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The Impact of COVID-19 Confinement Measures on the Air Quality in an Urban-Industrial Area of Portugal

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Abstract: This study evaluated the temporal variability of the concentrations of pollutants (namely, NO₂, O₃, PM_{2.5}, PM₁₀ and SO₂) in an urban-industrial area of mainland Portugal during two decades (from 2001 to 2020), to assess the impact of the COVID-19 pandemic on the levels of these atmospheric pollutants. Mean levels of pollutants in 2020 were compared with those measured in the six previous years (2014–2019). A significant improvement in air quality, namely regarding PM₁₀ and NO₂, was found and it can be attributable to the restrictions of anthropogenic activities (such as traffic) promoted during the March–May 2020 national lockdown that occurred due to the pandemic. Significant and expressive reductions of 44.0% and 40.3% were found in April 2020 for NO₂ and PM₁₀, respectively, showing the impact of local traffic in the study area. A similar trend of reduction for these pollutants was also found in the following months. However, ozone levels did not show the same trend, with significant increases in several months after the lockdown period, highlighting other contributions to this pollutant. This unique period can be considered as a living lab, where the implementation of strict measures due to COVID-19 confinement promoted the reduction of anthropogenic activities and allowed us to understand more comprehensively their impact on local air quality.

Keywords: air quality; urban-industrial; COVID-19 confinement; PM₁₀; ozone; nitrogen dioxide; sulphur dioxide; temporal analysis



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1. Introduction

In December 2019, an unknown disease was detected in Wuhan, China, and on 11 March 2020, the World Health Organization (WHO) declared COVID-19—the disease caused by the new coronavirus SARS-CoV-2—as a pandemic. Its rapid spread has become a global public health crisis. To contain the SARS-CoV-2 virus, many countries have adopted drastic measures to reduce human interaction, including applying strict quarantines, encouraging social distancing, imposing a curfew and even closing entire cities [1].

These extreme measures led anthropogenic activities (such as production, traffic and transportation) almost to a standstill, with enormous socio-economic costs, but a clear short-term improvement in air quality has also arisen, as shown, for instance, by satellite images that captured a sharp drop in NO₂ pollution in several countries [2,3].

Several studies have demonstrated that COVID-19 lockdowns caused a positive impact on air quality [1,4,5]. The number of studies published relating to Europe is more limited, but already point to similar reductions of air pollutants [6–8].

Nevertheless, although reductions in primary pollutants are decisive in improving air quality, the response of secondary pollutants (notably O₃ and PM_{2.5}) to emission reductions

caused by COVID-19 is complex and still poorly known, given the interdependencies and non-linearities in atmospheric chemistry [9]. Thus, to fully assess the global air quality consequences of COVID-19, the impact on secondary pollutants must also be investigated, as enhanced secondary pollution has been found to sometimes offset the reduction of primary emissions during the COVID-19 lockdown [10]. For all these reasons, the pandemic context offers a unique opportunity to examine the effects of human-related activities, especially human mobility, on air quality [11].

In Portugal, on 12 March 2020, all schools closed and on March 19, Portugal decreed a state of emergency, including mandatory confinement and movement restriction of the citizens. Public transportation was reduced and non-essential business, such restaurants, shops, fitness centers or shopping malls, were closed.

This work aimed to evaluate the temporal evolution of the concentration of the pollutants NO_2 , O_3 , $\text{PM}_{2.5}$, PM_{10} and SO_2 in an urban-industrial area in Portugal (Paio Pires, Seixal), from 2001 to 2020, and to assess the impact of the COVID-19 pandemic on the levels of these air pollutants. Moreover, the interest in this specific area is due to the regular complaints of inhabitants regarding local air quality and their worries about the impact of the local industries on air quality [12]. Since local industries kept their regular workflow during the COVID-19 lockdown imposed by national authorities, this particular moment may provide new insights regarding the impact of these industries on the local air quality.

2. Materials and Methods

This study was carried out in Aldeia de Paio Pires, in the municipality of Seixal (Portugal), an urban-industrial area near Lisbon, with 167,294 inhabitants in 95.5 km² [13], characterized by a high influence of steelworks and other industries.

The air quality concentration values used in this study were obtained from the Paio Pires-Seixal station (38°37'15.7" N, 9°04'55.4" W) of the National Air Quality Monitoring Network, operated by the Portuguese Environment Agency, which results are available through the national information system of air quality, designated as QualAr. Its location is shown in Figure 1. The Paio Pires-Seixal station has an industrial suburban typology, according to the Air Quality monitoring sites classification in Europe [14]. The validated hourly mean concentrations of the pollutants NO_2 , O_3 , $\text{PM}_{2.5}$, PM_{10} and SO_2 were obtained from the QualAr database [15] of the Portuguese Environment Agency, with the percentage of collected data per year described in Table 1. Data regarding $\text{PM}_{2.5}$ were available only in 2020, since it was the year that its assessment started for this monitoring air quality station. Annual mean concentrations were calculated from hourly values, from 2001 to 2020 for NO_2 , O_3 and SO_2 , and from 2008 to 2020 for PM_{10} .

Daily meteorological data (namely, mean and maximum temperatures, relative humidity, precipitation and wind speed) was obtained from the Barreiro-Lavradio weather station located in the study area (38°40'28" N, 9°2'51" W) and it was supplied by the Instituto Português do Mar e da Atmosfera, I.P. (IPMA, I.P.). Anomalies were defined as the difference in the mean monthly values between the year 2020 and the previous period 2014–2019.

The impact of COVID-19 confinement on the pollutants concentrations was evaluated through the analysis and comparison of hourly and monthly means between the years 2020 and the baseline conditions based on 6-year averaged data (2014–2019). This methodology was adopted considering that 6-year baseline conditions were long enough to reduce inter-annual variability in atmospheric pollutants concentrations and meteorology data, minimizing the influence of seasonal variability in the results [16].

Statistical calculations were carried out using STATISTICA software version 13. The non-parametric Mann–Whitney U test was employed to compare identified means, with differences being significant at p -value < 0.050.

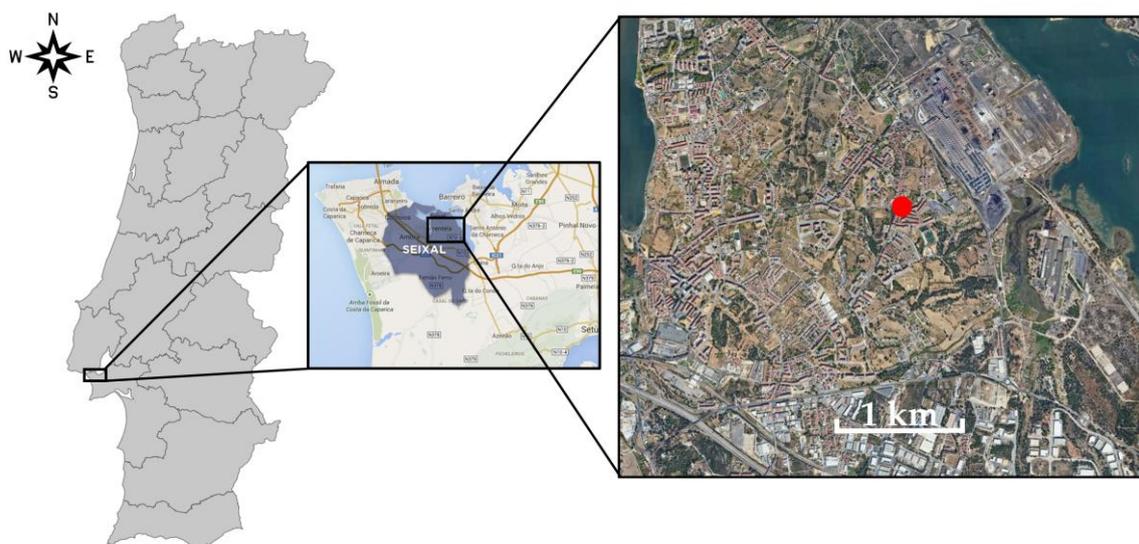


Figure 1. Location of the air quality monitoring station “Paio Pires-Seixal” within Seixal area (**right**, red circle) and its location within mainland Portugal (**left**).

Table 1. Percentage of the yearly data collected for each pollutant. Bold values refer to a year with a percentage of data collected below 80%.

Year	Percentage of Collected Data Per Year (%)				
	NO ₂	O ₃	PM _{2.5}	PM ₁₀	SO ₂
2001	95.4	93.6	n.a.	n.a.	99.7
2002	99.1	97.9	n.a.	n.a.	99.2
2003	58.0	99.7	n.a.	n.a.	98.8
2004	72.3	98.9	n.a.	n.a.	99.1
2005	92.0	91.0	n.a.	n.a.	92.5
2006	98.5	99.9	n.a.	n.a.	99.7
2007	98.8	96.5	n.a.	n.a.	98.9
2008	99.1	97.1	n.a.	93.3	99.7
2009	95.2	98.2	n.a.	96.6	99.7
2010	95.2	99.2	n.a.	83.9	97.9
2011	94.8	91.3	n.a.	93.7	99.6
2012	67.5	93.3	n.a.	n.a.	94.8
2013	76.8	93.1	n.a.	44.7	98.6
2014	93.3	85.7	n.a.	92.5	98.8
2015	99.0	99.4	n.a.	94.0	98.0
2016	97.8	99.6	n.a.	90.1	99.3
2017	85.2	98.4	n.a.	91.3	99.1
2018	90.1	95.3	n.a.	98.3	98.5
2019	99.9	96.0	n.a.	98.3	99.8
2020	98.2	99.5	93.6	99.7	98.2

3. Results

3.1. Air Quality Temporal Analysis and Legal Compliance

For each studied air pollutant, a temporal analysis and an overview of the legal compliance of the air quality in the study area was evaluated for the last two decades, based in the Portuguese legislation (Decree-Law No. 47/2017, of 10 May, that transposed the EU Directive 2015/1480).

3.1.1. NO₂

Regarding NO₂, the Portuguese legislation establishes an hourly limit value (HLV) of 200 µg·m⁻³, which must not be exceeded more than 18 times a year, and an annual limit

value (ALV) of $40 \mu\text{g}\cdot\text{m}^{-3}$, both mandatory since 2010. Figure 2 provides the levels of NO_2 from 2001 and 2020, focusing on the 19th highest hourly means per year and annual means.

During the studied period, no exceedances of HLV and ALV were found. The mean annual concentration of NO_2 reached a maximum of $29.8 \mu\text{g}\cdot\text{m}^{-3}$ in 2007 and a minimum of $17.2 \mu\text{g}\cdot\text{m}^{-3}$ in 2020. The reduction in NO_2 levels between 2009 and 2014 is probably due to the global economic and financial crisis of 2007–2008 and the subsequent eurozone public debt crisis [17]. In 2015 there were signs of economic growth, which may have led to a slight increase in NO_2 concentrations. In Europe, in the period 2000–2017, it was reported that the mean annual concentration of NO_2 decreased by 25% in suburban stations, 28% at traffic stations, and 34% at industrial and rural stations [18]. In 2018, it was reported that in the EU-28 the greatest contribution to NO_x emissions was the transport sector (47%, with 39% of the road transport and 8% of the non-road transport), followed by the energy supply (15%), agriculture (15%) and industry sectors (15%) [19].

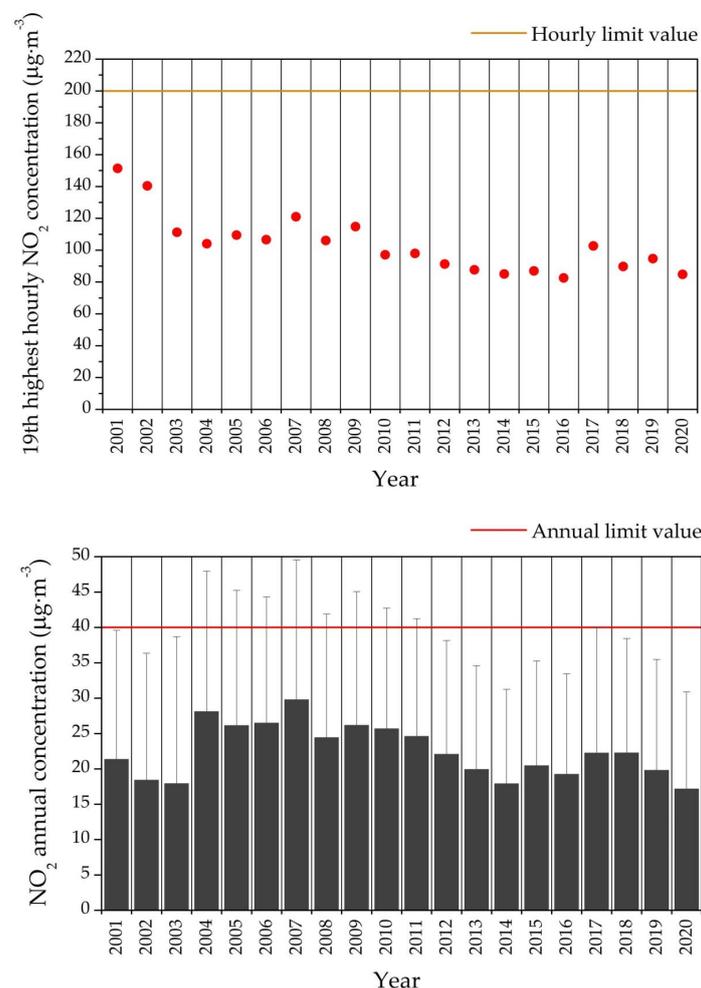


Figure 2. Levels of NO_2 in Seixal from 2001 to 2020: (top) 19th highest hourly means, (bottom) annual means (with standard deviations).

The trend observed in the Paio Pires-Seixal monitoring station is not a clear decrease as seen in Europe. As already noted, in Paio Pires-Seixal, increasing and decreasing trends can be observed during the period 2001–2020 but, the overall balance during the two studied decades (excluding 2020) is a decrease of 7.5% in the annual levels of NO_2 (in 2001 $21.4 \mu\text{g}\cdot\text{m}^{-3}$ was registered, while in 2019 $19.8 \mu\text{g}\cdot\text{m}^{-3}$ was registered). The lower decrease in NO_2 levels when compared with the rest of Europe may be due to the local sources at the study area that may continue to have a strong and continuous contribution, namely industry and traffic. However, it is important to highlight that the 19th highest hourly

mean concentration of NO₂ in each year has shown a clear decreasing trend (in 2001 it was 151.4 µg·m⁻³, while in 2019 it was 94.7 µg·m⁻³, showing a reduction of 37.5%).

3.1.2. O₃

For O₃, the Portuguese legislation establishes a target value (TV) for the protection of human health of 120 µg·m⁻³, which should not be exceeded daily more than 25 times per year, over a period of three years (starting on 2010 and onwards). Figure 3 provides the yearly mean levels of O₃ (bottom) and its temporal analysis of compliance (middle and top).

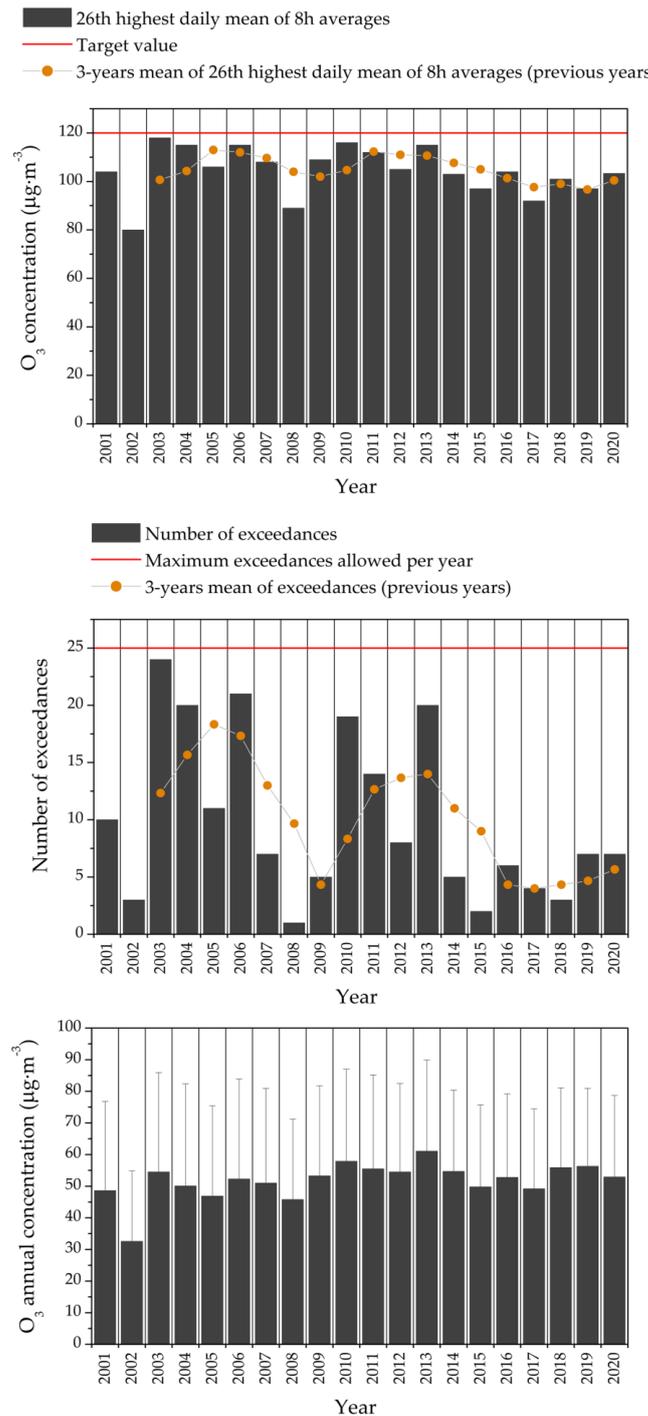


Figure 3. Levels of O₃ in Seixal from 2001 to 2020: (top) 26th highest hourly means, (center) number of exceedances, (bottom) annual means.

During the studied period of 20 years, the 26th highest daily mean of O₃ was always below 120 µg·m⁻³, and, therefore, considering the 3-years mean (with values for the first time only in 2012) no exceedances were registered as well. Regarding the 3-years mean of the 26th highest daily mean of O₃, a decreasing trend can be observed from 2012 to 2019. Therefore, the number of daily exceedances in each year was always below 25, with 2003 registering the highest number of 24.

The mean annual concentration of O₃ reached a maximum of 61.1 µg·m⁻³ in 2013 and a minimum of 32.6 µg·m⁻³ in 2002, without a clear trend overtime. The Mediterranean climate characteristics influence the formation of O₃, with high concentrations being related to local/regional photochemical production. The variation in O₃ levels in Europe is also attributed to meteorology and climate conditions, as well as to the intercontinental transport of O₃ and its precursors NO_x and NMVOCs [19].

3.1.3. PM_{2.5}

The year of 2020 was the first year that this pollutant was monitored in the study area by the local air quality monitoring station. A PM_{2.5} annual mean of 9.5 ± 8.5 µg·m⁻³ was registered (ranging from 5.0 ± 3.6 µg·m⁻³ in June to 16.7 ± 16.9 µg·m⁻³ in January), which is below the annual limit value of 20 µg·m⁻³ established by the Portuguese legislation.

3.1.4. PM₁₀

Regarding PM₁₀, the Portuguese legislation defines, with the objective of protecting human health, an ALV of 40 µg·m⁻³, and a daily limit value (DLV) of 50 µg·m⁻³, which must not be exceeded more than 35 times a year, mandatory since 2005. Figure 4 provides the yearly PM₁₀ levels, the 36th highest daily PM₁₀ means per year and the number of exceedances for the period between 2008 and 2020.

It is important to highlight that, in Portugal, the contribution of natural sources to the levels of suspended particles has proved to be significant, namely those resulting from the transport from the deserts of North Africa [20], and thus according to legislation, this contribution should be discounted in the calculation of the annual and daily mean PM₁₀ concentrations [21,22]. Currently, the method adopted by the Portuguese Environment Agency to identify the events of African dust intrusion in Portugal and their contributions to the PM₁₀ levels is based on a statistical approach regarding the variability at rural background sites. Shortly, the methodology is based on the application of a 30-day moving 40th percentile to the PM data series in rural background stations, after excluding those days impacted by African dust, that should be identified based on satellite observations, model back-trajectories and/or dust forecast models [22].

Considering the DLV, only in 2009 and 2011 were exceedances registered with the 36th highest PM₁₀ means after the discounts from natural sources being higher than 50 µg·m⁻³. However, in 2008 no data were available for 36th highest PM₁₀ means after the discounts from natural sources but the 36th highest PM₁₀ mean without discounts exceeded the DLV (59.0 µg·m⁻³). Regarding the number of daily exceedances, if not considering the discount from natural sources, from 2008 to 2011, the limit number of 35 daily exceedances per year were surpassed. Discounting the contribution of natural sources, from these four years, only 2010 had less than 35 daily exceedances during the whole year. From 2011 onwards, the number of annual exceedances registered was always below the established maximum number of exceedances allowed.

PM₁₀ concentrations reached a maximum of 38.8 µg·m⁻³ in 2011 and a minimum of 24.4 µg·m⁻³ in 2016, showing an overall decreasing trend (without considering 2020, when the minimum PM₁₀ annual level of 20.1 µg·m⁻³ was reached). Regarding the ALV, no annual PM₁₀ levels (with and without the contribution of natural sources) were above the limit value of 40 µg·m⁻³ in any of the years considered in this study.

The evolution of the PM₁₀ concentrations in the study area followed the European trend, since during the decade 2009–2018 in Europe, there was a reduction of 18–19% in the annual average concentrations of PM₁₀ for all types of monitoring stations, except for

rural (only 13%), a decrease that was in line with the reduction of primary PM₁₀ emissions (22%) and their precursors (54% for SO_x, 34% for NO_x and 16% for NMVOCs) [19]. In 2018, it was reported that in the EU-28 the greatest contribution to PM₁₀ emissions was the residential, commercial and institutional sector (41%), followed by manufacturing and extractive industry (22%) and the agriculture (18%) [19].

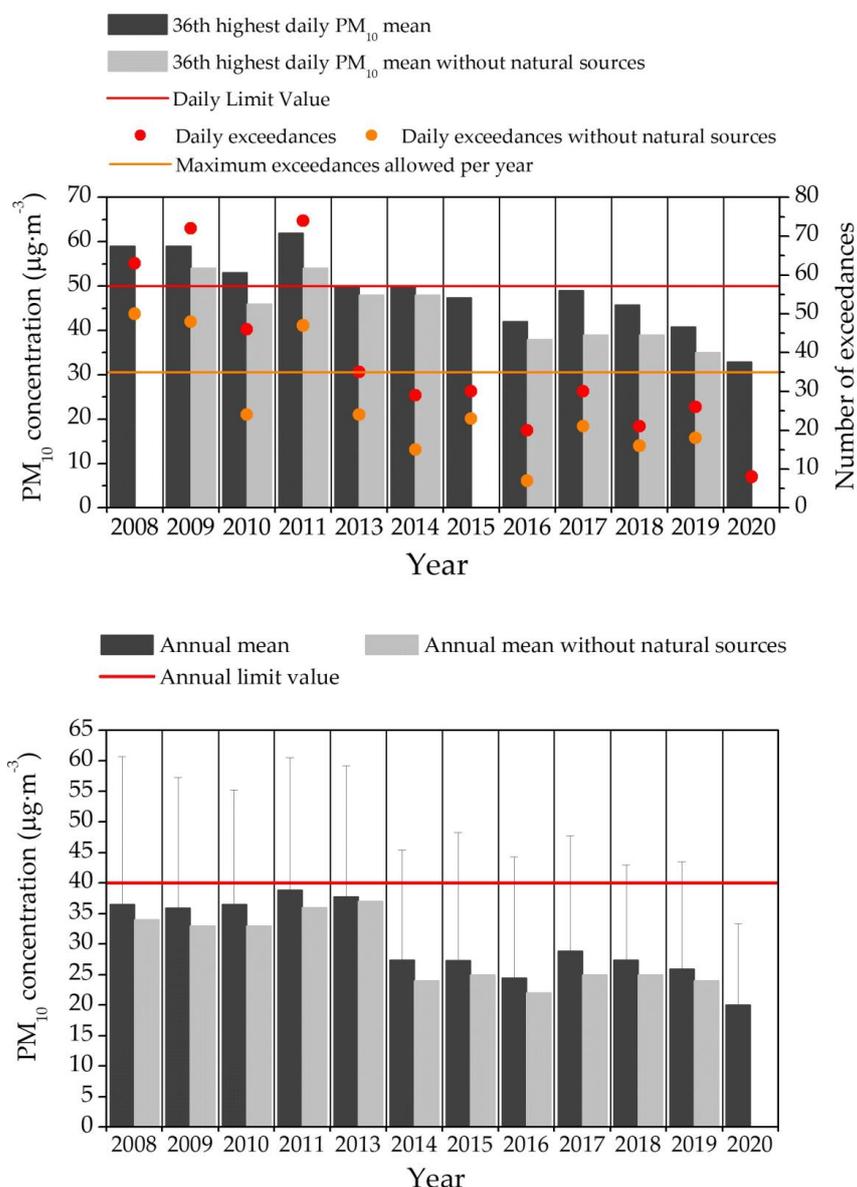


Figure 4. Levels of PM₁₀ in Seixal from 2008 to 2020: (top) 36th highest daily means with and without natural sources, along with number of exceedances, (bottom) annual mean with and without natural sources.

Some examples of episodes of high PM pollution occurred during 2017, one of the most devastating years for fires in Europe and, in particular, in Portugal where around 120 deaths occurred and a record of total burned area of 540,000 ha was registered. After an intense heat wave and extremely dry conditions, several fires occurred in the Centre of Portugal [23]. The worst incident occurred in June, near Pedrógão Grande, and led to the death of 64 people, the highest number of deaths due to forest fires in Portugal recent history, and 53,000 ha of burned area. The mean daily concentrations of PM₁₀ in the Iberian Peninsula was 17 µg·m⁻³ before and after the episode, while the daily average during the episode was 26 µg·m⁻³ [24]. Later in that year, in October, a series of wildfires

also occurred throughout the country due to special climacteric conditions promoted by the tropical storm Ophelia (with influence of the Saharan dust from north-western Africa), where 50 fatalities occurred. During that period, the Portuguese population was exposed in average to additional PM_{10} levels that ranged from 16.2 to $120.6 \mu\text{g}\cdot\text{m}^{-3}$ in smoky days with dust and from 6.1 to $20.9 \mu\text{g}\cdot\text{m}^{-3}$ in dust-free smoky days [25]. The implementation of effective fire management and prevention methodologies will, therefore, become increasingly important in the future, as the severity of fires is expected to increase as a result of climate change [26].

3.1.5. SO_2

Regarding SO_2 , the Portuguese legislation establishes an hourly limit value (HLV) of $350 \mu\text{g}\cdot\text{m}^{-3}$, which must not be exceeded more than 24 times a year, and a daily limit value (DLV) of $125 \mu\text{g}\cdot\text{m}^{-3}$, which must not be exceeded more than three times a year. Figure 5 provides the levels of SO_2 from 2001 to 2020, focusing on the fourth highest daily mean and 25th highest hourly mean per year and annual means.

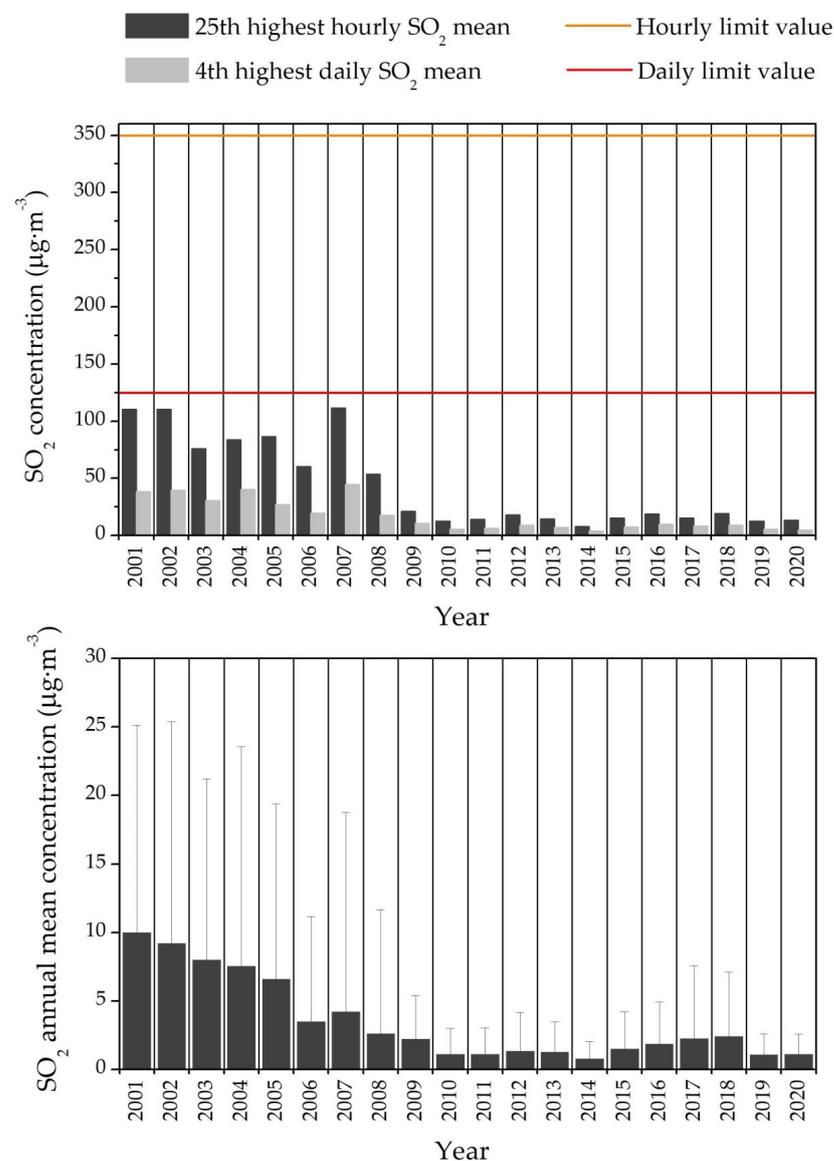


Figure 5. Levels of SO_2 in Seixal from 2001 to 2020: **(top)** highest hourly and daily means, **(bottom)** annual mean.

Considering both limit values, the monitored levels of SO_2 always complied with the legislation for the whole study period, with no exceedances reported. Until 2007, it was possible to observe a decreasing trend in the SO_2 levels and, after that period, annual mean levels were always below $3 \mu\text{g}\cdot\text{m}^{-3}$.

3.2. Impact of COVID-19 Containment Measures on Air Quality

The comparisons between the hourly and monthly mean levels of NO_2 , O_3 , $\text{PM}_{2.5}$, PM_{10} and SO_2 monitored during the period 2014–2019 and the year 2020 (when COVID-19 containment measures were employed in the Portuguese territory) are shown in Figures 6 and 7. These comparisons were conducted focusing only on the last six years since the early years represent different technological conditions. Regarding $\text{PM}_{2.5}$, only data for 2020 are shown since it was the year when such monitoring activity started.

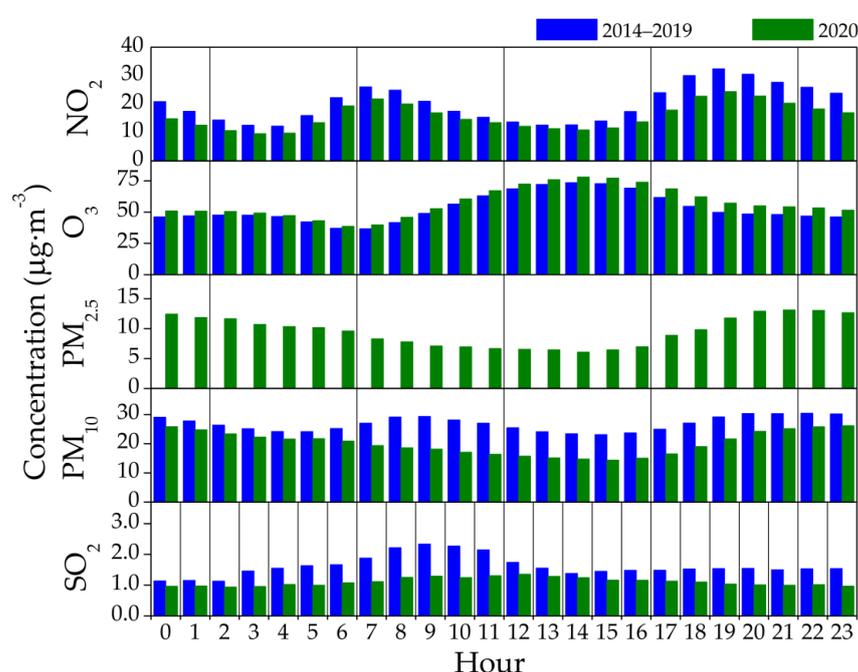


Figure 6. Mean hourly levels of NO_2 , O_3 , $\text{PM}_{2.5}$ (only for 2020), PM_{10} and SO_2 during the periods of 2014–2019 and 2020 in the studied urban-industrial area.

The anthropogenic activities can be identified in hourly profiles of the air pollutants levels, as shown in Figure 6, since the calculation of the average of a large amount of measurement data allows for the independence of the results from the meteorological conditions.

NO_2 displays a daily cycle with two maximums at peak traffic hours (from 6 a.m. to 9 a.m. and 5 p.m. to 9 p.m.), typically conditioned by the volume of traffic emissions. Regarding 2020, a reduction in the mean hourly concentrations of NO_2 was found, when compared with the previous period of 2014–2019, that did not have any traffic constraints on the population.

The hourly profile of O_3 has higher levels from 11 a.m. to 4 p.m., following obviously the levels of solar radiation and presenting lower levels during the evening. In fact, O_3 is not emitted directly into to the atmosphere (therefore, it is considered as a secondary pollutant) but it results from the photochemical reactions between nitrogen oxides and volatile organic compounds [27]. When comparing both studied periods, it is found that ozone levels are similar during the morning but with slightly higher levels after 1 p.m. and until midnight in 2020, when comparing with the period 2014–2019.

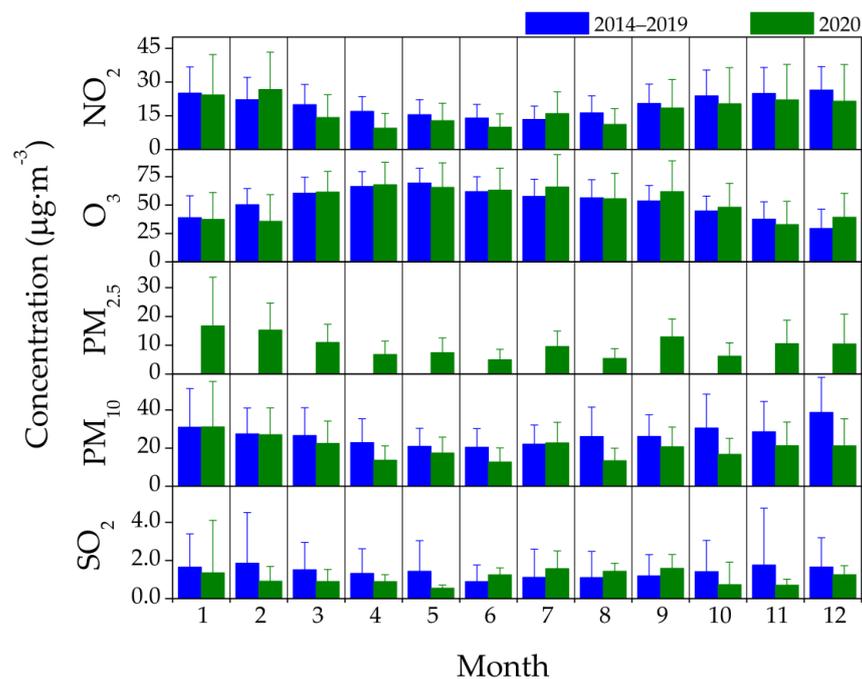


Figure 7. Mean monthly levels of NO_2 , O_3 , $\text{PM}_{2.5}$ (only for 2020), PM_{10} and SO_2 during the periods of 2014–2019 and 2020 in the studied urban-industrial area.

Regarding PM_{10} , two peaks in its levels are observed from 7 to 11 a.m. and from 6 to 11 p.m. When comparing the two different periods, a strong reduction on PM_{10} levels in 2020 can be found, which flattened the PM_{10} hourly profile in 2020 when compared with the 2014–2019 period and that can be attributable to the containment measures that limited the mobility of the population and other anthropogenic activities. The $\text{PM}_{2.5}$ hourly profile in 2020 has a flattened similar trend to that observed for PM_{10} .

During the 2014–2019 period, the SO_2 hourly pattern showed higher levels between 7 a.m. and 12 a.m., which reflects its anthropogenic source, such as fossil fuel combustion [28]. In 2020, the SO_2 hourly pattern showed slightly lower levels and without any visible peak period, reflecting the decrease of anthropogenic activities that typically occurred during the period between 7 a.m. and 12 a.m. previously to the confinement period (such as traffic).

Figure 7 provides the seasonal trends for all studied pollutants during 2020 and the mean levels of the six previous years (2014–2019). NO_2 , $\text{PM}_{2.5}$ and PM_{10} and SO_2 show higher levels during the cold season, which can be explained by the greater atmospheric stability which promotes thermal inversion, accentuating the accumulation of pollutants in the lower atmosphere [29]. By contrast, O_3 presents higher levels in spring and summer since, as explained above, its formation is related to the intensity of solar radiation.

When comparing both studied periods, it is possible to observe lower mean monthly levels of NO_2 and PM_{10} during 2020 (after the month of February, since the confinement measures were introduced in Portugal only in March) than the registered ones in the previous six year period. In fact, after the declaration of the state of emergency in Portugal and the nationwide lockdown imposition on 19 March (to 31 May 2020), the concentrations of NO_2 and PM_{10} in the studied urban-industrial area, registered a drastic and significant decrease in April, namely reductions of 44.0% (p -value = 0.000) and 40.3% (p -value = 0.000), respectively. This significant reduction was the result of the mandatory lockdown confinement, restrictions of movement on public roads and prohibition of travelling outside the municipality of residence during the Easter period (9–13 April). As seen, these measures had a strong impact on PM_{10} and NO_2 levels, confirming that traffic is one of the main sources of these pollutants in the study area.

The scenario of reduction of NO₂ and PM₁₀ levels in April 2020, has been seen all over the world [30,31]. In a study that focused on the impact of the COVID-19 lockdown on the air pollution levels in 697 cities worldwide, the lockdown measures caused a decrease of 23–37% in the NO₂ levels and of 14–20% in the PM₁₀ levels [31]. In Europe, estimates show that from 15 March to 30 April, the mean percentage variations of NO₂ were: −47% in Madrid, −39% in Rome, −30% in Paris, −47% in Geneva, −46% in Ankara, −33% in Berlin, −26% in London [19]. Taking into account that road transport was the most affected emission source during the COVID-19 lockdown in urban areas [31,32], the reductions observed in NO₂ levels can be directly associated to the traffic reduction, which can supply an estimate of the traffic contribution in a specific site.

Nevertheless, the reductions of PM₁₀ and NO₂ levels in the studied urban-industrial area occurred during the rest of the year 2020 (from March to December), long after the nationwide lockdown period (16 March to 31 May 2020). For instance, PM₁₀ registered significant reductions relative to the last six-year averages, namely, in May (16.7%, *p*-value = 0.000), June (38.0%, *p*-value = 0.000), August (48.6%, *p*-value = 0.000), September (20.7%, *p*-value = 0.012), October (45.2%, *p*-value = 0.000), November (25.6%, *p*-value = 0.018) and December (45.3%, *p*-value = 0.000). Regarding NO₂, significant decreases were observed in May (17.4%, *p*-value = 0.048), June (29.0%, *p*-value = 0.000), August (31.6%, *p*-value = 0.000) and December (18.7%, *p*-value = 0.012). However, significant increases of NO₂ levels in 2020 were observed in February (20.2%, *p*-value = 0.008—before the implementation of the COVID-19 confinement measures) and July (19.8%, *p*-value = 0.030), when comparing with the mean levels registered in the previous six years.

Overall, the PM₁₀ annual average in the study area in 2020 was 20.1 µg·m^{−3} (compared with the mean value of 26.9 µg·m^{−3} registered during the period 2014–2019), and this was the first time that the WHO annual air quality guideline of 20 µg·m^{−3} [19] was attained in the study area.

The observed reductions are possibly the result of the measures applied during the year of 2020 in Portugal after March onwards to slow down the transmission of the new coronavirus SARS-CoV-2, which included teleworking, restrictions of movement on public roads and curfews, promoting as well the slowing down of the economic activity.

Regarding the differences between O₃ levels during 2020 and the previous six years, a significant reduction was found in February (29.0%, *p*-value = 0.000—before the implementation of COVID-19 confinement measures) and significant increases were found in July (14.4%, *p*-value = 0.005), September (15.2%, *p*-value = 0.007) and December (33.6%, *p*-value = 0.003). In some months, it was found that both NO₂ and O₃ increased (July) or decreased (May), but there were other months in which a decrease in NO₂ was accompanied by an increase in O₃ (December) and vice versa (February). This non-linearity of the ozone production efficiency with NO_x concentration is long known, since the balance between the NO_x and VOC precursors is decisive [33,34]. Additionally, O₃ concentrations are determined not only by precursor emissions, but also by meteorological conditions and long-distance transport.

Similar increasing trends of O₃ during lockdown were also found in other regions of the world [1,31,35]. The generally higher levels of O₃ during lockdown worldwide, considered similar to the weekend effect, are attributable to the reduction in NO_x emissions from road traffic which leads to a lower O₃ titration by nitric oxide, along with higher solar radiation due to the lower PM emissions (favoring O₃ formation) and the increase of O₃ precursors emissions from home and garden activities (considering that people are more time in their homes due to the lockdown measures) [35]. In urban or urban-industrial areas, such as the studied site in the present study, where NO_x emissions are dominant in normal meteorological conditions, a VOC-limited regime of O₃ production is predicted [36]. As a consequence of the lockdown, the concentrations of NO_x decreased more than those of NMVOCs, leading to higher NMVOC/NO_x ratios and increased ozone concentrations [35,37].

In our study site, during the March–May lockdown, the variations of O₃ concentrations relative to the last six years were all non-significant and contradictory in sign (March: +1.7%, *p*-value = 0.966; April: +2.2%, *p*-value = 0.704; May: −5.5%, *p*-value = 0.104). The significant and sharp decreases in NO₂ concentrations (in March, April and May) could have caused the O₃ concentrations to increase in that period, as seen in the rest of Europe except for Iberia [38], due to the reduced O₃ titration by NO, but that has not happened significantly (in fact, O₃ levels in May have decreased).

In order to evaluate the impact of meteorological conditions at the study site on the levels of O₃, the differences between the mean levels of meteorological data in the study site between 2020 and the six previous years were evaluated, as shown in Figure S1 (Supplementary section).

In our study site, meteorological factors may have contradicted the rise in O₃ concentrations, since there was a significant increase in the mean relative humidity in March (8.5%, *p*-value = 0.001), April (15.1%, *p*-value = 0.000) and May (13.7%, *p*-value = 0.000). This trend was also observed in another study where, from 15 March to 30 April, an O₃ reduction in the Iberian Peninsula was registered, which was mostly attributable to the low solar radiation and high specific humidity [38].

After the March–May lockdown, the O₃ positive anomaly in July can perhaps be associated with elevated temperatures relative to the last six years, since in July there was a positive variation in the mean temperature (7.8%, *p*-value = 0.000) and in the maximum temperature (11.7%, *p*-value = 0.000); and with the mean wind speed, since in July, there was a negative variation of this parameter (14.5%, *p*-value = 0.006).

In September, no significant variations of NO₂ levels nor of meteorological variables have occurred and so no definite causes for the O₃ positive anomaly in this month may be pointed to. In December, the significant increase in O₃ concentration may have been caused by the decrease in NO₂ concentration (18.7%, *p*-value = 0.012), due to the reduction in the titration by NO, but precipitation levels may also have had some influence, since there was a significant decrease in this parameter (14.0%, *p*-value = 0.005). The other meteorological factors all presented non-significant variations in this month.

This impact of meteorological factors into ozone levels during the pandemic period has also been found in other studies. For instance, a study where a model was employed to evaluate the global changes in secondary atmospheric pollutants during the pandemic period in 2020 [39] found that a large fraction of the ozone increase in February was associated with meteorological anomalies. In short, the used model showed that atmospheric meteorological anomalies produced substantial variations in the concentrations of chemical species during the pandemic, despite the reductions of precursors' emissions.

The levels of SO₂ during the year of 2020 presented both significant reductions and increases when compared with the previous six-year period. Significant reductions were found in January (18.0%, *p*-value = 0.020), March (40.7%, *p*-value = 0.034), May (61.7%, *p*-value = 0.001) and October (48.0%, *p*-value = 0.011), while significant increases were found mainly for the summer period, namely, June (39.6%, *p*-value = 0.000), July (40.6%, *p*-value = 0.000), August (30.0%, *p*-value = 0.000) and September (33.0%, *p*-value = 0.001). This variability in SO₂ levels in 2020 may be mainly due to the workflow of the industrial area nearby, since it maintained its typical work process during the confinement period. In fact, a general decrease between 2 and 20% in the SO₂ levels was found in urban settings worldwide promoted by the lockdown measures [31]. In the present study, despite lower levels were found from March to May (probably due to traffic decrease due to lockdown measures) with April not being statistically significantly, higher levels were found during all summer, which highlights the impact of the local industries of the study area into SO₂ levels in the air.

Overall, the COVID-19 pandemic had a significant impact on the air quality of the studied urban-industrial area during 2020. This unique situation can be addressed as a living lab where it is possible to understand the effects of reducing specific pollution sources, such as traffic, in local air quality. Future efforts are needed to maintain the

pollutant concentrations, namely PM₁₀ and NO₂, at lower levels than the previous six years to minimize the population exposure when the pandemic is over and the economy fully restarts. Existing environmental policies and rethinking mobility strategies could achieve similar air quality improvements, at a much lower economic cost, since city lockdowns are an unsustainable option to address environmental issues.

4. Conclusions

The impact of COVID-19 lockdown in the air quality in an urban-industrial area in Portugal was assessed, by comparing air quality data collected during the pandemic (2020) with baseline conditions, namely the six-year averaged data (from 2014 to 2019). These measures, which promoted a great reduction in traffic during 2020, proved to have a significant impact on PM₁₀ and NO₂ levels in the studied area, namely their reduction. This study provides insights and confidence to regulators, policy makers and municipalities that a significant improvement in local air quality may be achieved if strict air quality control plans and mitigation measures (targeting, for instance, traffic) are implemented.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/atmos12091097/s1>. Figure S1. Monthly statistics for weather parameters (mean and maximum temperatures, relative humidity, precipitation and wind speed) during the periods of 2014–2019 and 2020 in the studied urban-industrial area.

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