, metallurgical and plastic packaging industries. In CNS, influences come from vehicle emissions, factories and industries in the metal, mechanical, electrical, furniture, agricultural, forging and gas sectors and the Alberto Pasqualini Refinery (REFAP). In SL, the equipment was positioned near BR-116. The municipality concentrates industries in the metal-mechanic and rubber sectors (Alves et al., 2016; Alves et al., 2020).

CNL and GRA make up the tourist region, known as the 'Hydrangea Region,' with an estimated 50,613 and 41,621 inhabitants in 2024, respectively (IBGE, 2025). In CNL, sampling was performed in rural and environmental preservation areas. No industrial influence was identified nearby, only light- and heavy-duty vehicle traffic. In GRA, PM collection was performed at two points: one of extreme vehicular influence, characterized by frequent traffic jams; and another point near an important federal highway, with high circulation of heavy-duty vehicles (Pletsch, 2019; Pletsch et al., 2025).

Sampling and quantification of metal variables

PM samples were collected by Alves et al. (2016), Pletsch (2019) and Alves et al. (2020) according to the conditions specified in Chart 1. The dichotomous collection equipment effected the inertial separation of fine and coarse particles using a virtual impactor, dividing the sample flow into two separate systems and fractionating the air sample at a sampling flow rate of 900 L/min ($PM_{2.5}$) and 100 L/min ($PM_{2.5\text{-}10}$). Extraction procedures are detailed in Alves et al. (2016), Pletsch (2019) and Alves et al. (2020).

Next, the metallic elements in the particles were quantified using chemical analysis and subsequent source identification. Alves et al. (2016), Pletsch (2019), and Alves et al. (2020) determined Ba and Zn using flame atomic absorption spectrometry (SpectrAA 110, Varian), and Al, Cd, Pb, Cu, Cr, Fe, Mn and Ni by graphite furnace atomic absorption spectrometry (ZEEnit 600, Analytik Jena AG).

Data processing

To determine the emitting sources from the PMF modeling, a database was organized gathering PM information reported by the three studies, indicating the date and place of collection, fraction and concentration collected ($\mu g/m^3$), and concentration of metallic elements (ng/m^3) quantified in each sample (Osório et al., 2022).

The initial database included Al, Ba, Cd, Pb, Cu, Cr, Fe, Mn, Ni, Zn and Hg. However, Hg was excluded for presenting values below the Method Detection Limit (MDL) throughout the analysis.

Positive matrix factorization

PMF is a mathematical model made available free of charge by the Environmental Protection Agency (USEPA), capable of identifying the emitting sources from data collected by receivers. Figure 2 illustrates its base operating model. PMF groups two data matrices into one matrix, and the combination between variables is known and reported in the literature because they present a pattern of behaviors and facilitate source identification (Adeyemi et al., 2021; Chatoutsidou and Lazaridis, 2022).

PMF incorporates the uncertainties of the contributions linked to each variable into the modeling, reducing influences from missing data or data below the method detection limit (MDL), attributing greater reliability to the analysis (Lee et al., 2023). Uncertainties

Chart 1 – Particulate matter — PM_{10} and $PM_{2.5}$ — sampling conditions in Campo Bom (CB), Canela (CNL), Canoas (CNS), Gramado (GRA) and São Leopoldo (SL).

Study	Location	Geographic Coordinate (UTM) Datum: SIRGAS 2000 Zone 22 S	PM collection equipment	Sampling duration (h)	Freq.	Filter type	Period
Alves et al. (2016)	CB	-	Stacked Filter Holder (SFH)	24	Monthly	47 mm diameter polycarbonate membrane	April/2013 to March/2014
	SL	-					
	CNS	-					
Pletsch (2019)	GRA	512,423.8 m W 6,749,993.6 m S 514,679.1 m W 6,752,153.6 m S	Dichotomous MCZ particle sampling system (MicroPNS-Dichoto model) and Fine and Coarse Sampler (FCS)	24	Monthly	47 mm diameter polycarbonate membrane	April/2021 to March/2022
	CNL	514,837.4 m W 6,757,950.3 m S					
Alves et al. (2020)	CNS	482,758.6 m W 6,689,826.1 m S	Stacked Filter Unit Low Volume Dichotomous Sampler	24	Monthly	47 mm diameter polycarbonate membrane	September/2015 to July/2017
	SL	485,307.3 m W 6,706,474.6 m S					

(UNC) of data above and below the MDL are calculated according to Equation 1 and Equation 2, respectively (US-EPA, 2014; Alves et al., 2020).

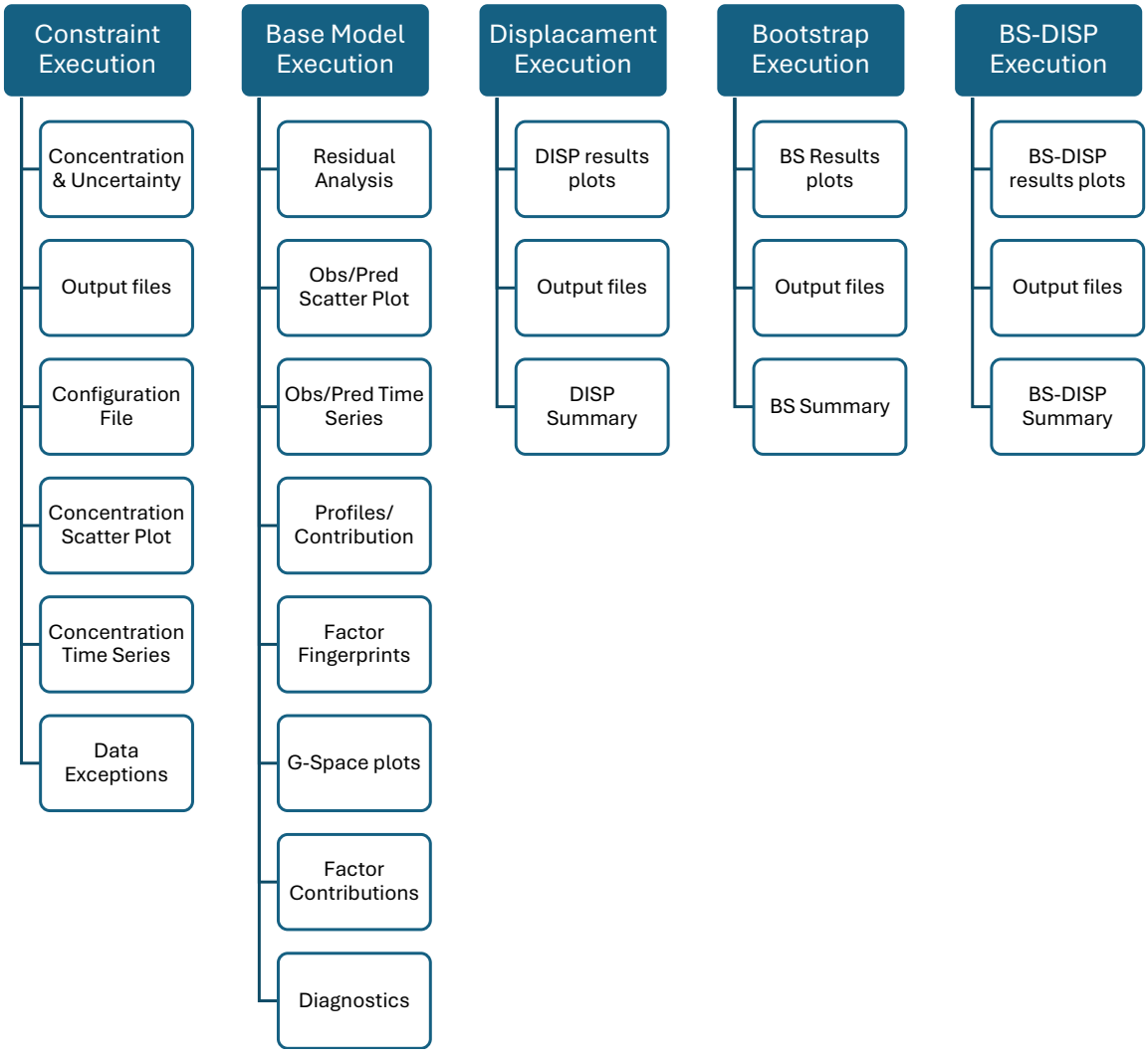
$$UNC = \frac{5}{6}\, x\, MDL \quad (1)$$

$$UNC = \sqrt{(Error\ Fraction\ x\ Concentration)^2 + (0{,}5 x MDL)^2} \quad (2)$$

where:
UNC (uncertainty): Uncertainty related to the concentration of the elements;
MDL: Method detection limit;
Error Fraction: Percentage of error;
Concentration: Concentration value of elements.

Hybrid single-particle lagrangian integrated trajectory

Developed by the National Oceanic and Atmospheric Administration - Air Resources Laboratory (NOAA-ARL), the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) is a mathematical model that estimates the trajectory of atmospheric particles. Backwards trajectories are defined according to recorded meteorological data (Endale et al., 2024). This study used data provided by the Global Data Assimilation System (GDAS), considering a 72-hour period and a height of 500 m above ground level to calculate the backwards trajectories of air masses (Alves et al., 2020). Coordinates of the PM sampling points were used as the point of arrival of the air masses. As Cu showed no association with the other metallic variables, remaining isolated in one of the factors, air mass trajectory was performed for Cu considering the days of highest Cu concentration in both PM fractions.



Source: Adapted from US-EPA (2014).
Figure 2 – Flowchart of Positive Matrix Factorization (Base Model) operations.

Enrichment factor

EF (Equation 3) estimates whether atmospheric particles have been chemically enriched by anthropogenic factors or are derived from natural processes.

$$EF = \frac{\frac{Cs}{Crs}}{\frac{Cc}{Crc}} \quad (3)$$

In which:

EF: an enrichment factor (dimensionless value);

Cs: the concentration of the metallic variable in the sample;

Crs: the concentration of the reference element in the sample;

Cc: the concentration of the metallic variable found in the Earth's crust;

Crc: the concentration of the reference element in the Earth's crust.

In other words, *EF* is given by the ratio between the concentration of the chemical element of interest and the concentration of a reference element, which must be a potential chemical component of the Earth's crust. Aluminum (Al) is abundantly present in the chemical composition of the lithosphere and has been used as a reference element for EF determination, except by Pletsch (2019), who did not quantify Al in the PM concentrations collected.

Data on the concentration of metallic elements in the Earth's crust used as a reference were extracted from Wedepohl (1995). Notably, other studies (Vieira et al., 2024; Paccosonco-Sucapuca et al., 2025; Souza et al, 2025) used this same reference to evaluate EF, thus enabling a comparison of the obtained results with those reported in the literature. The degree of enrichment was defined by the contribution scale described by Elhadi et al. (2018), in which: results below 5 indicate that the particles are of crustal origin; between 5 and 10, that they have moderate EF, possibly originating from natural or anthropogenic processes; and above 10, that they have high EF, confirming that the chemical contributions present in the particles derive from anthropogenic activities.

Results and Discussion

Positive matrix factorization

Table 1 indicates the PM_{10} and $PM_{2.5}$ concentrations (μg/m³) available in the databases of the studies by Alves et al. (2016), Pletsch (2019) and Alves et al. (2020).

Table 2 shows the concentrations of metals quantified by analyzing the filters used to collect the PM_{10} and $PM_{2.5}$ samples, as reported by Alves et al. (2016) and Alves et al. (2020). Pletsch (2019), in turn, identified the present metals, but without the respective quantification.

Source identification used a database with 141 samples and ten metals (Al, Ba, Cd, Pb, Cu, Cr, Fe, Mn, Ni and Zn). The modeling groups the factors based on the correlation between the metallic elements. The metallic composition of each factor was defined considering variables with occurrence greater than or equal to 40%. Source identification is based on the distribution of variables into factors, and this number is defined by a prediction derived from output data interpretation. All performed tests considered three and four factors; however, the best distribution scale occurred with four-factor tests (Figure 3).

The three-factor PMF identified light-duty vehicles, heavy-duty vehicles and industrial sources, whereas soil dust resuspension was confused with the emission factor of light vehicles. Additionally, from three to four factors, the Q_{true}/Q_{Robust} ratio dropped from 1.92 to 1.47, 100% of which were mapped.

Factor 1 (F1) correlates the elements Ba, Pb, Cr, Fe, and Ni, suggesting that 35% of all PM concentration derives from light-duty vehicular emissions. Chatoutsidou and Lazaridis (2022) describe that Ba, Pb, Cr, and Ni are used as additives in the composition of vehicle oils and fuels. Ba can also be used to manufacture synthetic rubber for tires, the particles of which are emitted during tire wear in friction with the asphalt, and is an indicator of brake wear (Alves et al., 2020). Pb emission can be associated with brake pad wear (Fernandes et al., 2021; Gurgatz et al., 2025), and Ni is emitted during the combustion of

Table 1 – Mean, median, minimum, maximum concentrations (μg/m³), standard deviation (SD) and number (n) of particulate matter — PM_{10} and $PM_{2.5}$ samples

Study	Location	$PM_{2.5}$						PM_{10}					
		Mean	Median	Min.	Max.	SD	n	Mean	Median	Min.	Max.	SD	n
Alves et al. (2016)	CB	5.2	-	1.8	11.6	3.6	10	15	-	2.2	51.2	13.5	10
	SL	39.1	-	8.9	108.5	27.9	12	24.8	-	1.9	73.5	28.1	12
	CNS	26.2	-	2.0	77.6	22.4	10	20.5	-	2.0	69.4	22.3	10
Pletsch (2019)	GRA	18.79	9.28	1.39	102.5	-	11	72.08	61.81	2.51	163.90	-	11
	CNL	7.23	5.91	0.23	21.52	-	11	8.48	5.63	1.04	35.08	-	11
Alves et al. (2020)	CNS	25.09	21.38	6.94	69.44	18.40	28	68.80	76.39	6.94	168.65	46.59	31
	SL	20.12	13.89	6.61	150.46	29.46	28	50.96	33.07	7.31	358.80	71.82	31

Table 2 – Mean concentration (ng/m³) of metals in the particulate matter — PM_{10} and $PM_{2.5}$ — samples identified in Alves et al. (2016) and Alves et al. (2020).

PM fraction	Metal	Mean concentration				
		Alves et al. (2020)		Alves et al. (2016)		
		SL	CNS	CB	SL	CNS
$PM_{2.5}$	Al	1,477.18	637.24	30.00	76.92	99.77
	Ba	273.54	23.01	nd	313.12	359.25
	Cd	5.09	1.23	0.03	2.07	1.75
	Pb	9.16	10.88	18.72	8.25	6.13
	Cu	48.81	40.84	3.50	2.26	4.42
	Cr	3.24	3.82	3.51	6.00	42.60
	Fe	139.54	269.39	36.89	121.18	86.89
	Mn	9.07	6.27	8.12	3.87	3.67
	Ni	6.78	7.22	5.05	17.42	11.46
	Zn	76.52	29.82	37.67	57.08	120.00
PM_{10}	Al	3,589.26	1,049.94	78.89	68.89	138.35
	Ba	30.26	117.52	nd	311.41	558.49
	Cd	0.88	1.28	nd	12.55	6.28
	Pb	7.71	8.98	0.57	31.53	6.68
	Cu	489.87	27.46	2.16	7.46	10.85
	Cr	3.61	3.37	2.18	4.33	78.25
	Fe	419.62	565.47	106.27	43.09	78.42
	Mn	24.99	15.2	6.13	9.95	28.33
	Ni	19.44	10.13	2.25	1.86	46.59
	Zn	160.81	41.04	40.29	81.99	171.34

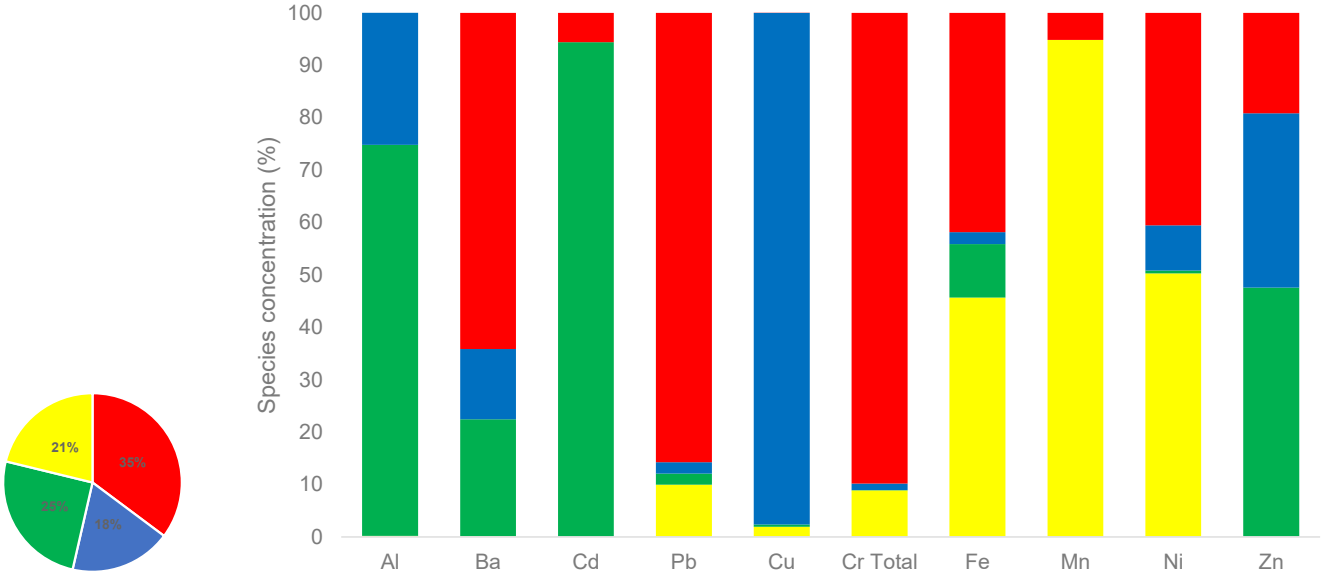


Figure 3 – Main particulate matters emitting sources identified by positive matrix factorization.

petroleum products (Costa et al., 2018). Associated with the other F1 elements, Fe can originate from road dust resuspension (Viana et al., 2008), whereas Cr and Ni have vehicle emissions as their source (Miranda et al., 2018; Guo et al., 2022).

Fe, Mn and Ni distribution in Factor 2 (F2) represents 21% of the entire PM concentration analyzed, suggesting that particles presenting this metallic association come from soil dust resuspension and vehicle emissions. Fe, Mn, and Ni are abundant elements in the composition of the lithosphere, and can be naturally resuspended during erosion and weathering processes, or by anthropogenic processes in the topographic modification performed for project implementation (Costa et al., 2018; Yang et al., 2023). Gurgatz et al. (2025) also attributed the presence of Fe and Mn to soil resuspension in a coastal Paraná municipality. Similarly, Costa et al. (2025) associated the presence of Fe with this same source in Aracaju, Sergipe.

Despite their natural contribution, Fe and Mn are also associated with vehicle emissions — Fe is emitted during brake pad wear (Shahne et al., 2022), Mn can be used to replace Pb in gasoline composition (Costa et al., 2018), and Ni is emitted by the combustion of petroleum derivatives (Park et al., 2022).

Factor 3 (F3) derives from the emission of heavy-duty vehicles, representing 18% of the entire studied PM concentration, and is composed of Cu not associated with another metal. Due to its antioxidant properties, Cu is often used as an additive in the composition of motor oils and released as gas in the vehicle exhaust process (Miranda et al., 2018; Javed and Guo, 2021). To support the PMF results, we traced the trajectory of the air masses using the HYSPLIT dispersion model. Cu and Ni achieved their highest concentration on August 7, 2013, in Canoas (Figure 4). The third highest Ni concentration occurred on February 19, 2014 (Figure 5). HYSPLIT modeling identified the particle trajectories, revealing their transportation from the states of Minas Gerais and São Paulo, in southeastern Brazil, to the receiver (Figure 4).

The association between Al, Cd and Zn represented by Factor 4 (F4) equals 26% of the entire PM data, and suggests that the particles originate from industrial sources, since the rubber industry vulcanizes tires with zinc oxide, characterizes the correlation between Al and Zn as an industrial source, and identifies Cd in the composition of rubber during tire manufacturing (Alves et al., 2015; Alves et al., 2020). Additionally, Cd is used as a by-product of zinc mining, explaining its frequent association (Illi et al., 2017), and Zn is related to galvanizing activities (Pabroa et al., 2022).

Enrichment factor

EF evaluated the chemical contributions in the $PM_{2.5}$ and PM_{10} derived from natural or anthropogenic sources. EF calculation considered Al as a reference element; thus, the PM concentrations from Pletsch (2019) were disregarded, since the study did not quantify Al. Figure 6 shows the obtained EF results for each PM fraction, of which EF values above 10 are classified as strongly enriched.

EF presented similar behavior for both studies and PM fractions. For most metallic elements, EF was higher for $PM_{2.5}$ compared with PM_{10} in both studies, corroborating the anthropogenic influence of fine particles ($PM_{2.5}$) in the atmosphere (Pabroa et al., 2022).

Alves et al. (2020) identified strong enrichment in $PM_{2.5}$, with concentrations of Ba, Cd, Pb, Cu, Cr, Ni and Zn. PM_{10} showed enrichment for the same elements, except for Ba, indicating that their occurrence in the atmosphere comes from anthropogenic activities, mainly industries and vehicles. Benatti et al. (2022) described the association of Cd with diesel combustion by heavy-duty vehicles, and that of Pb, Cu and Zn with the circulation of light-duty vehicles, pointing out that Pb and Cu make up vehicle components like fuels and lubricating oils.

Feng et al. (2022) and Gamelas et al. (2023) identified Ni emissions in the burning of diesel fuels by marine engines. The municipalities studied by Alves et al. (2016) are near the Atlantic Ocean, confirming that part of the Ni concentration may present maritime contributions reaching the receiver from the displacement of air masses. Air mass trajectories from February 19, 2014 (date of the third highest observed Ni concentration in the city of SL) indicated the passage of the air mass over the Atlantic Ocean (Figure 5). Thus, part of the Ni emission may come from marine engines.

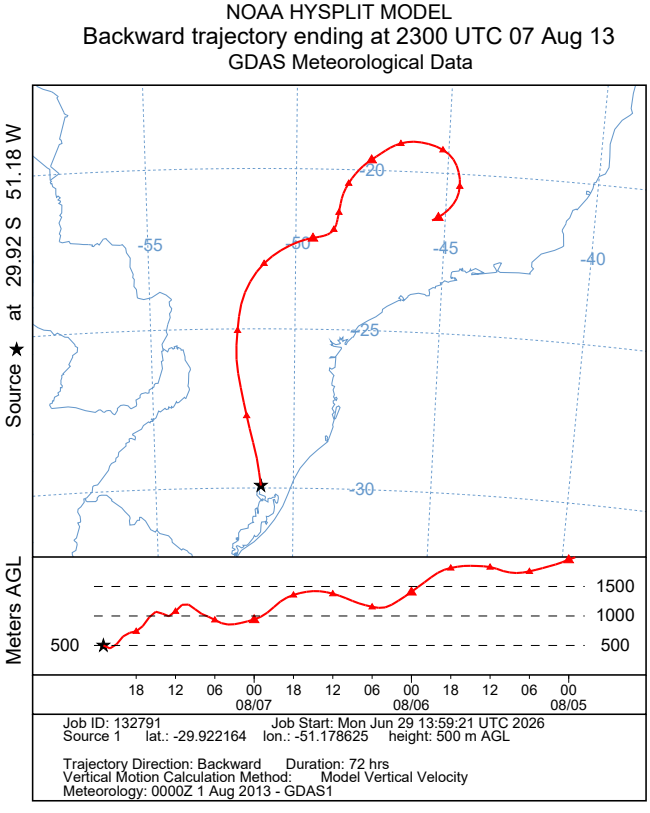


Figure 4 – Backward trajectory of air masses on the day of highest Cu and Ni concentration.

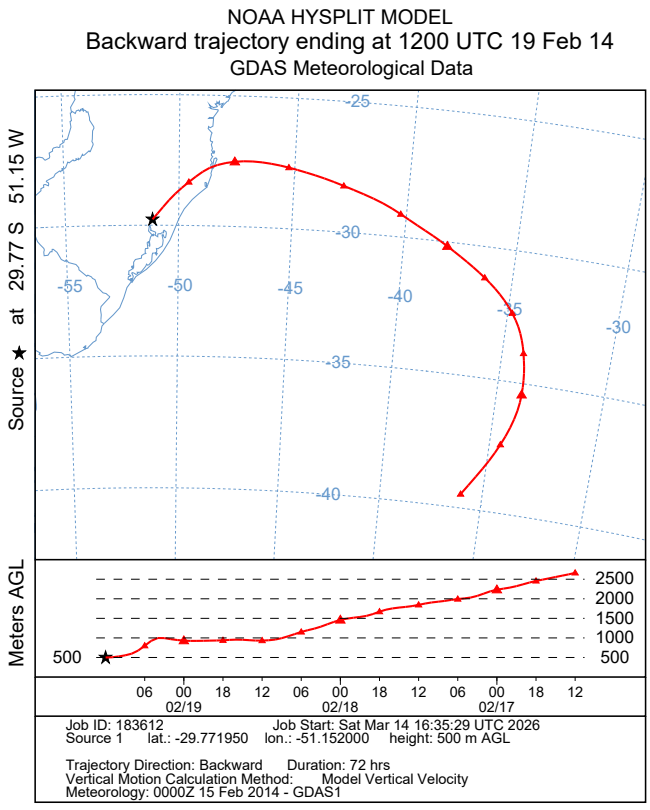


Figure 5 – Backward trajectory of air masses on the third day of highest Ni concentration.

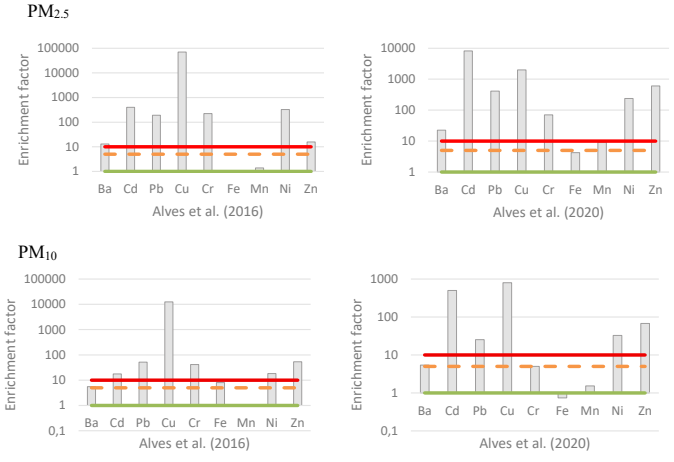


Figure 6 – Enrichment Factor for particulate matter — PM_{10} and $PM_{2.5}$.

Alves et al. (2020) identified the elements Ba, Cd, Pb, Cu, Cr, Mn, Ni, Zn and Hg as strongly enriched in $PM_{2.5}$, and Cd, Pb, Cu, Ni, Zn and Hg in PM_{10}. Presence of Cr can be related to vehicular traffic and Hg to industrial emissions, such as the production of castings from non-ferrous metals and their alloys (Guo et al., 2022).

Regarding Fe, the particles showed no strong enrichment in any of the studies, pointing to natural sources for this element. This observation can be attributed to the distance of the sampling stations to mining zones, since the proximity to such activities usually results in high enrichment factors. However, the coarse Fe fraction quantified by Alves et al. (2016) and the fine Fe fraction quantified by Alves et al. (2020) showed moderate enrichment, indicating that a percentage of Fe particles have an anthropogenic origin, since the metal is used in manufacturing tools and automotive parts, and in civil engineering.

According to the modeling employed, the sources identified by PMF were consistent with the EF calculation results. Results suggest that Fe and Mn were not significantly enriched, underscoring that their occurrences in the atmosphere stem from natural particles in the crust. Ba, Cd, Cu, Pb, Cr, Ni and Zi were strongly enriched, indicating that industrial activities and the circulation of vehicles produce concentrations of air pollutants.

Conclusion

PMF applied for source identification revealed that the PM load is predominantly of anthropogenic origin, with the transport sector appearing as the most significant contributing source. Of the four factors estimated and identified as the main emission sources, two were associated with vehicle emissions (53%), one with soil resuspension (21%), and another with industrial sources (26%).

Concurrently, the EF values obtained corroborate the human influence on the chemical composition of the samples, showing that metals such as Ba, Cd, Cu, Pb, Cr, Ni, and Zn have an anthropogenic origin and a high EF. In contrast, Fe and Mn derive from natural sources and present a low degree of enrichment.

Convergence between the PMF results and the enrichment indices reinforces that the identified metallic trace elements are mostly derived from anthropogenic processes, highlighting the robustness and methodological complementarity of the statistical approaches employed.

Our results underscore the need for measures to control emissions, and can serve as a technical basis for better management of environmental air quality policies.

Authors' Contributions: Gonçalves, P.B.: conceptualization; formal analysis; writing – review & editing; Nicioli, L.: conceptualization; investigation; data curation; software; writing – original draft; Nogarotto, D.C.: methodology; formal analysis; writing – review & editing; Osório, D.M.M.: methodology; formal analysis; writing – review & editing; Pozza, S.A.: conceptualization; methodology; formal analysis; project administration; writing – review & editing.

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