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The Impact of Heavy Industrial Activity on Air Quality in Barreiro, Portugal: A Comprehensive Study

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Industrial emissions have a considerable impact on urban air quality, releasing a range of deleterious gases that contribute to environmental concerns and public health issues. In light of the aforementioned issues, this study aims to assess the impact of the closure of certain industries on air quality in the city of Barreiro, Portugal. The evolution of air quality in the city was examined over the period from 2000 to 2011. During this period, a number of heavy industries in the city were closed down. Consequently, an investigation was conducted to ascertain the impact of the gradual closure of industrial units in the city on the evolution of air quality. The analysis of the evolution of daily and monthly average concentrations of PM_{10} and SO_2 in the city over the years, from January 2000 to December 2011, indicates a general improvement in air quality levels throughout this period. The results demonstrate that following the closure of certain industrial facilities, the mean concentrations of PM_{10} exhibited a decline of 33.30% and 26.50%, respectively, at the Escavadeira and Lavradio air quality (AQ) stations within the city. Similarly, the mean concentration of SO_2 decreased by 64.70% and 84.60%, respectively, in the same AQ stations. With regard to the maximum values (peaks) of PM_{10} concentrations, a decrease of 40.90% and 26.50% was observed in the analysed AQ stations, while SO_2 maximum concentrations (peaks) decreased by 61.30% and 89.60% in the same AQ stations. This evaluation revealed a significant enhancement in air quality following the closure of numerous industrial facilities.

Keywords: Air quality, gas emissions, industrial activity, SO_2, PM_{10}, environmental pollution.

Introduction

Industrial emissions constitute a significant source of urban air pollution, releasing a complex mixture of harmful gases that can have profound implications for human health and the environment (MEE, 2021). The sustained release of pollutants, including sulphur dioxide (SO_2), nitrogen oxides (NO), and particulate matter

(PM), not only affects air quality but also poses a significant risk to public health, leading to respiratory problems and other diseases. These pollutants have been linked to a range of health issues, including respiratory and cardiovascular diseases, and are also implicated in the broader environmental challenge of climate change (Lin et al., 2023; Manisalidis et al., 2020).

One significant consequence is the exacerbation of respiratory and cardiovascular diseases among the urban population (Burroughs et al., 2017; Abdel-Shafy and Mansour, 2016). Fine particulate matter, released by industrial processes, has the potential to penetrate deeply into the lungs, thereby causing or exacerbating respiratory conditions (Kelishadi et al., 2010). Long-term exposure to air pollutants has been linked to an increased risk of cardiovascular disease, representing a significant public health concern (Manucci and Franchini, 2017).

Moreover, industrial emissions play a substantial role in the formation of ground-level ozone (O_3), a primary constituent of smog. Ozone has been demonstrated to cause respiratory irritation and to exacerbate existing health conditions (Singh et al., 2009). In addition to the immediate health impacts, air pollution from industrial sources also contributes to climate change. Greenhouse gases, including carbon dioxide (CO_2) released during combustion processes, contribute to global warming (Stjern et al., 2020).

It is imperative that these issues are addressed with the utmost urgency. The implementation of sustainable practices and the reduction of emissions represent pivotal steps towards the safeguarding of urban populations and the environment (Guo et al., 2017; Hoesly et al., 2018; Incecik et al., 2014; Garcia et al., 2012). This encompasses the adoption of cleaner technologies, the enforcement of more rigorous emission standards, and the dissemination of information to the public regarding the consequences of air pollution (Crippa et al., 2018, Crippa et al., 2019).

It is a complex challenge that requires a unified approach from industries, policymakers, and communities to ensure a healthier future for our cities and the planet.

The urban environment is undergoing significant transformation as a result of the closure of heavy industries due to economic shifts, technological advancements and environmental concerns. The impetus behind investigating the impact of these closures on air quality is rooted in the recognition of air pollution as a significant public health concern (West et al., 2013). The closure of heavy industries provides an opportunity to study the impact of reduced industrial emissions on air quality and, subsequently, the well-being of urban populations (Halliburton et al., 2006).

The potential health implications related to the benefits associated with the closure of heavy industries are well documented (Anenberg et al., 2012). The objective of this study is to analyse the changes in air quality before and after the closure in order to evaluate the positive effects on both air quality and public health.

The study of the impact of industries is aligned with global efforts to promote environmental sustainability. The assessment of the impact of heavy industry closure on air quality is a crucial step in understanding how urban areas can transition towards cleaner and more sustainable economic practices. This supports the global agenda for reduced carbon emissions and the mitigation of climate change (Vallius, 2005; Iijima et al., 2008).

In terms of policy and regulatory implications, the insights derived from this research have the potential to inform and influence policy and regulatory frameworks. The findings can inform the formulation of evidence-based policies by governments and environmental agencies that balance industrial development with the need to protect air quality and public health (Haines et al., 2017).

The involvement of local communities in air quality studies has been shown to foster a sense of awareness and empowerment (Kumar et al., 2010). By illustrating the concrete consequences of heavy industry closure on air quality, communities can become proponents for sustainable urban development and contribute to the informed decision-making of authorities.

Materials and Methodology

Methodology

The research project employed a multi-disciplinary approach, integrating historical data analysis, meteorological assessments and industrial source identification, with the objective of evaluating air quality trends and the impact of industrial activities in Barreiro. The study comprised a number of stages designed to ascertain the impact of historical and current industrial activities on air quality. The city's geographical and demographic context was initially delineated, with particular attention paid to its industrial history and the significant levels of traffic that traverse it. The characterisation of air quality was conducted through an examination of historical data on PM_{10} concentrations from 2010, provided by the Portuguese Air Quality Network (CCDR-LVT). The data was employed for the purpose of identifying pollution trends and sources. In order to gain insight into the meteorological conditions that influence the dispersion of pollutants, data from the Lavradio meteorological station were subjected to analysis, including temperature and wind patterns observed over several decades. The data on wind direction and speed were of particular importance in evaluating the dispersion of pollutants across the city. Additionally, the study identified significant industrial sources of pollution, including the Energia de Portugal (EDP) cogeneration unit, the Quimigal/Lavradio complex, and others. Information regarding emissions from these sources, including pollutants such as SOx, NOx, and particulates, was obtained from historical records and reports. Furthermore, the influence of recent developments, such as the FISIGEN cogeneration plant, was evaluated, noting enhancements in emission control technologies.

Barreiro localization and activities

The city of Barreiro is situated within the municipality of Barreiro, in the district of Setúbal, on the south bank of the Tagus River, in close proximity to Lisbon and Almada. The municipality of Barreiro, which encompasses an area of approximately 33 km², is constituted by the following boroughs: the boroughs of Santo António da Charneca, Alto do Seixalinho, Santo André and Verderena, Barreiro and Lavradio, and Palhais and Coina are all united boroughs. The municipality is bordered to the north by the municipalities of Palmela and Sesimbra, to the south by the municipality of Moita, to the west by the Esteiro, a 6 km long waterway where the Tagus River and Coina Creek converge, and to the east by the municipality of Moita, from the Quinta dos Morgados area to Penalva. The municipality's northern border is defined by the Tagus River, which forms the municipality's eastern and southern boundaries. The western border is formed by the Esteiro, a waterway where the Tagus River and Coina Creek converge. The municipality is situated within the Tagus River hydrographic basin, which encompasses a largely flat area. The population in 1991, was 85,800 residents,

Fig. 1. *Study area (source: Google Earth)*

dropping to 78,400 in 2021, in a gross area of 34 km^2, in spite of the variation in the resident population had a large increase in the 60s and 90s (around 40%). Furthermore, the city of Barreiro had one of the highest ratios of motor vehicles per capita, ranking just after Lisbon and Porto. Presently, despite the gradual deactivation of a portion of its industrial sector, the municipality continues to exhibit a considerable degree of industrial activity. The municipality is part of the Lisbon Metropolitan Area, with a significant proportion of its population engaged in employment within the city of Lisbon. This contributes to the municipality adopting a mixed urban typology, comprising residential, industrial and agricultural functions. The city is connected to Lisbon by a permanent river route. The economy was predominantly oriented towards the metalworking and chemical industries.

Characterisation of air quality in Barreiro

The city of Barreiro is distinguished in terms of air quality by the impact of the predominant activities conducted within its boundaries. Accordingly, the principal sources of atmospheric contamination can be attributed to two primary factors: industrial activity within the city (Cerdeira et al., 2007) and vehicular traffic (Garcia et al., 2014). The industries that have been identified as the most problematic are the EDP cogeneration unit, the Adubos de Portugal facility engaged in the production of basic inorganic chemicals and fertilisers, and the Quimitecnia factories responsible for the manufacture of dicalcium phosphate and aluminium sulphate. In the borough of Paio Pires, which is located within the municipality of Seixal, the steelmaking unit of Lusolider is particularly noteworthy. Given the significant industrial presence in Barreiro, it was the only location in the Lisbon and Tagus Valley region to exceed the SO_2 limit values (Gomes, 2008), as indicated by measurements from air quality stations.

Table 1 presents a concise characterisation of the PM_{10} air concentration values for the typical year of 2010, as measured through the Portuguese Air Quality (AQ) Network (CCDR-LVT).

Table 1 illustrates that the Alto Seixalinho AQ station exhibits the highest values for PM_{10} concentrations, with an annual average of 33.5 μg/m^3 and a maximum hourly concentration of 164.6 μg/m^3.

Table 1. *Summary characterization of PM_{10} air concentrations in 2010 (Garcia et al., 2010)*

Air Quality Station	Alto Seixalinho	Escavadeira	Fidalguinhos	Lavradio
Average Annual hourly basis (μg/m^3)	33.50	22.00	23.90	23.60
Annual Average daily basis (μg/m^3)	33.60	22.00	23.90	23.60
Maximum Annual hourly basis (μg/m^3)	164.60	149.90	178.70	125.40
Maximum Annual daily basis (μg/m^3)	106.50	80.10	115.20	105.20

Meteorological characterization

The identification of the city's principal meteorological parameters was based on meteorological data from the Lavradio meteorological station, the closest station to the study area. The data available for analysis correspond to the region's climatological normal and were made available by the Portuguese Institute of the Sea and Atmosphere (IPMA), previously known as the Meteorology Institute. *Table 2* provides a summary of the general features of the Lavradio Meteorological Station, while *Table 3* presents the meteorological parameters collected by this station.

Table 2. *General features of the Lavradio meteorological station (IPMA, 2022)*

Station	Latitude N	Longitude W	Altitude (m)
Lavradio	38°41'	9°03'	6

Table 3. *List of meteorological parameters recorded at the Lavradio station (IPMA, 2022)*

Average annual temperature (°C)
Total precipitation (mm)
Relative humidity (%)
Number of days per year with precipitation > 10mm
Fog (days)
Cloudiness (9 hours) (scale 0-10)
Frost (days/year)

Table 4 illustrates the monthly values of temperatures recorded by this station over a 23-year period (1967-1990).

The columns represent the respective averages for each temperature category: average temperature (TMED), average maximum temperatures (Average TMAX), average minimum temperatures (Average TMIN), absolute maximum temperature (Abs TMAX) and absolute minimum temperature (Abs TMIN).

Table 5 presents the monthly wind values recorded at the Lavradio station for the period between 1967 and 1990. The columns correspond to the respective directions of wind: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). The frequency of occurrence (FO) and the average wind speed (AS) are also indicated. The final column illustrates the frequency of periods of calm, defined as conditions with wind speeds below 1 knot.

Table 4. *Temperatures measured at the Lavradio station (IPMA, 2022)*

Month	TMED (°C)	Average TMAX (°C)	Average TMIN (°C)	Abs TMAX (°C)	Abs TMIN (°C)
JAN	10.80	14.50	7.10	20.50	-1.50
FEB	12.10	15.70	8.60	22.20	0.60
MAR	13.20	17.50	9.00	26.00	1.40
APR	14.90	19.20	10.60	28.50	0.00
MAY	17.10	21.60	12.70	35.00	3.50
JUN	20.10	25.10	15.20	37.00	5.00
JUL	22.40	27.80	17.30	38.50	11.00
AUG	22.70	28.10	17.30	37.50	10.00
SEP	21.40	26.60	16.30	37.50	8.50
OCT	18.00	22.50	13.50	32.00	3.50
NOV	14.00	17.90	10.20	25.10	0.80
DEC	11.40	15.20	7.70	24.50	-0.50
YEAR	16.50	21.00	12.10	38.50	-1.50

Table 5. *Wind intensity and frequency values collected at the Lavradio station (IPMA, 2022)*

M.	N FO	N AS	NE FO	NE AS	E FO	E AS	SE FO	SE AS	S FO	S AS	SW FO	SW AS	W FO	W AS	NW FO	NW AS
JAN	8.50	10.10	16.40	11.00	3.30	7.50	11.80	8.70	7.20	12.40	17.60	11.70	5.80	10.40	16.40	12.60
FEB	9.40	9.80	13.40	9.80	1.30	5.40	11.80	10.80	7.70	14.00	19.90	14.40	5.60	9.70	23.20	13.90
MAR	12.60	12.20	13.90	9.00	3.00	6.80	5.20	12.00	4.40	10.40	16.90	12.10	5.60	10.60	34.00	14.20
APR	11.20	11.10	12.60	12.40	2.30	7.90	5.80	12.30	3.60	13.60	14.90	12.70	7.9	11.10	38.60	16.20
MAY	11.20	12.30	6.40	10.90	0.90	8.10	3.00	13.00	3.00	16.20	18.20	13.40	7.6	12.00	48.00	15.6
JUN	11.80	12.60	6.80	9.20	0.60	12.40	2.70	10.90	2.40	12.00	17.80	12.10	6.6	11.80	50.50	14.30
JUL	17.10	12.10	6.10	9.00	1.20	5.00	0.70	10.20	1.30	11.90	12.80	12.00	5.4	11.50	53.00	14.00
AUG	16.00	13.10	6.30	10.10	1.20	4.40	1.40	9.50	0.70	13.70	9.20	12.00	4.7	11.10	58.50	14.50
SEP	10.50	11.30	11.90	8.10	1.40	4.60	6.00	8.60	3.00	12.20	16.80	12.20	8.8	9.80	37.80	13.10
OCT	9.70	10.50	15.60	8.20	1.90	10.60	10.00	9.20	6.30	11.30	14.60	10.30	6.6	9.90	24.40	12.00
NOV	15.00	12.30	23.40	10.20	2.60	7.40	10.60	10.40	3.90	10.90	9.90	9.30	4.5	8.20	19.10	12.70
DEC	13.40	10.90	22.20	10.20	3.10	6.50	8.60	10.30	4.90	13.90	12.70	12.30	3.7	8.60	15.60	12.10
YEAR	12.20	11.70	12.90	9.90	1.90	7.10	6.40	10.30	4.00	12.60	15.10	12.20	6.1	10.50	35.10	14.10

FO – Frequency (%); AS – Average speed (km/h).

Fig. 2. *Compass card from the Lavradio meteorological station (IPMA, 2022)*

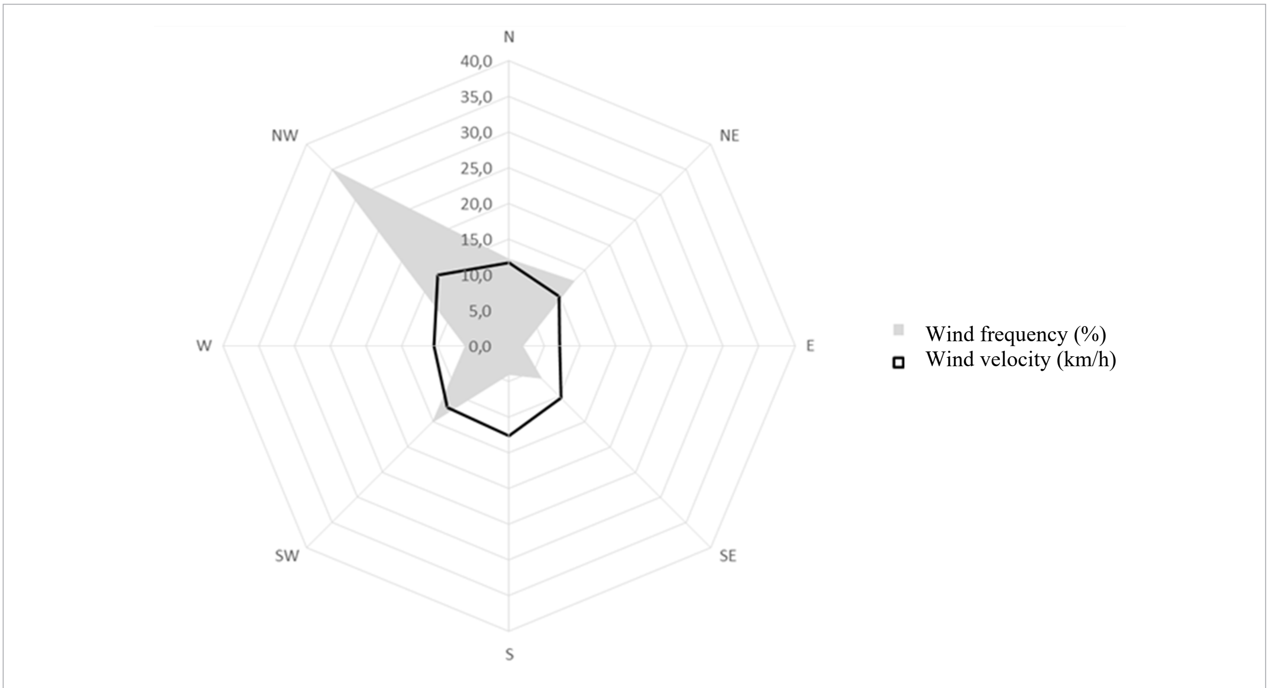


Fig. 2 illustrates the compass card of the Lavradio station for the period between 1967 and 1990. A detailed examination of the data reveals that the predominant direction of the winds is from the northwest (frequency 35.1%), with the highest wind speeds recorded corresponding to the south (12.6 km/h). Additionally, the data indicates that the predominant direction is also from the northwest (14.1 km/h). The highest frequency of north-west winds is observed during the summer months, specifically in June, July and August. The maximum value is recorded in August, at 58.5%. In this regard, the lowest frequency values are observed in December, with a recorded value of 15.6%. The mean wind speed is relatively constant throughout the year, with maximum values recorded in April (16.2 km/h) in the NW direction.

A further factor to be taken into account when characterising meteorology is the stability of the atmosphere. The local dispersion of pollutants is promoted to a greater extent when the atmosphere is very unstable, whereas dispersion is less effective when the atmosphere is very stable. The frequency values of the stability classes for Setúbal (Domingos et al., 1980) were considered, as no values for Barreiro could be found. The atmospheric conditions in both cities are identical due to the similarity of their environmental context and proximity. The frequency of occurrence of each stability class is presented in *Table 6*. It can be observed that the neutral class represents the most frequent stability condition (46.9%).

Table 6. *Frequency values of stability classes for Setúbal (Domingos et al., 1980)*

Stability Class	Frequency
Very Unstable	0.24%
Moderately Unstable	16.00%
Slightly Unstable	20.31%
Neutral	**46.90%**
Slightly Stable	3.25%
Moderately Stable	6.82%

Identification of industrial sources

As previously stated, the primary sources of air pollution in the city of Barreiro were predominantly associated with two key aspects that characterise the city's activity: industrial activity within the city and road traffic. The article does not address emissions resulting from road traffic, as its focus is on sources of industrial origin. Accordingly, the principal sources of pollution at the time of the study were identified as follows (García et al., 2014; Gomes, 2008; Camarão, 2008):

1 Barreiro Thermoelectric Power Plant – CPPE (giving rise to the FISIGEN cogeneration plant in April 2010).
2 Quimigal/Lavradio industrial complex.
3 Quimitécnica dicalcium phosphate factory.
4 Quimitécnica aluminium sulphate factory.
5 Lusol cooking oil factory.
6 Fisipe acrylic fibre factory.

The Barreiro thermoelectric power plant operated as a cogeneration unit, distributing steam to industrial units in the industrial complex (Fisipe and Quimigal), in addition to producing electrical energy for the grid. Since steam was produced by two fuel oil boilers, emissions of atmospheric pollutants came mainly from combustion gases, especially SOx, NOx and particulates, with SOx emissions being directly related to the sulphur content of the fuel. There were also emissions of carbon monoxide and heavy metals. However, emissions from the existing fuel tanks due to evaporation were of minor importance and consisted mainly of volatile organic compounds (VOCs). The plant was closed in 2009 and has been dismantled, demolished, soil decontaminated and waste managed.

The Quimigal/Lavradio industrial complex produced ammonia, nitric acid, ammonium nitrate and urea. At that time, the sulphur contained in the raw material of the ammonia plant was recovered to produce sulphuric acid. In 2000, the ammonia, urea, nitric acid, ammonium nitrate and sulphuric acid plants were in operation.

The ammonia plant was intended to produce NH_3 for further processing into nitrogen fertilisers. The main emissions at the time were from the boiler chimney and the overheater, with the pollutants emitted being SOx, NOx and particulates.

The urea plant produced urea from ammonia and carbon dioxide, both of which were produced in the ammonia plant. The main emissions at that time were from the prilling tower, with urea and ammonia particles as the main pollutants. Emissions of formaldehyde occurred sporadically when this compound was used as an additive.

The nitric acid plant developed a process based on catalytic oxidation of ammonia followed by absorption of the nitrogen oxides formed in water. The main source of emissions was the waste gas from the absorption tower (tail gas). The main resulting emissions were NOx, with ammonia also being emitted. The plant had a NOx catalytic reduction unit to control the flue gas emissions.

The ammonium nitrate plant produced an 88% ammonium nitrate solution from ammonia and nitric acid. Atmospheric emissions occurred due to the scrubbing of gases from the gas/liquid separator after the neutraliser. The emissions consisted mainly of ammonia and nitric acid and were therefore not considered.

The sulphuric acid plant used the sulphuric acid stream from the ammonia plant. H_2S was first oxidised to SO_2 in a furnace and then to SO_3 in a converter. The SO_3 produced was absorbed with water to produce sulphuric acid. Emissions under normal operating conditions were from SO_2 that was not converted to SO_3 and was released up the chimney.

Quimitecnia operated two plants, the dicalcium phosphate plant and the aluminium sulphate plant. In the dicalcium phosphate factory, this compound was produced from phosphorite, hydrochloric acid and lime, with atmospheric emissions from two drying lines, which emitted dicalcium phosphate particles together with the combustion gases, and emissions from a steam boiler. In the aluminium plant, this compound was produced as a result of the reaction between aluminium hydroxide and sulphuric acid. Emissions from this process came from combustion in the steam generator.

Fisipe produces synthetic acrylic fibres. The main emissions to the atmosphere are from the drying of the polymer, which results in the emission of particles from a chimney.

Lusol processed oilseeds that produced crude oil through a process of pressing and solvent extraction. The unused fraction, meal, was used in the manufacture of animal feed after granulation. Crude oil refining, also carried out in this unit, produced a fraction that was used in the production of soap. The main atmospheric emissions came from the flour granulation process and the presence of four steam production boilers, which produced combustion gases (SOx, NOx and particulates).

An aerial photograph from the time showing the location of the point sources in question is shown in *Fig. 3*.

Fig. 3. *Aerial photography showing the location of the main industries and AQ stations considered in study (adapted Garcia et al, 2010)*

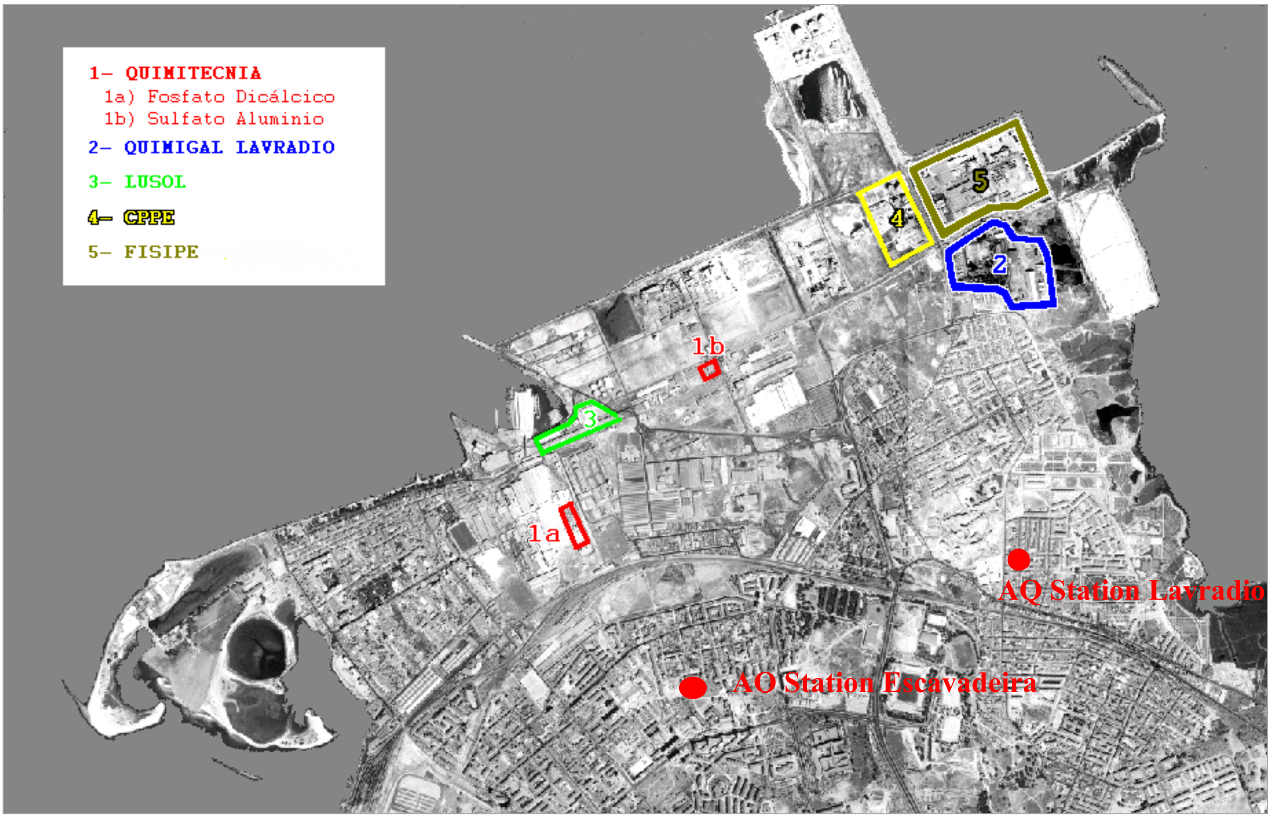


Table 7. *Location of point sources and emission conditions ((Garcia et al., 2010)*

Factory	Source	Chimney	UTM X	UTM Y	H (m)	Temp (°C)	Avg. Speed (m/s)	Diam. (m)
CPPE	Central Term.	General	95,388	80,975	104.00	165.00	12.87	2.50
Quimigal Lavradio	Ammonia	Boiler/over-heater	95,745	80,623	60.00	256.00	5.81	1.80
	Nitric acid	Tail gas	95,845	80,523	40.00	110.00	14.50	1.10
	Urea	Prilling	95,695	80,603	50.00	--	--	5.00
	Sulphuric acid	Acid coling	95,685	80,523	73.00	59.00	2.82	1.50
Quimitecnia	dicalcium phosphate	Dryer 1	93,915	79,293	25.00	65.00	20.06	0.60
	dicalcium phosphate	Dryer 2	93,915	79,293	25.00	65.00	11.28	0.80
	dicalcium phosphate	Steam Generation	93,915	79,293	19.00	190.00	0.85	0.30
	Aluminium sulphate	Steam Generation..	94,475	80,675	16.00	190.00	1.20	0.30
Lusol	Productive process	Flour granulate	93,950	79,875	13.00	16.00	0.19	0.60
	Productive process	Vapour generation 4	93,950	79,875	27.00	190.00	0.18	0.60
	Productive process	Vapour generation 5	93,950	79,875	27.00	190.00	0.35	0.60
	Productive process	Vapour generation 6	93,950	79,875	15.00	190.00	0.35	0.80
	Productive process	Vapour generation 7	93,950	79,875	15.00	190.00	0.60	0.60
Fisipe	Productive process	Dryer	95,575	81,175	12.00	45.00	3.84	5.90

Table 7 shows the identification of the source points considered, their designation, the production process to which they correspond, the Universal Transverse Mercator (UTM) coordinates of their location in metres, the height of the chimney in metres and the exit temperature of the pollutants in °C. The average exit velocity of the pollutants in m/s and the diameter of the chimney in metres are also given. It also provides the values of the average emission velocity of the pollutants in m/s and the diameter of the chimney in metres.

Table 8 shows the estimated average values for the emissions of the considered pollutants, sulphur oxides (SOx), nitrogen oxides (NOx) and particles (PM), for the considered industries.

Subsequently, FISIGEN embarked on the development of a new cogeneration plant (2008/2010) to supply steam to Fisipe. This new cogeneration plant in Barreiro, located in the Lavradio Industrial Estate, started industrial activity in April 2010 and distributes steam exclusively to Fisipe. It also produces electricity, with an installed capacity of 24.2 MWe/121 MWt. Steam is produced by two natural gas turbines equipped with dry low NOx burners, which allow the flame temperature to be reduced to minimise the formation of nitrogen oxides. The plant's continuous emission sources are the two gas turbines and, sporadically, two other process chimneys. These only operate during periods when the recovery boilers are unavailable, with the waste gases being discharged through these chimneys instead of being injected into the recovery boilers. *Table 9* shows the characteristics of the chimney from the cogeneration plant.

Table 8. *Estimates of average air emissions from industries (adapted Garcia et al., 2010)*

Source	Factory	Chimney	SOx (g/s)	NOx (g/s)	PM (g/s)
CPPE	Central Term.	General	217.90	35.42	7.41
Quimigal Lavradio	Ammonia	Boiler/over-heater	54.29	4.93	2.80
	Nitric acid	Tail gas	0.00	3.85	0.00
	Urea	Prilling	0.00	0.00	4.10
	Sulphuric acid	Acid col.	9.77	0.00	0.00
Quimitecnia	dicalcium phosphate	Dryer 1	0.85	0.08	4.00
	dicalcium phosphate	Dryer 2	0.85	0.08	4.00
	dicalcium phosphate	Steam Gen.	0.25	0.02	0.01
	Aluminium sulphate	Steam Gen.	0.24	0.02	0.01
Lusol	Productive process	Flour gran.	0.00	0.00	0.01
	Productive process	Vapour gen. 4	0.08	0.01	0.01
	Productive process	Vapour gen. 5	0.15	0.03	0.00
	Productive process	Vapour gen. 6	0.22	0.05	0.00
	Productive process	Vapour gen. 7	0.27	0.05	0.00
Fisipe	Productive process	Dryer	0.00	0.00	8.69

Table 9. *Characteristic data on emissions from the FISIGEN cogeneration plant (adapted Garcia et al., 2010)*

Source	Factory	Chimney	UTM		Height (m)	Temp. (°C)	Speed (m/s)	Emission of Pollutants (g/s)			
			X	Y				NO_X	PM	VOC	CO
FISIGEN (New Plant)	Cogeneration Plant	FF1	120,157	190,430	30	139	14.10	1.02	0.05	0.06	0.55
		FF2	120,147	190,452	30	118	6.90	0.73	0.04	0.09	0.16

Results and Discussion

Evolution of Air Quality in relation to industrial closures

Since 2005, we have seen the closure of some of these emission sources of industrial origin, namely Quimitecnia, which ceased its activity in 2005, and the old CPPE thermoelectric plant, which ceased its activity in December 2009, when the Fisigen cogeneration plant started its activity. Also in July 2007, the Ministry of Environment closed the Quimigal/Lavradio ammonia plant for a week because its SO_2 emissions exceeded the limit set by law (Garcia et al., 2014). This plant was finally closed permanently in February 2009. AQ data from the Portuguese network (CCDR-LVT, 2022), namely from its Lavradio and Escavadeira stations, were used to analyse the evolution of AQ over time and its relationship with the evolution of industrial sources.

Evolution of the monthly average concentration of PM_{10} and SO_2 for the Lavradio and Escavadeira stations

Fig. 4 shows the evolution of the monthly average PM_{10} concentration from January 2000 to October 2011. Over the years, the global concentrations range from 20 to 50 μg/m³ (35 μg/m³ average) with no major differences between years until January 2009. It can be seen that PM_{10} concentrations decreased slightly in 2009 to an average of 20 μg/m³, which is directly related to the closure of the ammonia plant (January 2009), urea plant (February 2009) and CPPE (January 2010). The concentrations of the remaining industrial sources come from FISIPE and the production of dicalcium phosphate. The same assessment was carried out for SO_2, as shown in *Fig. 5*.

Analysis of *Fig. 5* shows that one of the highest monthly averages for SO_2 concentrations (59.81 μg/m³) was reached in July 2007, and then decreased until around March 2008. This coincides with the closure of the Amoníaco de Portugal (AP) plant, which was forced by law to shut down during these months due to SO_2 emissions exceeding the legal limit. In fact, from April to June 2007, the daily average SO_2 concentration exceeded 800.00 μg/m³ on several consecutive days, whereas the legal limit for the daily average SO_2 concentration is 125.00 μg/m³ (see *Fig. 8*). When the plant resumed operation, the concentrations increased again until the beginning of 2009. In the course of this year,

Fig. 4. *Evolution of the monthly mean concentration of PM_{10} (μg/m³) at the Lavradio and Escavadeira stations*

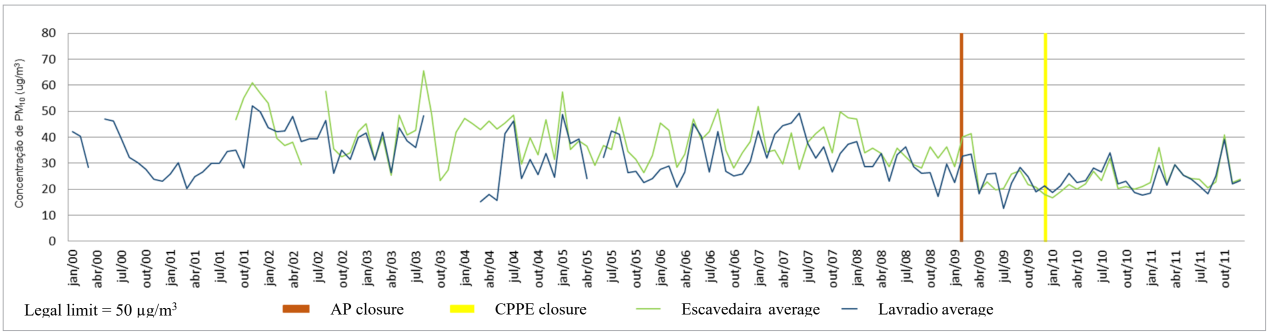
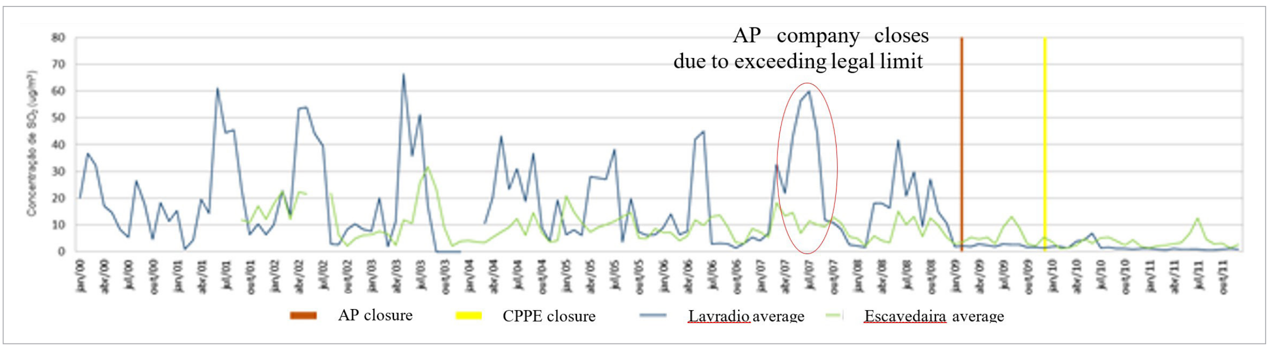


Fig. 5. *Evolution of monthly average SO_2 (μg/m³) concentrations at the Lavradio station and Escavadeira station*



however, the SO_2 concentrations fell drastically and reached insignificant levels. This is due to the fact that the ammonia plant was definitively closed in this year. It can be seen that since the closure of the AP plant in June 2009, the SO_2 concentration has decreased to residual values (5.00 µg/m^3 daily average).

In order to better understand the evolution of pollutant concentrations, four graphs showing the evolution of daily PM_{10} and SO_2 concentrations for the Lavradio station are presented for specific periods from 2007 to 2011 (*Figs. 6* to *9*). *Fig. 6* shows the evolution of the PM_{10} daily mean concentration from 2007 to 2009. *Fig. 7* shows the evolution of the PM_{10} daily mean concentration from 2009 to 2011. *Fig.* 8 shows the evolution of the average daily SO_2 concentration from 2007 to 2009 and *Fig. 9* shows the evolution of the average daily SO_2 concentration from 2009 to 2011.

Figs. 6 to *9* show the shutdown times of the ammonia plant, both the shutdowns due to SO_2 exceedances and those due to the definitive shutdown, as well as the closure of the CPPE (January 2010). For PM_{10}, a slight change in the average concentration was observed

Fig. 6. *Evolution of the average daily concentration of PM_{10}, (µg/m^3) from 2007 to 2009, at the Lavradio station*

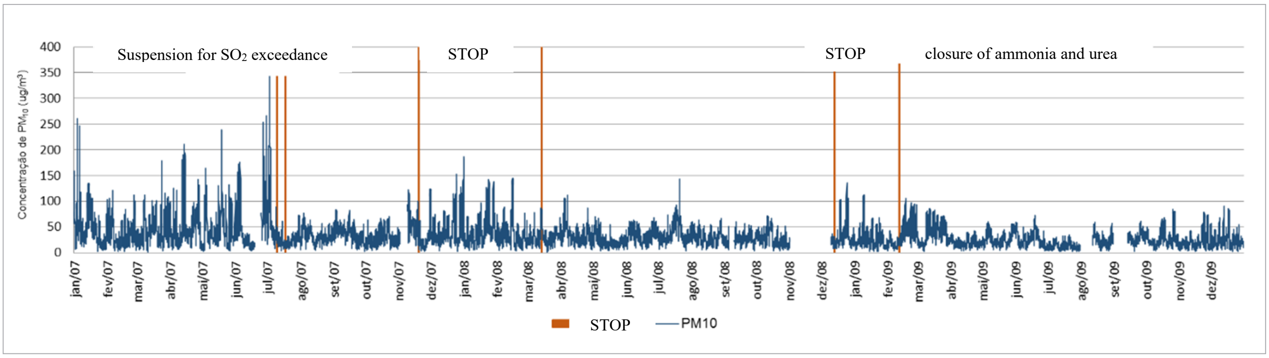


Fig. 7. *Evolution of the average daily concentration of PM_{10}, (µg/m^3) from 2009 to 2011, at the Lavradio station*

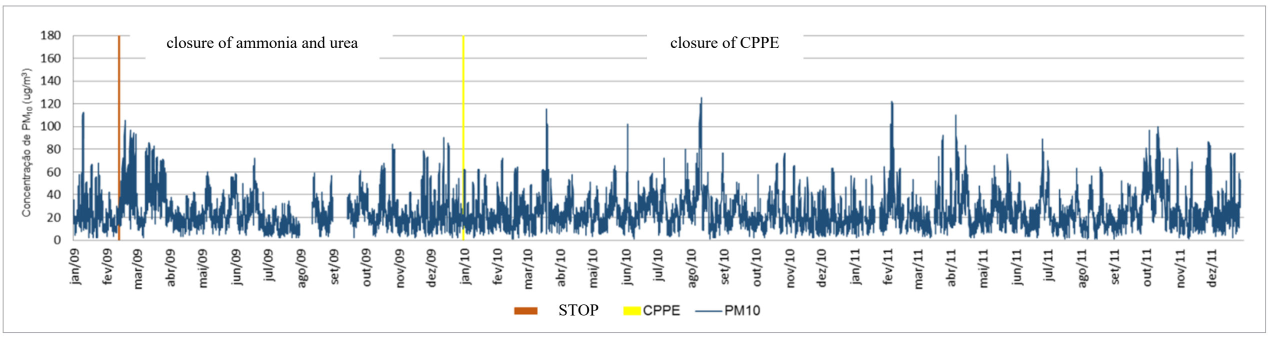


Fig. 8. *Evolution of the average daily concentration of SO_2, (µg/m^3) from 2007 to 2009, at the Lavradio station*

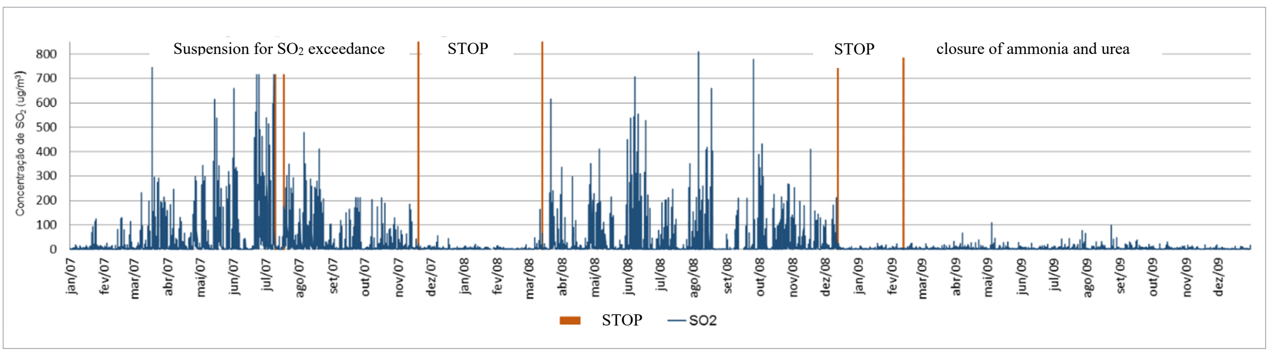
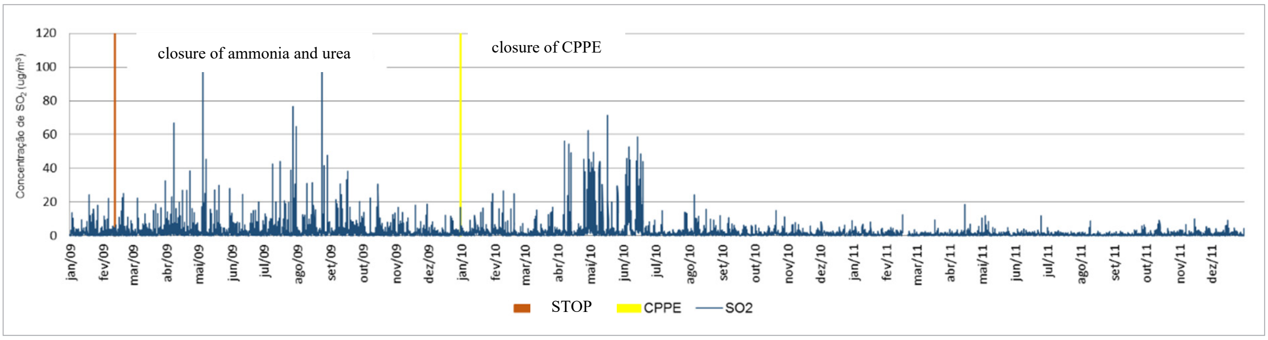


Fig. 9. *Evolution of the average daily concentration of SO_2 (μg/m³) from 2009 to 2011, at the Lavradio station*



after the shutdown of the ammonia plant and the definitive closure of the two industrial units. In the case of SO_2, all the shutdowns and closures of industries become even more evident, showing the importance of these sources, especially the ammonia plant, for the emission of this pollutant.

Evolution of the average daily concentration for the Escavadeira AQ station

An identical analysis is carried out for the Escavadeira AQ station; four graphs detail the evolution of daily PM_{10} and SO_2 concentrations for this station for specific periods from 2007 to 2011 (*Figs. 10* to *13*). *Fig. 10* shows the evolution of the daily average PM_{10} concentration from 2007 to 2009, *Fig. 11* shows the evolution of the daily average PM_{10} concentration from 2009 to 2011, *Fig. 12* shows the evolution of the daily average SO_2 concentration from 2007 to 2009 and *Fig. 13* shows the evolution of the daily average SO_2 concentration from 2009 to 2011.

The analysis carried out for the Escavadeira station (*Figs. 10* to *13*) shows the same results as for the Lavradio

Fig. 10. *Evolution of the average daily concentration of PM_{10}, (μg/m³) from 2007 to 2009, at the Escavadeira station*

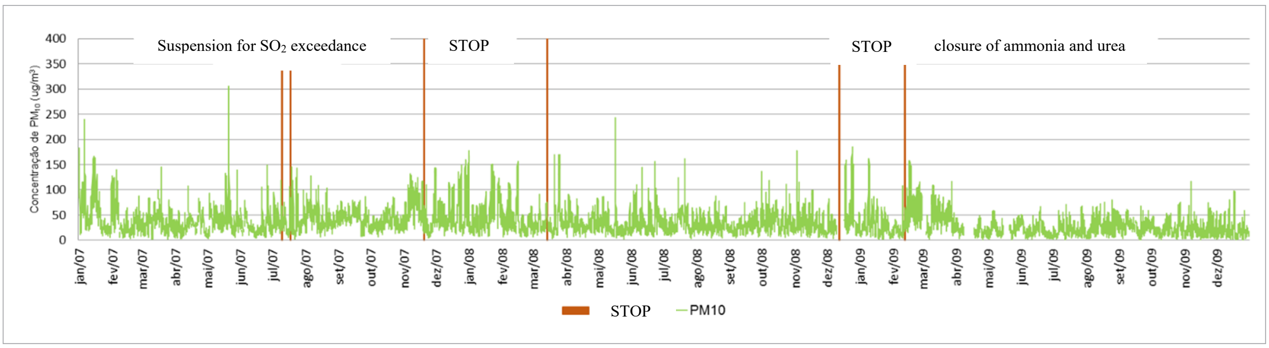


Fig. 11. *Evolution of the average daily concentration of PM_{10}, (μg/m³) from 2009 to 2011, at the Escavadeira station*

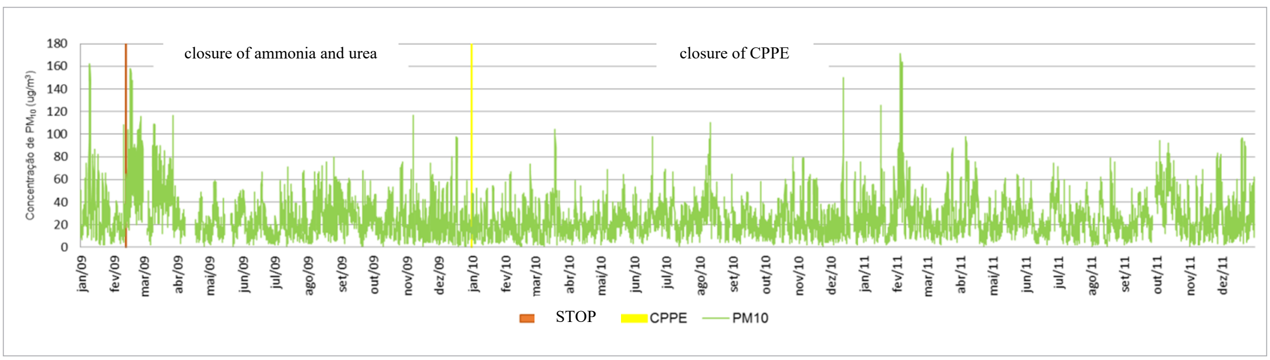


Fig. 12. *Evolution of the average daily concentration of SO_2 (μg/m³) from 2007 to 2009, at the Escavadeira station*

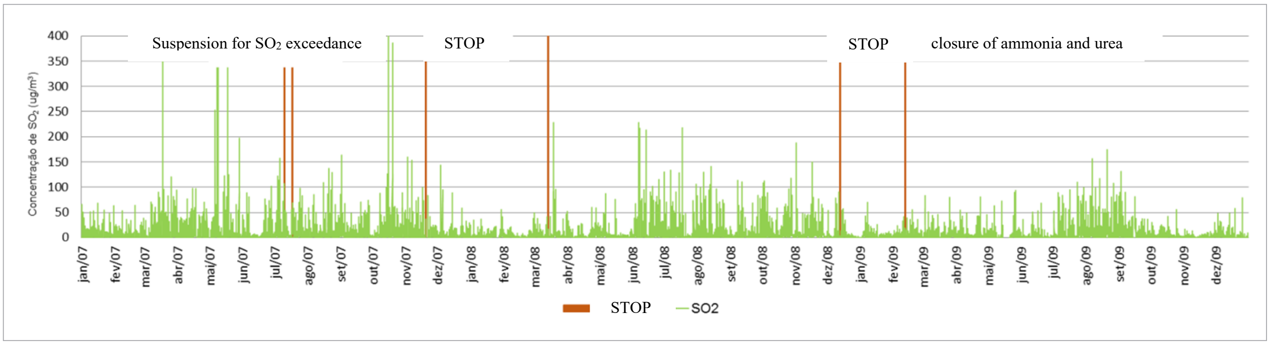
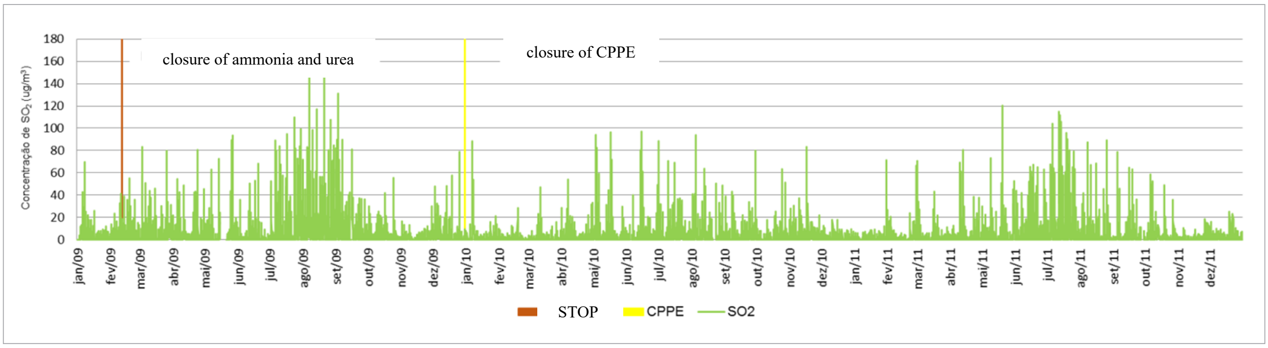


Fig. 13. *Evolution of the average daily concentration of SO_2 (μg/m³) from 2009 to 2011, at the Escavadeira station*



station for both PM_{10} and SO_2, confirming the importance of industry in the release of these two pollutants. Nevertheless, the results for the Lavradio station are slightly more significant, since it is physically closer to the industrial area. It should also be noted that the electrification of the railway line between Barreiro and Praias-Sado ended in December 2008, and the reduction of this source contributed to the concentration of PM_{10}.

Resume macro analysis

In order to better understand the impact of the closure of industries during the analysed period, monthly average concentration values and peak values of PM_{10} and SO_2 were calculated for the periods before (2000 to 2009) and after the closure of industries (2010 to 2011). *Table 10* gives a summary of the average and maximum concentration values during this period. The average value represents the average of the monthly concentrations in the previously analysed periods from January 2000 to December 2009 (before the closure of the industries) and in the period from January 2010 to October 2011 (after the closure of the industries).

The results of the analysis, shown in *Table 10* above, indicate that the average and maximum concentrations of PM_{10} and SO_2 at the air quality monitoring stations in Escavadeira and Lavradio decreased significantly after the closure of the industries. In fact, during the analysed period when the industries were operating (from 2000 to 2009), the observed average concentrations of PM_{10} were 39.00 μg/m³ (Escavadeira) and 34.00 μg/m³ (Lavradio), and the observed average concentrations of SO_2 during this period were 17.00 μg/m³ (Escavadeira) and 26.00 μg/m³ (Lavradio). The maximum concentrations (peaks) during this period were 66.00 μg/m³ (Escavadeira) and 49.00 μg/m³ (Lavradio) for PM_{10}, and 31.00 μg/m³ (Escavadeira) and 67.00 μg/m³ (Lavradio) for SO_2.

After the closure of the industries, which took place between January 2009 and January 2010, the average concentrations of PM_{10} decreased from 39.00 μg/m³ to 26.00 μg/m³ (Escavadeira) and from 34.00 μg/m³ to 25.00 μg/m³ (Lavradio), representing a decrease of 33.30% and 26.50%, respectively. For SO_2, the average concentrations during this period decreased from 17.00 μg/m³ to 6.00 μg/m³ (Escavadeira) and from 26.00 μg/m³ to 4.00 μg/m³ (Lavradio), representing a decrease of 64.70% and 84.60%, respectively.

Table 10. *Macro analysis of PM_{10} and SO_2 concentrations before and after the closure of industries*

	Period 2000 to 2009		Closure of Ammonia factory **January 2009**	Closure of Urea Factory **February 2009**	Closure of AP Factory **June 2009**	Closure of CPPE **January 2010**	Period 2010 to 2011	
	Average value (μg/m^3)	Maximum value (μg/m^3)					Average value (μg/m^3)	Maximum value (μg/m^3)
PM_{10} Escavadeira	39.00	66.00					26.00	39.00
PM_{10} Lavradio	34.00	49.00					25.00	36.00
SO_2 Escavadeira	17.00	31.00					6.00	12.00
SO_2 Lavradio	26.00	67.00					4.00	7.00

A similar situation can be observed for the maximum concentrations of PM_{10} and SO_2. The maximum concentrations of PM_{10} decreased from 66.00 μg/m^3 to 39.00 μg/m^3 (Escavadeira) and from 49.00 μg/m^3 to 36.00 μg/m^3 (Lavradio), representing a decrease of 40.90% and 26.50%, respectively. For SO_2, the maximum concentrations (peaks) decreased during this period from 31.00 μg/m^3 to 12.00 μg/m^3 (Escavadeira) and from 67.00 μg/m^3 to 7.00 μg/m^3 (Lavradio), representing decreases of 61.30% and 89.60%, respectively.

Discussion

Although the data analysed in this study covers the period from 2000 to 2011, it provides important historical insights into the relationship between industrial activity and air quality. The study period was characterised by significant industrial activity in the region, followed by the closure of several major emission sources. This unique sequence of events allows us to observe the direct impact of industrial closures on pollutant concentrations, providing a clear case study of how industrial regulation can lead to substantial improvements in air quality.

To place our findings in a contemporary context, it is important to compare the historical data with more recent air quality trends. Although specific data for the period after 2011 is not included in this study, general trends show that air quality has continued to improve with the implementation of stricter environmental regulations and the development of cleaner technologies. For example, recent studies (Saffell and Nehr, 2023) suggest that air quality has continued to improve due to ongoing efforts to reduce emissions from various sources (Abecasis et al, 2022).

Our results can also be compared with other significant periods of reduced industrial activity, such as the COVID-19 pandemic. During the pandemic, many countries experienced a temporary reduction in industrial activity and transport, leading to significant reductions in air pollutants such as NO_2 and $PM_{2.5}$. Studies conducted during this period (Mehmood et al., 2022, Silva et al., 2022) have shown similar trends to those observed in our study, reinforcing the conclusion that reductions in industrial and vehicle emissions lead to improved air quality.

The results of this study align with earlier findings by other researchers on the impact of industrial closures and environmental regulations. For example, the introduction of stricter emission standards in various regions of the world has led to significant improvements in air quality, similar to the effects observed following the closure of the ammonia and urea plants and the CPPE thermoelectric plant in our study area (Lobus et al., 2023, Silva et al., 2022). These comparisons highlight the importance of regulatory measures and the potential benefits of transitioning to cleaner industrial practices.

Conclusions

An analysis of the evolution of the daily and monthly average concentrations of PM_{10} and SO_2 over the years, from January 2000 to December 2011, highlights a general improvement in air quality over this period. This fact is closely linked to the gradual closure of several industrial units in the city, the most important of which are the ammonia factories, the urea factory and the CPPE thermal plant.

The results show that the evolution of the monthly average PM_{10} concentration in the period from January 2000 to January 2009, globally, ranged from 20.00 μg/m^3 to 50.00 μg/m^3 (35.00 μg/m^3 average), with no major differences over the years. In 2009, PM_{10} concentrations decreased slightly (average 20.00 µg/m^3), which is directly related to the closure of the ammonia plant (January 2009), urea plant (February 2009) and CPPE (January 2010).

It can also be seen that the highest values of monthly average SO_2 concentrations were reached in July 2007 (59.81 µg/m^3), decreasing until around January 2009, coinciding with the closure of the Amoníaco de Portugal (AP) plant. It can be seen that since the closure of the AP plant in June 2009, the SO_2 concentration has decreased to residual values (5.00 µg/m^3 daily average). In the case of PM_{10}, a slight change in the average concentration was observed after the closure of the ammonia plant and the definitive closure of the two industrial units. In the case of SO_2, all the shutdowns and closures of industries become even more apparent, showing the importance of these sources, especially the ammonia plant, for the emission of this pollutant.

The results also show that after the closure of the industries, the average concentrations of PM_{10} decreased by 33.30% and 26.50%, respectively, in the Escavadeira and Lavradio AQ stations. Similarly, the average SO_2 concentrations decreased by 64.70% and 84.60%, respectively, in the same AQ stations. Regarding the maximum values (peaks) of PM_{10} concentrations, the values decrease by 40.90% and 26.50%, respectively, in the Escavadeira and Lavradio stations, while the maximum SO_2 concentrations (peaks) decrease by 61.30% and 89.60%, respectively, in the same AQ stations.

The analysis of air quality data from January 2000 to December 2011 shows a significant improvement in pollutant levels following the closure of major industrial sources. This research shows that the reduction in PM_{10} and SO_2 concentrations is closely linked to the closure of key facilities, including ammonia and urea factories and the CPPE thermoelectric plant.

These results highlight the significant impact that the reduction of industrial emissions can have on air quality and underline the importance of regulatory measures and industrial management in controlling pollution. The significant improvements observed underline the importance of continued enforcement of environmental policies to maintain and improve air quality. The results also provide valuable insights for future urban planning and environmental strategies, suggesting that proactive measures can lead to healthier and more sustainable urban environments. Overall, this study provides compelling evidence that targeted industrial closures are effective in reducing air pollution and improving public health outcomes.

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