Received: 25 February 2022 | Revised: 23 September 2022 | Accepted: 8 October 2022
DOI: 10.1002/sd.2432

RESEARCH ARTICLE

Sustainable Development
WILEY

# Sustainable policies for air pollution reduction after COVID-19 pandemic: Lessons learnt from the impact of the different lockdown periods on air quality

Ana Catarina T. Silva[1,2] | Pedro T. B. S. Branco[1,2] | Patricia Ferrini Rodrigues[1,2] | Sofia I. V. Sousa[1,2]

[1]LEPABE – Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Porto, Portugal

[2]ALiCE – Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Porto, Portugal

**Correspondence**
Sofia I. V. Sousa, LEPABE – Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, Porto 4200-465, Portugal.
Email: sofia.sousa@fe.up.pt

**Funding information**
Fundação para a Ciência e a Tecnologia, Grant/Award Numbers: LA/P/0045/2020 (ALiCE), UIDB/00511/2020-UIDP/00511/2020 (LEPABE)

## Abstract

Due to the COVID-19 pandemic, governments imposed several mobility restrictions which can be used to evaluate their impact on air quality and generate better-targeted policies to improve it. Therefore, this study aimed to define sustainable mitigation measures to reduce air pollution based on quantifying the impacts of the restrictions imposed during the COVID-19 pandemic on air quality in Portugal. Thus, hourly concentrations of $PM_{10}$, $PM_{2.5}$, $NO_2$, $O_3$, CO and $SO_2$ were obtained from the Portuguese Air Quality Monitoring Network. Data was then divided into six periods (2020–2021) and compared with the corresponding historical periods (2015–2019). Furthermore, the satellite data of $NO_2$, CO, and absorbing aerosol index (AAI) from the sentinel-5P TROPOMI was collected to complement the analysis conducted for the monitoring data. Overall, air quality improved in all study periods and areas, except in industrial sites. The satellite data corroborated the results herein achieved and thus validated the real effect of the measures adopted in the country during the pandemic on air quality. Sustainable policies to improve air quality could include remote (or hybrid) work whenever possible as a long-term measure and prohibition of travelling between municipalities when an extraordinary event of high air pollution is predicted or occurs. Other policies should be adopted for industrial areas. Given this, and as the restrictive mobility measures had a strong effect on reducing air pollution, the post-COVID era represents an opportunity for society to rethink future mobility and other emerging policies, that should favour softer and cleaner means of transportation.

KEYWORDS
air quality, COVID-19, lockdown, mobility, policy-making, sustainable development

## 1 | INTRODUCTION

Nowadays, preserving and/or improving the air quality is a major concern of society. Clean air is crucial for human beings, and its pollution, mainly caused by anthropogenic activities, has been causing 4.2 million premature deaths per year worldwide, according to estimations made by the World Health Organisation (WHO) in 2016 (WHO, 2018). For this reason, it is crucial to control and minimise air pollution by reducing the leading cause of this phenomenon: human activities. There is an urgent need for policies favouring cleaner and more sustainable technologies and effective strategies contributing to improved air quality (Fong et al., 2020). Usually, the effectiveness of those policies is evaluated based on empirical knowledge or modelling techniques, as their implementation frequently has enormous socio-economic costs.

The world is facing a pandemic of the respiratory disease COVID-19 declared by WHO on 11 March 2020, caused by the coronavirus SARS-CoV-2 (Cucinotta & Vanelli, 2020). Due to the COVID-19 pandemic, governments imposed several restrictions on their citizens and companies, including lockdowns. These events can be used as a country-scale or even a world-scale laboratory to evaluate the real impact of policies based on mobility restrictions on air quality (Dangelico et al., 2022; Liu et al., 2021).

Several news and studies rapidly emerged worldwide, claiming a global improvement in air quality due to the reduction of pollutants' concentrations during lockdown periods, especially nitrogen dioxide ($NO_2$) (Barua & Nath, 2021; Liu et al., 2021). On the other hand, those studies also reported that air pollutants' concentrations increased as soon as the lockdown restrictions started to be lifted worldwide (Kumari & Toshniwal, 2020). Although different studies have been published evaluating the impact of the COVID-19 pandemic on air quality, they were mostly based on data from the first lockdown (just after the declaration of the COVID-19 pandemic), mostly focused on urban sites, mainly in countries highly affected by air pollution (India and China), and often using a limited statistical analysis (Silva et al., 2022). Particularly in Portugal, only two studies were published so far as the author's knowledge goes, both also focusing only on the first lockdown in 2020 (Gama et al., 2021; Slezakova & Pereira, 2021).

Hence, it becomes crucial to study the impact of the restrictions imposed during the different COVID-19 lockdown and lifting periods on air quality so that the lessons learned can originate novel and better-targeted policies to improve air quality in the near future.

Therefore, this study aimed to define sustainable mitigation measures and policies to reduce air pollution based on the quantification of the impacts of the restrictions imposed during the COVID-19 pandemic on air quality in Portugal. Moreover, this study: (1) quantified the impact of the mobility restrictive measures imposed during the lockdown and lifting periods of 2020 and 2021 (total of 6 periods) on the concentrations of $PM_{10}$, suspended particles with an equivalent aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$), $NO_2$, tropospheric ozone ($O_3$), sulphur dioxide ($SO_2$), and CO; and (2) evaluated urban, suburban, and rural areas, including industrial areas by comparing with historical data, considering the same periods in the previous 5 years.

## 2 | MATERIALS AND METHODS

### 2.1 | Data collection

The air quality data was obtained from the Portuguese Air Quality Monitoring Stations from the regions of *Norte*, *Lisboa e Vale do Tejo*, and *Algarve*, namely: (1) the hourly pollutants' concentrations of $PM_{10}$, $PM_{2.5}$, $NO_2$, $O_3$, $SO_2$, and CO from the *Norte* and *Algarve* from 1 January 2020 to 30 April 2021; and (2) the hourly data of $PM_{10}$, $PM_{2.5}$, $NO_2$, and $O_3$, from *Lisboa e Vale do Tejo* from 1 January 2020 to 31 December 2020.

Concerning the air quality monitoring network of each Portuguese region studied, the *Norte* region is divided into two zones, *Norte Litoral* and *Norte Interior*, and two agglomerations, *Porto Litoral* and *Entre Douro e Minho*, composed by 22 monitoring sites. The highest number of monitoring stations can be found in the *Porto Litoral* agglomeration (CCDRN, 2014; QualAr, 2019). The *Lisboa e Vale do Tejo* region is divided in three agglomerations, *Área Metropolitana de Lisboa Norte* (AML Norte), *Área Metropolitana de Lisboa Sul* (AML Sul), and *Setúbal*, and one zone, *Oeste, Vale do Tejo e Península de Setúbal*. It is composed of 23 monitoring stations in operation (CCDRLVT, 2017; Mesquita, 2013). The AML Norte has the highest number of air quality monitoring stations (CCDRLVT, 2017). Finally, the *Algarve* Region has four monitoring stations, located in *Portimão (Lagoa)*, *Albufeira (Loulé)*, *Faro (Olhão)*, and *Alcoutim* (CCDR Algarve, 2015). Figure 1 illustrates the topographic location of the monitoring stations of the regions studied according to their type of area and influence, with a particular focus on the *Norte* and *Lisboa e Vale do Tejo* regions.

To allow comparisons with the 2020–2021 data, the historical hourly data (from 1 January 2015 to 31 December 2019) were obtained from the Portuguese Air Quality database "QualAr". For the monitoring station *Cascais-Escola da Cidadela* from the *Lisboa e Vale do Tejo* region, the historical data considered was only from 1 January 2017 to 31 December 2019, due to the relocation of this station that occurred in 2016. Besides this, the monthly mean tropospheric concentrations of $NO_2$, CO, and the monthly mean absorbing aerosol index (AAI), as indicative of PM, were retrieved from the sentinel-5 Precursor TROPOshperic Monitoirng Instrument (TROPOMI) between March 2019 until May 2021, using Google Earth Engine (Gorelick et al., 2017). These data were collected to complement the results obtained from monitoring and validate the real influence of the lockdown and lifting periods imposed during the pandemic on air quality. Furthemore, the hybrid single-particle Langragian Interpolation method (HYSPLIT) was used to simulate the trajectories of air masses to verify the origins of the air masses that occasionally affected Portugal with high levels of PM during the study periods (Stein et al., 2015).

### 2.2 | Study periods: Lockdown and lifting

In Portugal, the first COVID-19 positive case was detected on 2 March 2020, and on 16 March the first restrictive measures to prevent the

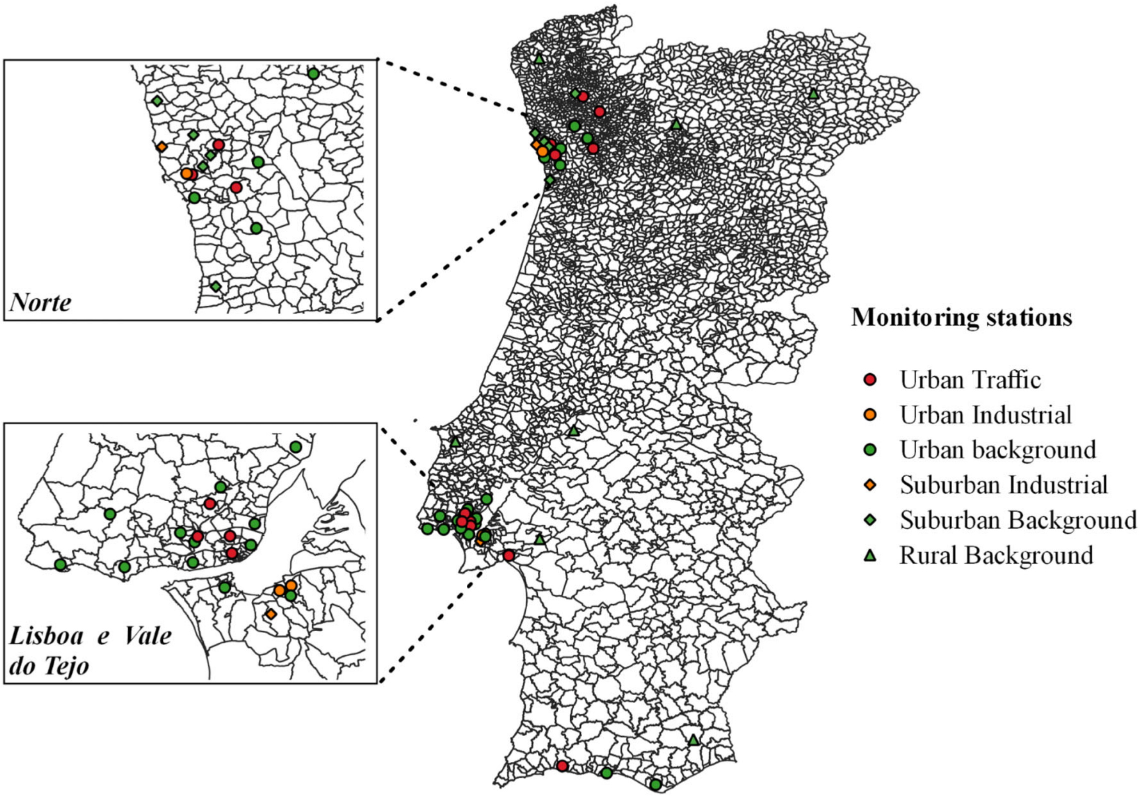


**FIGURE 1** Topographic representation of the Portuguese air quality monitoring network from the regions *Norte*, *Lisboa e Vale do Tejo*, and *Algarve*, according to their type of area and influence. [Colour figure can be viewed at wileyonlinelibrary.com]

spread of the disease were applied: the first general lockdown (República Portuguesa, 2020d). The country started the first State of Emergency on 19 March 2020 (declared on 18 March) with the initial duration of 15 days, but then renewed several times until 4 May 2020, the first day of the gradual lifting (Presidência da República, 2020; República Portuguesa, 2020b; República Portuguesa, 2020c). Several restrictive measures were applied to prevent the spread of the COVID-19. After that period (considered the 1st lockdown), the restrictiveness of the measures varied according to the epidemiologic situation, leading to different lockdown and lifting periods (República Portuguesa, 2021e).

Thus, five periods were considered in the present study, with the last one divided into two sub-periods, corresponding to lockdown and respective lifting periods according to the measures defined by the Portuguese government. These study periods are described in detail in Table 1.

## 2.3 | Data analysis

From the original 1-h time series datasets, daily means were calculated for $PM_{10}$, $PM_{2.5}$, $NO_2$, and $SO_2$, whenever at least 50% of data per day were available. Other criteria were tested, namely 90%, 75% (as indicated in *Decreto-Lei n.*° 102/2010), and 65% of data per day, but all of them led to losing a significant number of air quality monitoring stations and consequently losing diversity concerning the type of monitoring stations. The daily historical mean concentration was calculated using at least three of the 5 years considered (>50%). For $O_3$ and CO, daily maximum of the 8-h running mean for both historical and 2020–2021 data was considered, considering 75% of available data as defined by the *Decreto-Lei n.*° 102/2010. In each study period, each air quality monitoring station was considered if it had at least 50% of the paired (historical-2020/2021) daily mean concentrations for a given pollutant. As the year-to-year variability of the meteorological conditions have a strong influence on the air pollutants concentrations, the comparison with the mean of all years from the historical period (i.e., the mean of the pollutants' concentrations from 2015 to 2019) was performed to soften the effect of extraordinary events and season trends that might have occurred. Thus, by comparing with this mean the influence of the weather conditions and seasonal trends on air pollutants' concentrations could be considered negligible (Gama et al., 2021).

Descriptive statistics were used to express the concentrations of each air pollutant in each monitoring station. Normality was assessed through the Shapiro–Wilk normality test. The parametric Student's *t*-test and the non-parametric Wilcoxon Rank-Sum test were used to test the significance of the differences between the study periods and historical concentrations.

Additionally, the pollutants' concentrations in each period were compared with the reference limit values in the Portuguese legislation (*Decreto-Lei n.*° 102/2010) and with the WHO guidelines to calculate exceedances, namely: (1) $PM_{10}$ was compared with the daily limit

TABLE 1 The study periods defined based on the respective main mobility restrictive measures applied by the Portuguese national government

| Study period | Date | Main mobility restrictive measures applied | References |
|---|---|---|---|
| 1st lockdown | 16 March 2020–3 May 2020 | • Suspension of the face-to-face classes, with mandatory online school for everyone;<br>• Closure of services that provide non-essential goods;<br>• Suspension of several activities, like religious and other events;<br>• All-day curfew; exits allowed only for essential needs;<br>• Flight's suspension;<br>• Circulation prohibited between municipalities;<br>• Interruption of rail and fluvial transport and circulation, except for essential goods transport;<br>• Mandatory remote work (whenever possible). | (República Portuguesa, 2020d) |
| 1st lifting | 4 May 2020–15 June 2020 | • Allowed events with 20 people or less;<br>• Remote work is still mandatory, but in-person work is partially allowed (reduced number of workers simultaneously);<br>• Permission for opening every commercial and cultural place, like restaurants, coffee shops, museums, etc;<br>• Re-opening schools for in-person classes: nursery schools, and 11th and 12th grades, and schools for disabled people. | (Portuguesa, 2020c; República Portuguesa, 2020a) |
| Partial lockdown | 31 October 2020–12 January 2021 | • Curfew during the night on weekdays and during the afternoon and night on weekends;<br>• Mandatory remote work (whenever possible);<br>• Staying at home as a civic duty. | (República Portuguesa, 2020e) |
| 2nd lockdown | 13 January 2021–14 March 2021 | • Restaurants and similar: only allowed take-away or home delivery;<br>• Suspension of several activities and establishments not intended to meet essential needs;<br>• Circulation prohibited between municipalities during the weekends;<br>• Suspension of the face-to-face classes, with mandatory online school for everyone;<br>• Suspension of the presential educational activities, nurseries, or other activities/establishments of social support. | (República Portuguesa, 2021c; 2021d) |
| 2nd lifting, 1st phase | 15 March 2021–4 April 2021 | • Re-opening schools for in-person classes: nursery, pre- and primary schools and similar, as well as social support activities;<br>• Permission of citizens' circulation to other countries. | (República Portuguesa, 2021b) |
| 2nd lifting, 2nd phase | 5 April 2021–30 April 2021 | • Re-opening of all educational facilities for all ages, including university;<br>• Opening of establishments that provide non-essential goods and services, like museums, art galleries, shopping malls. | (República Portuguesa, 2021a) |

value imposed in the *Decreto-Lei n.°* 102/2010 and to the WHO guidelines (both 50 μg/m$^3$); (2) $PM_{2.5}$ was compared with the WHO guideline (25 μg/m$^3$); (3) $O_3$ was compared with the *Decreto-Lei n.°* 102/2010 target value (120 μg/m$^3$) based on the daily maximum of the 8-h running mean concentrations; (4) $NO_2$ was compared with the annual limit value/WHO guideline of 40 μg/m$^3$, which was used as a daily

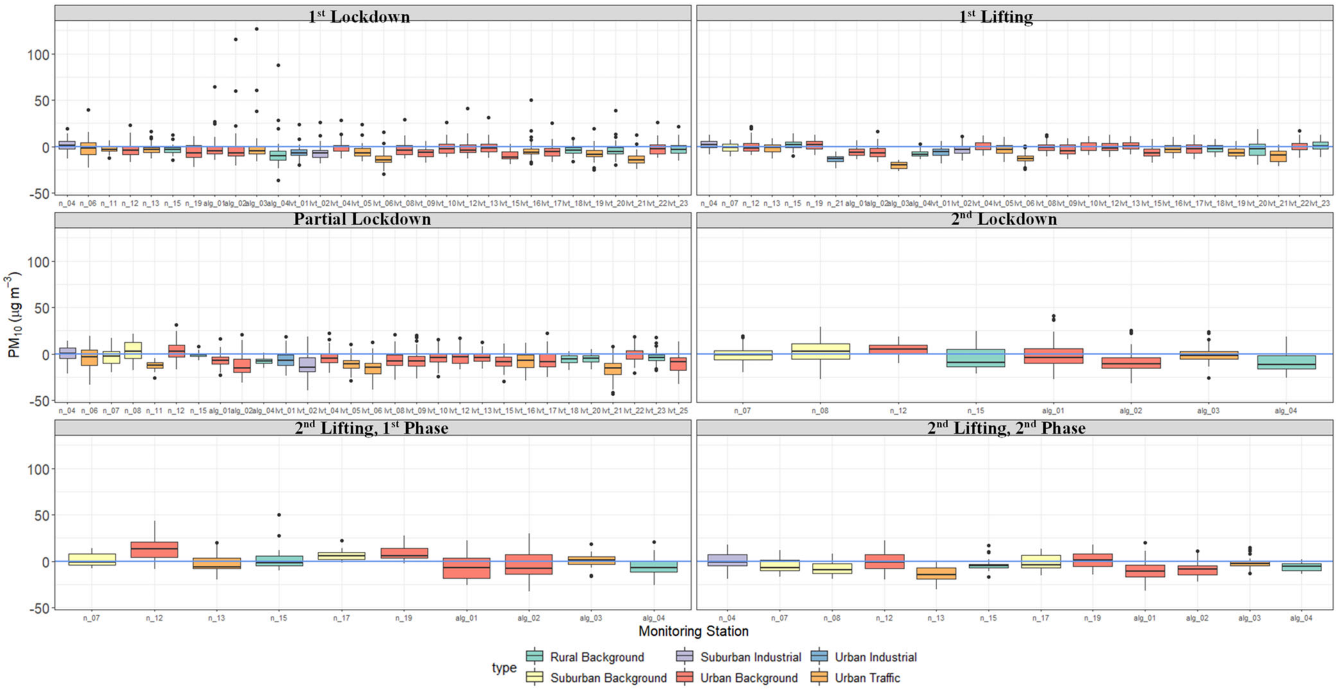


**FIGURE 2** Boxplot of the difference in $PM_{10}$ concentrations between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station. [Colour figure can be viewed at wileyonlinelibrary.com]

limit; (5) CO was compared with the limit value in the *Decreto-Lei n.*° 102/2010 (10 mg/$m^3$); and (6) $SO_2$ was compared with the limit value imposed in the *Decreto-Lei n.*° 102/2010 (125 μg/$m^3$), that should not be exceeded more than 3 times in a year, and WHO guideline of 20 μg/$m^3$.

The air quality monitoring stations and the respective types and pollutants measured are summarised in Appendix A, Supporting Information. An ID was given to each air quality monitoring station for coding purposes, as described in Appendix A.

Moreover, the calculation of the air pollutants' reduction per 100 hab per each region studied was also performed using the inverse distance weighting method (IDW), a commonly used method due to the realibility of its results and its simplicity in execution (Wong et al., 2004). Hence, the results achieved in this study as well as the population data from the most recent Census available (2011) (ESS, 2021) were used as input data for these calculations.

Statistical computations were performed with R Studio (version 4.0.5), with the support of the *openair* package (Carslaw & Ropkins, 2012). The level of statistical significance was set at 0.05. All the maps were created using QGIS open-source software (QGIS, 2021).

# 3 | RESULTS

## 3.1 | Air quality characterisation

In general, the time series patterns along the six study periods were similar to the respective historical time series patterns in most of the monitoring stations evaluated for all pollutants as expected, except for $SO_2$. In this case, the concentrations were higher at industrial stations and the specific urban background station *Malpique* (alg_02), and lower at the rural background *Cerro* (alg_04) and urban background *Joaquim Magalhães* (alg_01) stations. The descriptive statistical analyses and geographical distribution of $PM_{10}$, $PM_{2.5}$, $NO_2$, $O_3$, CO, and $SO_2$ are presented in the Appendices B–AK and AL–BC, respectively, for each studied period.

### 3.1.1 | $PM_{10}$ and $PM_{2.5}$

The geographical distributions of $PM_{10}$ and $PM_{2.5}$ differences in concentrations between the study period and the corresponding historical period in all monitoring stations evaluated are represented in the Appendices AL–AQ. Figures 2 and 3 present boxplots of the differences in $PM_{10}$ and $PM_{2.5}$ concentrations between the study period and the corresponding historical period in each study site by type of station.

*Lockdown periods*

In the 1st and partial lockdown periods (Appendices AL and AM, respectively), $PM_{10}$ and $PM_{2.5}$ concentrations reduced significantly (*p*-value < .05) in the majority of the locations studied when comparing to the corresponding historical periods. Thus, reductions varied from 0.745 to 13.6 μg/$m^3$ and from 0.349 to 4.72 μg/$m^3$, respectively, corresponding to reductions between 1.5% to 4.5% per 100 hab, for both pollutants. The highest reductions were found in the urban traffic and urban background stations, respectively. Yet, during the partial

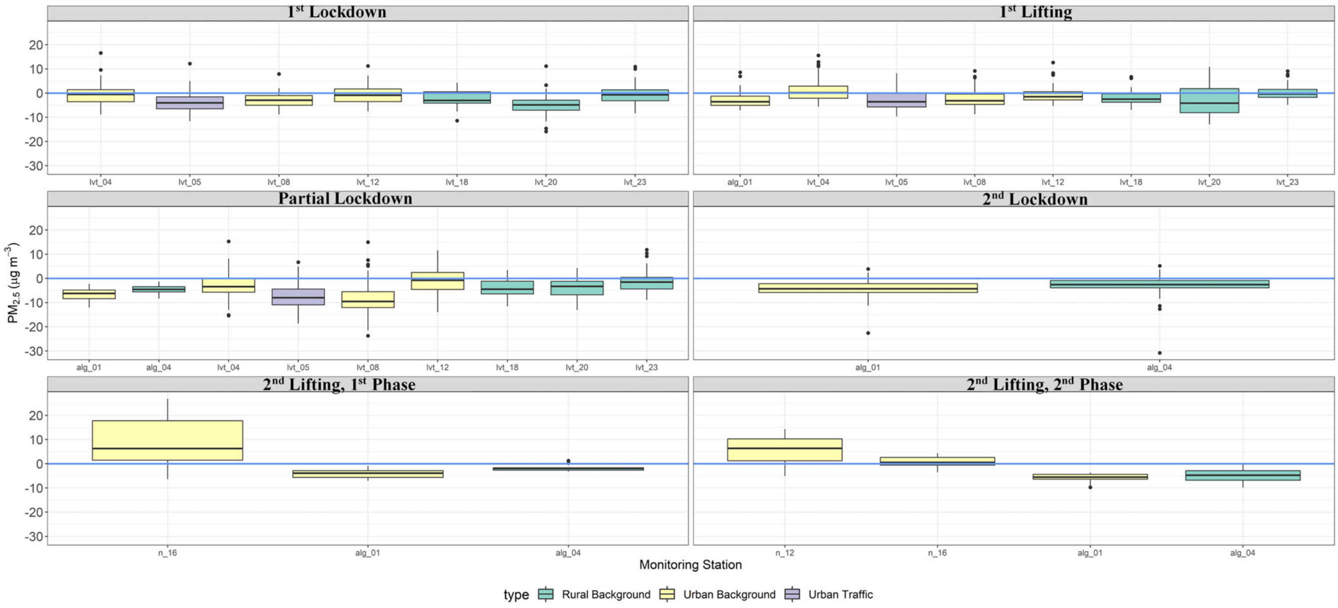


**FIGURE 3** Boxplot of the difference in $PM_{2.5}$ concentrations between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station [Colour figure can be viewed at wileyonlinelibrary.com]

lockdown was noted that in two of the studied background stations located in the *Norte* region, *Leça do Balio-Matosinhos* (suburban, n_08) and *Paços de Ferreira* (urban, n_12), the $PM_{10}$ concentrations significantly increased (*p*-value < .05) in comparison with the corresponding historical period. During the 2nd lockdown (Appendix AN), the differences in $PM_{10}$ varied between −9.40 to 4.62 μg/m$^3$, with only a few statistically significant reductions (*p*-value < .05). $PM_{2.5}$ concentrations reduced significantly, with reductions varying from 2.90 to 4.13 μg/m$^3$ in the two studied stations, both background stations (urban and rural) in *Algarve* region.

Concerning the exceedances to the legal limit values and WHO guidelines (Appendix BD–BF) in these periods, in general reduced to zero for $PM_{10}$, particularly in the urban (traffic and background) stations, whilst for $PM_{2.5}$ zero exceedances were verified in almost every monitoring station, having reduced when compared to the historical period. Yet, in *Algarve* during the 1st lockdown, the number of days with exceedances in 2020 doubled compared to the historical period even though on average the concentrations decreased significantly. In the same region, during the 2nd lockdown, the exceedances to the reference $PM_{10}$ values (Appendix BF) increased in *Algarve* (urban background station *Joaquim Magalhães*, alg_01) from 1% to 5%, where a statistically significant increase in the concentrations was also verified.

*Lifting periods*

During the 1st and 2nd lifting periods (Appendix AO, and 1st phase – Appendix AP and 2nd phase – Appendix AQ, respectively), the differences between study and historical periods in $PM_{10}$ and $PM_{2.5}$ concentrations varied from −20.1 to 14.8 μg/m$^3$ and −5.74 to 9.12 μg/m$^3$ respectively, corresponding to variations in the concentrations of −5.8% to 5.9% per 100 hab. In the 1st lifting, the highest significant decrease of $PM_{10}$ concentrations (20.1 μg/m$^3$) occurred at the urban traffic station *David Neto* (alg_03) in *Algarve*, whilst in the 2nd lifting, 1st phase, for $PM_{10}$, both statistically significant (*p*-value < .05) reductions and increases were found in background (urban and rural) stations. $PM_{2.5}$ concentrations increased in the studied station in the *Norte* region, whilst they significantly decreased (*p*-value < .05) in *Algarve* stations. In the 2nd lifting, 2nd phase, in the background stations (urban and suburban) the differences in $PM_{10}$ and $PM_{2.5}$ concentrations between study period and the corresponding historical period were not statistically significant.

In general, the percentage of exceedances to the legal limit values and WHO guidelines (Appendix BG) reduced to zero in the 1st lifting, mainly in the urban (traffic and background) stations, for both pollutants. In the 2nd lifting, 1st phase PM exceedances to the reference limit values increased from 10% to 24% in the stations where a significant increase in concentrations was also found (Appendix BH). For the 2nd phase, PM concentrations almost never exceeded the reference limit values in both study and historical periods (Appendix BI). In fact, both PM fractions evidenced a similar behaviour in all lifting periods, namely the 1st lifting and 2nd lifting, 1st phase and 2nd phase, since less restrictive measures were imposed when compared with the lockdown periods.

### 3.1.2 | $NO_2$

The geographical distributions of the differences in $NO_2$ concentrations between the study period and the corresponding historical period are represented in the Appendices AR-AT. Fig. 4 presents boxplots of the differences in $NO_2$ concentrations between the study and the historical period in each study site by type of station.

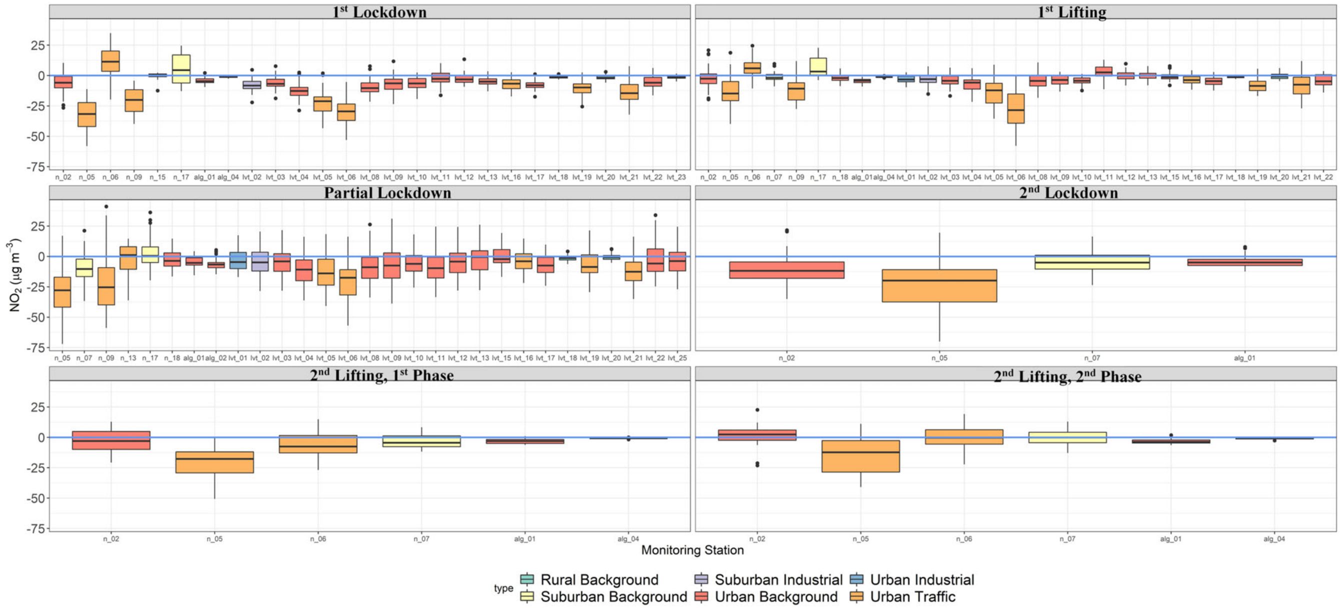


**FIGURE 4** Boxplot of the $NO_2$ difference concentration between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station. [Colour figure can be viewed at wileyonlinelibrary.com]

*Lockdown Periods*

Overall, during the total (1st and 2nd) and partial lockdown periods (Appendix AR and AS, respectively), $NO_2$ concentrations reduced significantly (p-value <.05) in the majority of the stations, from 0.137 to 31.6 μg/m$^3$, when compared with the historical periods, corresponding to reductions between 1.3% to 7.4% per 100 hab. The highest reduction of all periods occurred during the 1st lockdown at the urban traffic stations, yet two stations were exceptions in this latter period (n_06 and n_17) where $NO_2$ concentrations significantly increased (p-value < .05) by 11.7 and 6.08 μg/m$^3$ in average, respectively.

During the 1st lockdown, in most of the studied monitoring stations the percentage of exceedances to the reference limit values decreased to 0% or close, with the highest reductions (by more than 50%) in the urban traffic stations (e.g., in lvt_06 the exceedances reduced from 52% to 2%) (Appendix BD). The exceptions corresponded to the stations previously mentioned (n_06 and n_17) in which the percentage of exceedances increased, even from 0% (n_17). In the partial lockdown a higher number of exceedances to the reference limit values were encountered in this period compared to the previous periods (Appendix BE). Yet, in the urban traffic stations, expressive decreases in the number of exceedances were also registered. Lastly, in the 2nd lockdown the percentage of exceedances in this period reduced from the historical, although never reduced to 0%, with the highest reduction observed in an urban traffic station (*Francisco Sá Carneiro-Campanhã*, n_05) where the exceedances reduced from 77% to 46% (Appendix BF).

Globallly, when comparing the different lockdown periods, the differences in $NO_2$ concentrations were similar in both full lockdown periods, 1st and 2nd, whilst in the partial lockdown the differences in $NO_2$ concentrations varied more expressively (i.e., the range between the maximum and minimum value was higher).

*Lifting periods*

During the 1st and 2nd lifting periods (Appendix AS and AT, respectively), $NO_2$ concentrations reduced significantly (*p*-value < .05) compared to the historical periods, with reductions from 0.0366 to 28.1 μg/m$^3$, corresponding to reductions between 2.7% to 5.9% per 1000 hab. The highest reduction was registered during the 1st lifting in the urban stations. Nevertheless, the stations n_06 and n_17 also registered a significant increase during the 1st lifting as they had registered in the lockdown periods.

Concerning the exceedances to the reference limit values (Appendix BG), similar results to the 1st lockdown were found in the 1st lifting, with the highest reductions in the urban traffic stations also (e.g., in lvt_06 the exceedances reduced from 69% to 14%). In the 2nd lifting, 1st phase, only a few monitoring stations registered exceedances to the reference limit values in both study and historical periods (Appendix BH). Yet, only in the urban traffic station *Francisco Sá Carneiro-Campanhã* (n_05) the percentage of exceedances remained equal. The percentage of exceedances reduced in the other monitoring stations, even to 0% in one station (urban background *Ermesinde-Valongo* station, n_02). Similar results were observed in 2nd lifting, 2nd phase (Appendix BI), with the highest decrease in the station n_05 (from 87% to 50%).

In general, for $NO_2$ similar results were found in the lifting periods, 1st and 2nd, even though in the 2nd lifting, 1st phase a higher number of decreases were encountered.

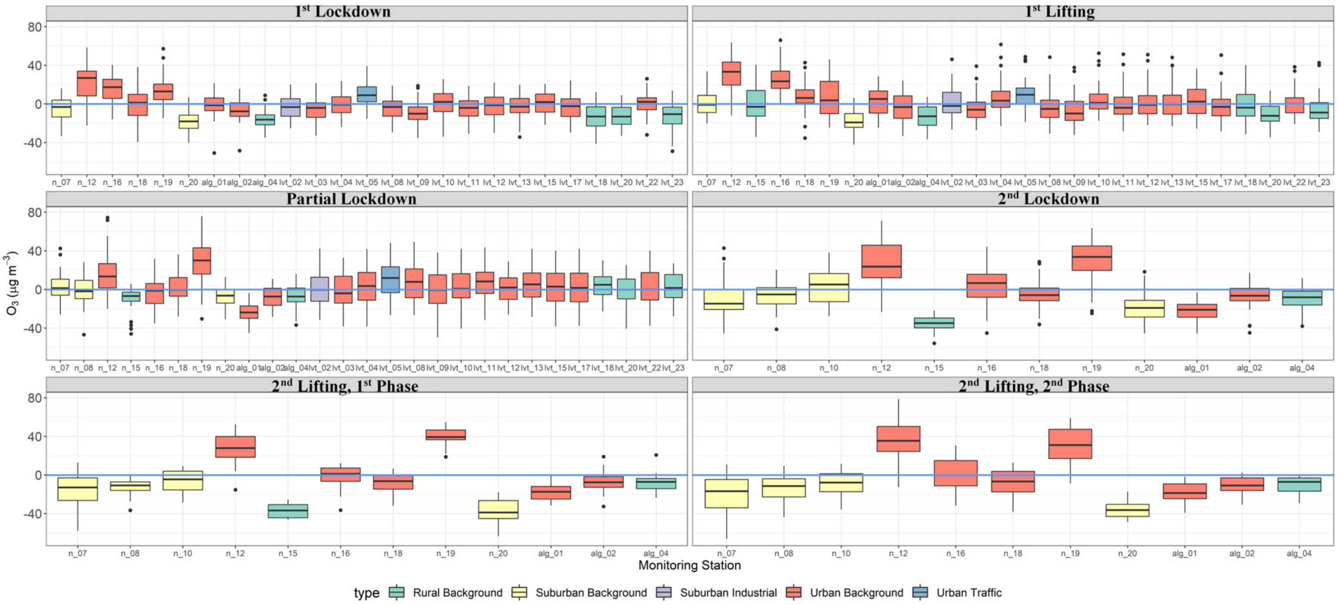


**FIGURE 5** Boxplot of the $O_3$ difference concentration between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station. [Colour figure can be viewed at wileyonlinelibrary.com]

### 3.1.3 | $O_3$

The geographical distributions of the differences in $O_3$ concentrations between the study period and the corresponding historical period in all the studied monitoring stations evaluated are represented in the Appendices AU–AW. Figure 5 presents boxplots of the differences in $O_3$ concentrations between the study and the historical period in each study site by type of station.

*Lockdown periods*

During the 1st and 2nd lockdown periods (Appendix AU) differences in $O_3$ concentrations varied between −35.1 and 29.8 μg/m$^3$, with statistically significant reductions (*p*-value < .05) in most of the stations, particularly during the 1st lockdown. Thus, these variations correspond to variations in concentrations between −2.6% to 2.2% per 100 hab. Nevertheless, $O_3$ concentrations increased significantly in half of the *Norte* region stations, thus in more stations than in the remaining studied regions. In the same way, the percentage of exceedances to the reference limit values reduced in the *Lisboa e Vale do Tejo* and *Algarve* regions to 0%, whilst in the *Norte* region they increased from 0% to 2% (Appendix BD) during the 1st lockdown. In the 2nd one, only a few exceedances were encountered, but where exceedances occurred in the historical period, they all reduced to 0% in 2021 (Appendix BF).

In the partial lockdown (Appendix AV), differences in $O_3$ concentrations varied between −23.4 and 29.2 μg/m$^3$, with concentrations increasing in general, in comparison with the corresponding historical period, although not all of them were statistically significant (*p*-value > .05), corresponding to variations in concentrations between −1.0% to 0.7% per 100 hab. The *Norte* region did not register exceedances to the $O_3$ reference limit values in this study period and corresponding historical period, whilst in *Lisboa e Vale do Tejo* and *Algarve* regions the percentage of exceedances reduced in all cases to 0%, even though in most of that region $O_3$ concentrations increased (Appendix BE).

Globally, on average $O_3$ concentrations decreased in most of the monitoring stations in the 1st and 2nd lockdown periods when comparing with the corresponding historical periods, whilst in the partial lockdown $O_3$ concentrations increased in most of the studied stations.

*Lifting periods*

In the 1st and 2nd lifting periods (Appendices AV and AW, respectively), the differences in $O_3$ concentrations between the study and the corresponding historical period varied from −37.9 to 38.5 μg/m$^3$, corresponding to variations in concentrations between −3.6% to 3.1% per 100 hab. In the 1st lifting, the number of stations evidenced that increases and decreases in $O_3$ concentrations was similar. Nevertheless, the majority of the increases observed in this period were not statistically significant (*p*-value > .05). The *Norte* region registered a higher number of stations where $O_3$ concentrations increased (all statistically significant) than the other studied regions (*Lisboa e Vale Tejo* and *Algarve*). Furthermore, in the 2nd lifting the $O_3$ concentrations decreased in almost every monitoring station relatively to the corresponding historical period, including some statistically significant reductions (*p*-value < .05). Yet, in two urban background stations in *Norte* region (*Paços de Ferreira*, n_12, and *Avintes*, n_19) $O_3$ concentrations increased.

Whilst the monitoring stations studied in the *Norte* region never registered exceedances to the $O_3$ reference limit values in both lifting periods and corresponding historical periods, in *Lisboa e Vale do Tejo* and *Algarve* regions the percentage of exceedances reduced to 0% even in stations where the concentrations significantly increased in average (e.g., urban traffic *Entrecampos* station, lvt_05) (Appendix BG).

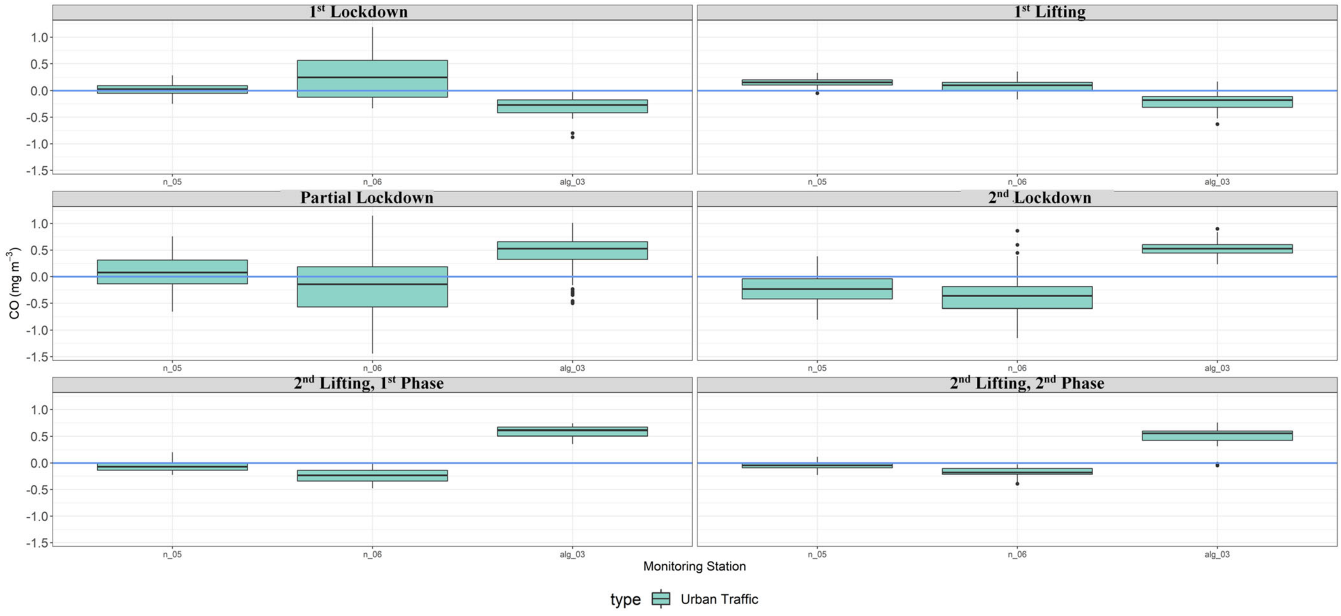


**FIGURE 6** Boxplot of the CO difference concentration between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station. [Colour figure can be viewed at wileyonlinelibrary.com]

In the stations that had exceeded the $O_3$ reference limit values in the corresponding historical period, they had been reduced to zero exceedances in the 2nd lifting (Appendices BH and BI).

Whilst the differences in $O_3$ concentrations were similar in the lockdown and lifting periods, a lower number of increases in $O_3$ concentrations during the 2nd lifting was observed than in the other lifting period.

### 3.1.4 | CO

The geographical distributions of the differences in CO concentrations between the study period and the corresponding historical period in all the studied monitoring stations are represented in Appendices AX–AZ. Figure 6 presents boxplots of the differences in CO concentrations between the study and the historical period in each study site by type of station.

*Lockdown periods*

In the 1st and partial lockdown periods (Appendix AX and AY, respectively), the differences in CO concentrations varied between −0.193 and 0.420 mg/m$^3$, with one of the three monitoring stations registering a statistically significant ($p$-value < .05) increase in both of these periods. Thus, these results corresponded to variations in concentrations between −5.3% to 5.9% per 100 hab. The differences in CO concentrations between the 2nd lockdown (Appendix AU), and the corresponding historical period varied between −0.358 and 0.522 mg/m$^3$, corresponding to variations in concentrations between −8.1% to 7.3% per 100 hab. All these differences were statistically significant ($p$-value < .05), with a higher number of stations where reductions occurred (2 out of 3).

*Lifting periods*

During the 1st lifting (Appendix AY), CO concentrations significantly increased in the *Norte* region from 0.0948 to 0.154 mg/m$^3$ ($p$-value < .05), corresponding to an increase of 7.9% per 100 hab. Yet, a significant reduction occurred in the *David Neto* (urban traffic, alg_03) station (−0.198 mg/m$^3$, $p$-value < .05), corresponding to a reduction of 4.3% per 100 hab. In the 2nd lifting (Appendix AZ), a similar scenario to the 2nd lockdown was observed, with CO differences varying between −0.251 and 0.578 mg/m$^3$ in the 1st phase and between −0.184 and 0.502 mg/m$^3$ in the 2nd phase, corresponding to variations in concentrations between −5.5% to 10.9% per 100 hab in both phases.

The observed CO concentrations never exceeded the reference limit values considered in any of the study and historical periods.

When comparing the different study periods, in *Francisco Sá Carneiro-Campanhã* (urban traffic, n_05) the CO concentrations were lower than the historical in the 2nd lockdown and 2nd lifting periods, whilst in the 1st lockdown, 1st lifting, and partial lockdown the CO concentrations were higher than the corresponding historical periods. The same occurred in the station *João Gomes Laranjo-S.Hora* (urban traffic, n_06), whilst in the *David Neto* (urban traffic, alg_03) station the variation was different, that is, CO concentrations increased in the partial lockdown, 2nd lockdown and 2nd lifting, and decreased in the 1st lockdown and 1st lifting.

### 3.1.5 | $SO_2$

The geographical distributions of the differences in $SO_2$ concentrations between the study period and the corresponding historical period in all the monitoring stations evaluated are represented in the

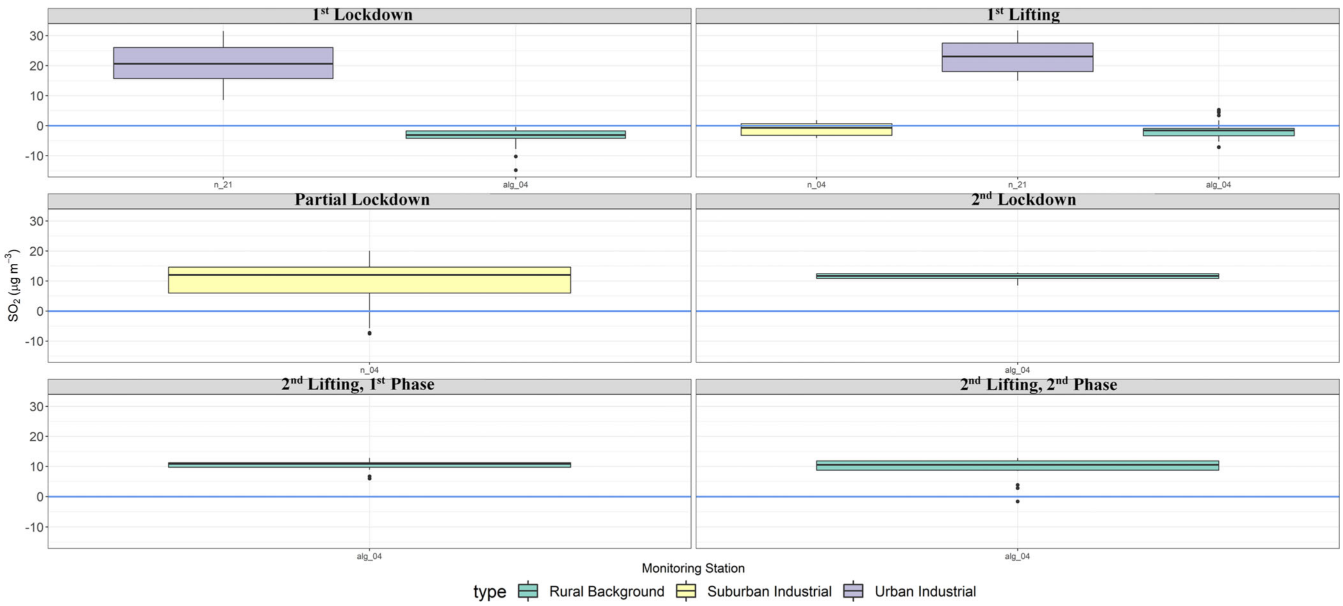


**FIGURE 7** Boxplot of the $SO_2$ difference concentration between the study period and the historical data, for all monitoring stations evaluated in each studied period, and according to the type of the station. [Colour figure can be viewed at wileyonlinelibrary.com]

Supplementary Material (Figure BA to BC ). Figure 7 presents boxplots of the differences in $SO_2$ concentrations between the study and the historical period in each study site by type of station.

*Lockdown periods*

In the 1st lockdown (Appendix BA) $SO_2$ concentrations increased significantly by 20.6 μg/m$^3$ ($p$-value < .05) in average at the urban industrial area (*Seara-Matosinhos*, n_21) and decreased significantly by 3.52 μg/m$^3$ ($p$-value < .05) in average at the rural background area (*Cerro*, alg_04). Thus, corresponding to variations in concentrations between −2.5% to 5.5% per 100 hab for both. In the partial and 2nd lockdown periods (Appendix BB and BA, respectively), $SO_2$ concentrations significantly increased in average by 9.79 and 11.5 μg/m$^3$ ($p$-value < .05) in that rural background area (*Cerro*, alg_04), corresponding to increases between 5.9% to 23% per 100 hab.

Overall, no exceedances to the $SO_2$ reference limit values in the Portuguese legislation were found during the 1st lockdown, and even reduced to 0% in the subsequent lockdown periods. In contrast, exceedances to the WHO guidelines were found in all the periods (Appendix BD–BF), increasing the most in the urban industrial station *Seara-Matosinhos* (n_21) (from 2% to 92%) during the 1st lockdown. Besides, even though a significant decrease of the mean concentrations was observed in the rural background station *Cerro* alg_04 in the 1st lockdown, the exceedances to the WHO references limits increased from 0% to 20% (Appendix BD).

*Lifting periods*

In the 1st lifting period (Appendix BB), results showed statistically significant reductions in $SO_2$ concentrations in comparison with the corresponding historical period, both in the suburban industrial station (*Meco-Perafita*, n_04) and the rural background station (*Cerro*, alg_04) of 1.19 and 1.52 μg/m$^3$ ($p$-value < .05), respectively. Thus, these results corresponded to reductions between 2.0% to 4.3% per 100 hab. Results also evidenced statistically significant increases in $SO_2$ concentrations in the urban industrial station during this period (*Seara-Matosinhos*, n_21) (22.6 μg/m$^3$, $p$-value < 0.05, increase of 34% per 100 hab). In the 2nd lifting period (Appendix BC), $SO_2$ concentrations significantly increased in the rural background station (*Cerro*, alg_04) (mean of 10.4 and 9.54 μg/m$^3$, respectively in the 1st and 2nd phases, $p$-value < .05), and significantly increased in the urban background station (*Malpique*, alg_02) (mean difference of 13.9 and 12.7 μg/m$^3$, respectively in 1st and 2nd phases, $p$-value < .05). Thus, these results corresponded to increases of 8.1% per 100 hab.

In the 1st lifting, the exceedances to the reference limit values in the Portuguese legislation reduced to 0% in all stations when compared with the historical data. The exceedances to the WHO guidelines increased in the urban industrial station (*Seara-Matosinhos*, n_21) (from 4% to 56%), but reduced in the rural background station (*Cerro*, alg_04) (from 13% to 0%) following the significant decrease in concentrations (Appendix BG). In the other periods, there were no exceedances to the $SO_2$ reference limit values (Appendices BH and BI).

When comparing the different study periods, it was not possible to establish a pattern as observed in the other studied pollutants. Nonetheless, it was verified that the $SO_2$ concentrations increased mostly in the industrial stations during the 2020 periods, the 1st lockdown, 1st lifting, and partial lockdown. Besides, higher levels *in Algarve* (alg_04) were found in 2021 study periods, 2nd lockdown and 2nd lifting, 1st phase and 2nd phase.

## 4 | DISCUSSION

Overall, across all regions the reductions in $PM_{10}$ concentrations were higher in the 1st lockdown than in the 2nd as expected, attending the restrictive measures imposed during the 1st lockdown, namely mandatory curfew, circulation forbidden between municipalities during the week, and exits only allowed for essential needs. In the partial lockdown, the COVID-19 restrictions were more effective in reducing $PM_{10}$ concentrations in the *Algarve* and *Lisboa e Vale do Tejo* regions than in the *Norte*. This might have happened since the *Norte* is predominantly an industrial region and industries did not close during the COVID-19 pandemic. Nonetheless, a lower reduction per 100 hab was found in *Lisboa e Vale do Tejo* (2% per 100 hab for *Lisboa e Vale do Tejo*, and 3% per 100 hab for *Norte* and *Algarve*). Regarding $PM_{2.5}$, the results were similar between regions and similar in the lockdown periods, 1st, partial, and 2nd lockdown periods, that is, concentrations during COVID-19 pandemic diminished in comparison with the historical period in most of the studied locations. In the literature, the reductions in PM concentrations during the 1st lockdown were in line with those observed in Portugal as studied by Slezakova and Pereira (2021) (when comparing with 2019) and in other countries, like in Poland (when comparing with 2018–2019) as studied by Filonchyk et al. (2021), and in Spain (when comparing with 2019) (Donzelli et al., 2021).

During the 1st lifting, less statistically significant reductions of PM were found compared to the 1st lockdown, revealing that the concentrations possibly increased during this period, as concluded in other studies (Bai et al., 2020), similarly to what happened during the 2nd lifting. Yet, the most statistically significant reductions of all regions occurred in *Algarve*, especially during the 1st lifting (with a reduction of 3.1% per 100 hab against the 0.9% and 0.6% per 100 hab in *Lisboa e Vale do Tejo* and *Norte* respectively), which is essentially a touristic region and tourism was one of the most affected economic activities due to COVID-19 pandemic (Porto Business School, 2020). Besides, the significant reductions found in the other regions *Norte* and *Lisboa e Vale do Tejo* might have to do with the mandatory remote work during this period, which diminished people's mobility, thus reducing traffic during this period compared to the usual before the pandemic. Notwithstanding, $PM_{2.5}$ registered increases in the *Norte* during the 2nd lifting, 1st phase, that as mentioned before might be due to the industries that never closed during the pandemic.

Natural events not related to the COVID-19 pandemic may have affected the concentrations of PM levels ($PM_{10}$ and $PM_{2.5}$) in some particular cases, even though a general reduction was observed. An air mass intrusion from the North of Africa carrying Saharan and Sahel dust affected the PM levels in some of the studied periods, in all stations but more evident in those closer to the desert (*Algarve* region). This phenomenon occurred in the total lockdown periods (1st and 2nd), 1st lifting, and 2nd lifting, 1st phase (APA, 2020; 2021; Macedo, 2020), being such traduced in some days of PM concentrations above the reference values and hence increasing the number of exceedances up to the double compared to the historical period (viz., 1st lockdown). Such can be seen in the time series of PM represented in Appendix BJ–CA. The influence of such phenomenon was also observed in the satellite data, particularly in the AAI from which is possible to infer the PM concentrations. Thus, in Appendix CB the monthly AAI for the three main councils of the three regions studied (*Porto*, *Lisboa*, and *Faro* from *Norte*, *Lisboa e Vale do Tejo* and *Algarve* regions, respectively) is represented. During the periods mentioned, some peaks are observed in the index, indicative of the intrusion of dust and other aerosols in the country. This was particularly seen in the index during the 2nd lifting, 1st phase, and also identified in the HYSPLIT model by the PM trajectory from the North of Africa (Appendix CC).

$NO_2$ and $O_3$ reduced across all regions during the lockdown periods even though less statistically significant reductions occurred in the *Norte* region when compared to the others, especially during the 1st lockdown. For instance, $NO_2$ increased in *João Gomes Laranjo-S. Hora* (urban traffic, n_06) which might have happened because in March 2020 the temperature was lower (mean 12°C) and the precipitation levels were higher than the usual for this month, particularly in the Northern region. Such suggests that a higher use of household fireplaces may have occurred, consequently increasing $NO_2$ concentrations in the residential area in the vicinity of this monitoring station (IPMA, 2020d). In the monitoring station *Mindelo-Vila do Conde* (suburban background, n_17), the increase may be linked to the pollutants emitted by a nearby refinery located South of the monitoring station, since the predominant wind direction registered during April and the beginning of May 2020 was from South (Weather Underground, 2021). Yet, a higher reduction per 100 hab (5.9%) was found in the *Norte* as higher reductions (in terms of concentrations) were found even though in just a few monitoring stations contrarily to the other regions (3.8% and 2.6% per 100 hab for *Algarve* and *Lisboa e Vale do Tejo*, respectively).

In general, the reductions found in the other regions for $NO_2$ during the 1st lockdown were also reported to be higher in urban traffic stations in other studies that followed a similar methodology like Vultaggio et al. (2020) and Gama et al. (2021). Slezakova and Pereira (2021) concluded the same whilst comparing the lockdown with the corresponding period in 2019. As for the reductions observed for $O_3$, the contrary was concluded in Turkey by Celik and Gul (2021) when comparing with the corresponding period in 2019. However, the study conducted by Ordóñez et al. (2020) in Europe revealed that $O_3$ concentrations decreased by 7% in the Iberian Peninsula due to the low solar radiation, when comparing the study with the same historical time interval considered in the present study (2015–2019). Slezakova and Pereira (2021) also had a similar conclusion for Portugal (when comparing with 2019). An unexpected significant decrease in $O_3$ was observed in the 1st lockdown in the weeks from 1 April 2020to 15 April 2020. Although April was considered hotter than the usual favouring the formation of this pollutant, during the weeks mentioned an anticyclone affected Portugal (continental part) with high precipitation levels, interfering with the $O_3$ formation (IPMA, 2020a). Yet, in the *Norte* region less reductions were found compared to the other regions, which is in line with the results achieved per 100 hab (2%, −0.6%, and −0.4% per 100 hab for *Norte*, *Algarve*, and *Lisboa e Vale do Tejo* respectively).

During the partial lockdown, the significant increases of $O_3$ that occurred in the *Norte* and *Lisboa e Vale do Tejo* regions were possibly linked to the significant reductions of $NO_2$ observed in the same stations/areas. Besides, the high temperature registered during November 2020, which was the second highest in that month since 2000 (IPMA, 2020c), could also favour $O_3$ formation.

During the lifting periods (1st and 2nd), many reductions of $NO_2$ were observed across all regions, with reductions of 2.7%–5.9%, 2.6%–4.0%, and 2% per 100 hab for *Norte*, *Algarve*, and *Lisboa e Vale do Tejo*, even though the measures in these periods were less restrictive than the ones in the lockdown periods. Hence, the mandatory remote work greatly contributed to the traffic reduction in urban areas, which might be one of the reasons causing the significant reductions in $NO_2$ concentrations in some stations. Nevertheless, the stations n_06 and n_17 also registered a significant increase during the 1st lifting as they had registered in the lockdown periods, which means that the restrictions imposed during the COVID-19 pandemic were not as effective in these cases as in the remaining stations studied in the same region (*Norte*). In the case of $O_3$, the significant increases that occurred during the 1st lifting were probably due to the high temperatures (~30°C) registered in the three regions studied that allowed favourable conditions for $O_3$ formation (AccuWeather, 2021), with the *Norte* region registering more significant increases as well for this later pollutant (with an increase of 3.1% per 100 hab against the reduction of 0.4% and 0% per 100 hab for *Algarve* and *Lisboa e Vale do Tejo*). In the 2nd lifting, more reductions were found similarly to $NO_2$, yet in the two stations from the *Norte* region where an increased occurred, the $O_3$ formation might have been favoured since March and April 2021 were considered as hot and dry, and very hot with normal precipitation levels months, respectively (IPMA, 2021a; 2021b).

Overall, $O_3$ concentrations were highly affected by meteorological conditions. However, the reductions observed might be connected to the effectiveness of some measures applied during these periods, like the mandatory remote work that significantly reduced the traffic mobility, and hence led to diminishing the emission of $O_3$ precursors and consequently diminishing its formation. This is more evident in the *Algarve* region where $NO_2$ concentrations reduced significantly in almost every station, which consequently led to a decrease of $O_3$ concentrations, but also the reduction of the touristic activity and the suspension of the flights until the 1st phase of the 2nd lifting period influenced this evidence.

When comparing with the satellite data available for tropospheric $NO_2$, the real effects of the lockdown/lifting periods are verified, since, in all periods, reductions in tropospheric $NO_2$ concentrations were found when compared to the previous year (2019), thus corroborating the results achieved and the influence of the restricitive measures in this pollutant concentrations. This can be seen in Appendix CD, that represents the monthly tropospheric $NO_2$ concentrations for the three main councils of the three regions studied (*Porto*, *Lisboa*, and *Faro* from *Norte*, *Lisboa e Vale do Tejo*, and *Algarve* regions, respectively).

For CO, since all the stations where this pollutant was evaluated were classified as urban traffic a decrease in CO concentrations was expected during the lockdown periods. However, the higher use of fireplaces in the surroundings of the station *João Gomes Laranjo-S. Hora* from the *Norte* region (n_06, urban traffic station) might be the reason for the observed increase during the 1st lockdown, as previously explained for $NO_2$ (leading to an increase of 5.5% per 100 hab in the *Norte* region). Results evidenced that in *Algarve* region the restrictive measures applied in this period were able to diminish CO concentrations (relatively to the historical period with a reduction of 5.3% per 100 hab). Other studies in the literature reported that the impact of restrictions imposed during COVID-19 in CO concentrations varied amongst different countries. In one hand, Sahraei et al. (2021) observed that CO was the pollutant that registered the highest reduction in Turkey during COVID-19 lockdown period (when compared with 2019). On the other hand, Kutralam-Muniasamy et al. (2021) observed an increase in this pollutant's concentration in Mexico when compared with a longer historical period (2015–2019). December 2020 (in the partial lockdown) was considered colder than usual, which could had led to an unusual increase in the use of fireplaces (wood burning) since people spent more time at home due to the mobility restrictive measures, thus increasing CO concentrations in that monitoring station from *Algarve* region (IPMA, 2020b). In the 2nd lockdown though, CO concentrations reduced in the *Norte* region (a reduction of 8.1% per 100 hab), as expected attending the restrictive measures applied in this period. Contrarily, in *Algarve* region the CO concentrations increased (about 7.3% per 100 hab), hence the COVID-19 pandemic measures in the 2nd lockdown were not as effective in this region as they were in the *Norte*.

During the 1st lifting, the decreases (of 4.3% per 100 hab) observed in the *Algarve* region were possibly due to the tourism that was one of the most socioeconomic sectors affected by the pandemic, as mentioned before. Furthemore, during the first phase of the 2nd lifting not all services were opened, and remote work was still mandatory which possibly led to the traffic decrease and consequently to the significant reductions observed in CO concentrations in the *Norte* region (of 5.5%–6.1% per 100 hab). The significant increase in the station in *Algarve* (of 10.9% per 100 hab), a predominantly touristic region, was probably due to the increase in touristic activity, not only by national citizens but also by foreign tourists, as during this period it was already possible to travel within the country without limitations, and travel to/from other countries.

When comparing with the satellite data available for tropospheric CO, the same results as above described were also found, thus revealing that for this pollutant the influence of the climate and the associated use of fireplaces were superior than the effects of the restrictive measures adopted during the pandemic (viz., 1st lockdown). Nonetheless, in the periods during the sunny and warm season, a reduction of this pollutant was found (viz., 1st lifting), proving the real effects of the measures adopted during the pandemic on air quality. This can be seen in Appendix CE, that represents the monthly tropospheric CO concentrations for the three main councils of the three regions studied (*Porto*, *Lisboa*, and *Faro* from *Norte*, *Lisboa e Vale do Tejo*, and *Algarve* regions, respectively).

Like CO, $SO_2$ concentrations during the 1st lockdown increased in the *Norte* region and decreased in *Algarve*, increasing in this later region in the other lockdown periods. Thus, during the 1st lockdown period, people stayed more time at home consuming more electricity (DGEG, 2020), which comes from an industrial plant with a cogeneration system that produces electricity for the grid, nearby the studied industrial site from the *Norte* (*Seara-Matosinhos*, n_21). To meet the increased demand, this industry might had to produce more than usual, which resulted in an increment of the $SO_2$ emissions (GALP, 2021), thus possibly contributing to the observed increase in $SO_2$ concentrations when compared with the corresponding historical period (increase of 55% per 100 hab). Aside this, the wind direction during this period was predominantly from North/North-West, and since the industry is situated at North-West of this urban industrial station (*Seara-Matosinhos*, n_21), the wind might have also contributed to the increase in the $SO_2$ concentrations registered by that station (Weather Underground, 2021). Notwithstanding, other urban sources may have influenced this increment. These results were in agreement with those from Gao et al. (2021) that observed an increase of this pollutant in China during the lockdown compared to historical data (2016–2019). Yet, the results from the present study were against those reported by Sannino et al. (2021) in Italy, where were found a significant reduction of $SO_2$ concentrations at the urban industrial areas and only small variations in the background areas when compared only to 2019 data.

The increase verified in the *Cerro* station from the *Algarve* region (rural background, alg_04) during the 2nd lockdown (13.7% per 100 hab) was possibly due to the same reasons as for urban industrial station from the *Norte* (*Seara-Matosinhos*, n_21) in the 1st lockdown. During part of this period, the wind was predominantly from the South, hence influencing the transport of the pollutants (namely $SO_2$) in the direction of the rural background station (*Cerro*, alg_04, *Algarve*) (Weather Underground, 2021). Besides, this increase might have to do with maritime traffic, especially due to the increased use of small fishing boats with a motor incorporated (Tsai, 2021). These fleets are not embraced by the current legislation of fuel used in ships, thus little or no control is applied concerning the type of fuel those boats use and its sulphur content (Neves et al., 2019). Several fishing ports and a marina (*Albufeira*) are located in the vicinity of that monitoring station (UA, 2019).

The observed increase (34.4% per 100 hab) in $SO_2$ concentrations in the urban industrial station from *Norte* (*Seara-Matosinhos*, n_21) during the 1st lifting was possibly due to the same reasons as in the 1st lockdown. This period represented a lifting of the restrictions immediately after the 1st lockdown, and the wind direction was also predominantly North-West. Given the proximity of the suburban industrial station (*Meco-Perafita*, n_04), it would be expected an increase on the $SO_2$ concentrations there also. However, that station is located in the opposite direction (North-West) of the referred industrial complex and the urban industrial station (*Seara-Matosinhos*, n_21). Thus the wind may have transported the emitted $SO_2$ to the opposite direction leading to the observed reduction (Weather Underground, 2021). Again an increase (8.1% per 100 hab) was observed in the 2nd lifting when comparing with the corresponding historical period in the rural background station from *Algarve* (*Cerro*, alg_04), possibly for the same reason as previously mentioned (the maritime traffic).

Overall, the restrictions imposed during the several periods seemed to have only a limited positive impact on the concentrations of this pollutant. The monitoring stations evaluated in the *Norte* were essentially influenced by the industrial activity that never closed, and even increased their activity in some cases. In *Algarve* region (alg_04), maritime traffic was also never forbidden.

## 4.1 | Sustainable measures to reduce air pollution

The previous sections evidenced that some of the mobility restrictive measures applied during the COVID-19 pandemic reduced the air pollutants' concentrations registered by most of the monitoring stations of the regions evaluated. Hence, based on those measures, it is possible to propose new policies to improve air quality in Portugal.

The main restrictions imposed by the national government that caused a general reduction of the air pollution were: mandatory/civic duty of staying at home (curfew), exits only allowed for essential needs, establishments closure, mandatory remote work whenever possible, and the prohibition of the circulation between councils during the weekends (measured solely applied in the 2nd lockdown). As a result of these measures, a significant positive impact (reducing air pollution) in all areas was obtained, except for the industrial ones, since industrial activities always remained open during the different lockdown and lifting periods imposed.

However, it is essential to consider the inherently socioeconomic impact of the restrictions adopted to suggest new mitigation measures. Although all the restrictive measures applied contributed to reducing air pollution, they compromised the economy, which had negative social impacts (e.g., unemployment, poverty, mental illnesses) (Armeanu et al., 2022). Thus, when considering which measures could be implemented to reduce air pollution, it is essential to consider a sustainable equilibrium between the environment, the economy, and human health (physical and mental).

Therefore, results indicated that one long-term measure that could be adopted is remote work whenever possible (or a hybrid work model) since it helps to reduce traffic in urban and suburban sites, and consequently the emissions of air pollutants. Besides, the majority of the Portuguese citizens revealed that they would like to work in an hybrid model, that is, having some flexibility to choose to work on-site or work from a remote location like home (Eurogroup Consulting, 2021). It is expected that this measure would benefit both the environment and human health without causing damages to the economy.

As a short-term measure, to be applied when a high air pollution event is predicted or occurrs, is the prohibition of circulation between municipalities during that phenomenon, that generally happens for a short period of time - 2 to 3 days, 3 to 4 times per year. This would highly contribute to diminish air pollutants' concentrations, namely by reducing emissions from transports (cars, taxis, etc), and given the very short-term of these events it would not represent high damage to the economy enhancing instead an equilibrium between the three main pillars of the sustainability. Other authors have previously suggested the adoption of a temporary lockdown on days of high pollution and/or even on normal days, as a way to reduce air pollution, as it was implemented in early periods (Das et al., 2021; Kumari et al., 2020; Sahoo et al., 2021). Nevertheless, adopting measures similar to those in the 1st lockdown (curfew, exits only allowed for essential needs, closure of establishements, etc) is not sustainable, thus having a strong negative impact on an economic and social level.

Given the results achieved in the present study, the policies developed from the restrictions imposed during COVID-19 pandemic are not expected to have a significant impact in industrial areas. Thus, additional policies based on specific measures to control emissions should be developed to reduce air pollution in industrial sites. Moreover, specific regulations are required to better control the emissions from ships not covered by the current legislation (fishing fleet), namely to control the sulphur content in the fuel used.

These results also allowed to propose specific measures for each region studied. In the case of the *Lisboa e Vale do Tejo* region, the mobility resctritive measures proved to be effective in reducing air pollution, thus evidencing the need of reducing traffic emissions in an area that is reflex of the terciary sector, by favouring soft means of transportation and reinforcing the existing low emission zone. Moreover, the use of public transports should be favoured by giving for example economic incentives to the population (viz., public transports get cheaper in days of high air pollution). As for the *Algarve* which is a predominant touristic region, the reduction of the air pollution was intrinsecly related to the decrease of the touristic activity and to the suspension of flights. Thus, as tourism is essential at regional and national level, the measures to be adopted need to be able to reduce air pollution without affecting the touristic activity. For such, diminishing the number of internal/national flights and encouraging the national citizens to travel by other means of transportation will have much less impact on air quality, compared to an airplane, without compromising the other two pillars of sustainability and without needing much more time to travel in the other modes when compared to the airplane.

Thus, the results achieved allowed rethinking the upcoming future regarding the reduction of air pollution, thus helping recognise the importance of reducing particularly traffic emissions. The post-COVID era represents a great opportunity for the legal entities to rethink the urban transport planning and reinforce the implementation of soft means of transportation, amongst other long-term measures. As an example, Piccoli et al. (2020) proposed a renewal on the urban design, planning and management to shorten the distance of the citizens' commuting, hence allowing the citizens to travel in soft and more sustainable ways, like walking and cycling. Thus, the creation of more bike lanes and bike rentals is suggested. Furthermore, public transport and car-sharing are also encouraged, especially whenever the soft means of transportation are not feasible. Besides, increasing the existing green areas and incorporating more in the urban environment, as well as the creation of Low Emission Zones in more cities of the country, would be an important key strategy to improve/maintain good air quality levels, especially in the urban sites. Another related measure that should be established as soon as possible is the transition from fossil fuels to renewable energies in vehicles, ships and aircrafts engines. These measures will have a positive direct impact on the environment through the abatement of air pollution and on human health and the economy, as citizens could still commute and travel but in more sustainable means. Even though these measures could be adopted regardless the COVID-19 pandemic, their importance and urgency to implement was enhanced with this crisis, that brought a clear vision of the best measures to adopt concerning the 3 sustainability pillars.

## 5 | CONCLUSION

This work evaluated the impact of the restrictions imposed during the COVID-19 pandemic on air quality in Portugal along 2020 and 2021. In general, this study evidenced that air quality improved during the study periods compared to the corresponding historical ones, mostly due to the restrictive measures imposed to citizens' mobility. By reducing citizens' mobility, those measures allowed to reduce the air pollution in all studied areas (urban, suburban and rural), except in the industrial sites.

PM ($PM_{2.5}$ and $PM_{10}$) and $NO_2$ were the pollutants that registered more significant reductions in concentrations when comparing with corresponding historical periods (2015–2019), mainly in the lockdown periods (1st, partial, and 2nd), and especially in the urban (traffic and background) areas. $NO_2$ registered the highest decreases. On the other hand, $O_3$, CO, and $SO_2$ concentrations significantly increased in a higher number of monitoring stations, namely at urban background, urban traffic, and industrial locations, respectively, even though significant decreases were also registered for these pollutants. Overall, the satellite data used in this work allowed to corroborate the results achieved from monitoring and evaluate the real influence of the lockdown/lifting periods on air quality. When comparing the study periods, in general the lockdown periods had more significant reductions (especially in the 1st lockdown), whilst in the lifting periods more reductions were noticed in the 2nd lifting period than in the 1st one for $PM_{10}$, $PM_{2.5}$, $NO_2$, and $O_3$. For CO and $SO_2$, both significant increases and decreases were found in the lifting periods. The percentage of exceedances to the reference limit values (Portuguese legislation and WHO guidelines) reduced overall in the study periods when compared to the historical, even reducing to zero exceedances in many cases, even though the concentrations had increased in some cases.

Although the restrictions imposed during the COVID-19 pandemic carried a strong negative socioeconomic impact, overall they positively impacted the environment by improving air quality. Based on those restrictions, some policies were proposed to help policymakers to improve the air quality in Portugal, taking into account a sustainable equilibrium between human health, the economy, and the environment. On one hand, remote work whenever possible (or a hybrid work model) should be adopted as a long-term measure. On the other hand, similar restrictions to those applied during the 2nd lockdown could be adopted, namely the prohibition of travelling between municipalities, as a short-term measure whenever an extraordinary event of high air pollution is predicted or occurs (typically between 2–3 days, 3–4 times per year). This study also concluded that the restrictions imposed did not reduce air pollution significantly in industrial areas, so other emissions' control policies should be adopted.

The post-COVID era is an opportunity for rethinking the future of mobility, and other emerging policies (besides those proposed) should favour softer and cleaner means of transportation. Future research should focus on developing novel urban planning solutions based on the proposed policies. Quantifying the positive health impacts of the restrictive measures imposed during the COVID-19 pandemic (avoided premature deaths, avoided morbidity and absenteeism) will also help policy-makers in particular, and citizens in general, to better understand the advantages of implementing those policies.

## ACKNOWLEDGMENTS

This work was financially supported by: LA/P/0045/2020 (ALiCE), UIDB/00511/2020 and UIDP/00511/2020 (LEPABE) funded by national funds through FCT/MCTES (PIDDAC). The authors are grateful to the Comissões de Coordenação de Desenvolvimento Regional (CCDR) from the Norte, Lisboa e Vale do Tejo, and Algarve regions for sharing the air pollutants' data from 2020/2021.

## ORCID

*Sofia I. V. Sousa* https://orcid.org/0000-0002-4139-673X

## REFERENCES

AccuWeather (2021). Lisboa. Retrieved from https://www.accuweather.com/pt/pt/lisbon/274087/may-weather/274087?year=2020.

APA; Agência Portuguesa do Ambiente (2020). Previsão de transporte de partículas naturais com origem em regiões áridas. Retrieved from https://qualar.apambiente.pt/node/eventos_naturais.

APA; Agência Portuguesa do Ambiente (2021). Previsão de transporte de partículas naturais com origem em regiões áridas. Retrieved from https://qualar.apambiente.pt/node/eventos_naturais.

Armeanu, D. S., Gherghina, S. C., Andrei, J. V., & Joldes, C. C. (2022). Modeling the impact of the COVID-19 outbreak on environment, health sector and energy market. *Sustainable Development*, *30*, 1387–1416. https://doi.org/10.1002/sd.2299

Bai, Y., Zhou, Y., Alatalo, J. M., & Hughes, A. C. (2020). Changes in air quality during the first-level response to the COVID-19 pandemic in Shanghai Municipality, China. *Sustainability (Switzerland)*, *12*(21), 1–12. https://doi.org/10.3390/su12218887

Barua, S., & Nath, S. D. (2021). The impact of COVID-19 on air pollution: Evidence from global data. *Journal of Cleaner Production*, *298*, 126755. https://doi.org/10.1016/j.jclepro.2021.126755

Carslaw, D. C., & Ropkins, K. (2012). Openair - an r package for air quality data analysis. *Environmental Modelling and Software*, *27–28*, 52–61. https://doi.org/10.1016/j.envsoft.2011.09.008

CCDR Algarve; Comissão de Coordenação e Desenvolvimento Regional do Algarve (2015). Qualidade do Ar na Região do Algarve - Relatório 2° Trimestre de 2015. Retrieved from https://www.ccdr-alg.pt/site/sites/ccdr-alg.pt/files/Ambiente/Qualidade-Ar/relqar-2t-2015.pdf.

CCDR LVT; Comissão de Coordenação e Desenvolvimento Regional de Lisboa e Vale do Tejo (2017). Avaliação da Qualidade do Ar na RLVT. Retrieved from http://www.ccdr-lvt.pt/pt/avaliacao-da-qualidade-do-ar-na-rlvt/8085.htm.

CCDR Norte; Comissão de Coordenação e Desenvolvimento Regional do Norte (2014). Relatório de Análise Estatística dos Dados de Qualidade do Ar, da Região Norte, em 2013. Retrieved from.

Celik, E. A.-O., & Gul, M. (2021). How Covid-19 pandemic and partial lockdown decisions affect air quality of a city? The case of Istanbul, Turkey. (1573–2975 (Electronic)).

Cucinotta, D., & Vanelli, M. (2020). WHO declares COVID-19 a pandemic. *Acta Bio-medica: Atenei Parmensis*, *91*(1), 157–160. https://doi.org/10.23750/abm.v91i1.9397

Dangelico, R. M., Schiaroli, V., & Fraccascia, L. (2022). Is Covid-19 changing sustainable consumer behavior? A survey of Italian consumers. *Sustainable Development*. https://doi.org/10.1002/sd.2322

Das, M., Das, A., Sarkar, R., Saha, S., & Mandal, A. (2021). Examining the impact of lockdown (due to COVID-19) on ambient aerosols (PM2.5): A study on Indo-Gangetic Plain (IGP) Cities, India. *Stochastic Environmental Research and Risk Assessment*, *35*(6), 1301–1317. https://doi.org/10.1007/s00477-020-01905-x

DGEG; Direção Geral de Energia e Geologia (2020). Estimativas rápidas de consumo energético. Retrieved from https://www.dgeg.gov.pt/media/ydvmzr0y/dgeg-aer-2020-04.pdf.

Donzelli, G., Cioni, L., Cancellieri, M., Llopis-morales A., & Morales-suárez-varela, M. (2021). Relations between Air Quality and Covid-19 Lockdown Measures in Valencia, Spain. *International Journal of Environmental Research and Public Health*, *18*(5), 2296. https://doi.org/10.3390/ijerph18052296.

ESS; European Statistical System (2021). 2011 Census Hub. Retrieved from https://ec.europa.eu/CensusHub2/query.do?step=selectHyperCube&qhc=false.

Eurogroup Consulting (2021). 77% dos portugueses revela que a sua empresa foi capaz de responder ao desafio de teletrabalho. Retrieved from https://www.eurogroupconsulting.pt/index.php/2021/01/04/77-dos-portugueses-revela-empresa-capaz-responder-ao-desafio-teletrabalho/.

Filonchyk, M., Hurynovich, V., & Yan, H. (2021). Impact of Covid-19 lockdown on air quality in the Poland, Eastern Europe. *Environmental Research*, *198*, 110454. https://doi.org/10.1016/j.envres.2020.110454

Fong, L. S., Salvo, A., & Taylor, D. (2020). Evidence of the environmental Kuznets curve for atmospheric pollutant emissions in Southeast Asia and implications for sustainable development: A spatial econometric approach. *Sustainable Development*, *28*(5), 1441–1456. https://doi.org/10.1002/sd.2097

GALP. (2021). Cogeração. Retrieved from https://www.galp.com/corp/pt/sobre-nos/o-que-fazemos/midstream/cogeracao.

Gama, C., Relvas, H., Lopes, M., & Monteiro, A. (2021). The impact of COVID-19 on air quality levels in Portugal: A way to assess traffic contribution. *Environmental Research*, *193*, 110515. https://doi.org/10.1016/j.envres.2020.110515

Gao, C., Li, S., Liu, M., Zhang, F., Achal, V., Tu, Y., Zhang, S., & Cai, C. (2021). Impact of the COVID-19 pandemic on air pollution in Chinese megacities from the perspective of traffic volume and meteorological factors. *Science of the Total Environment*, *773*, 145545. https://doi.org/10.1016/j.scitotenv.2021.145545

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27.

IPMA; Instituto Português do Mar e da Atmosfera (2020a). Abril 2020 Portugal Continental. Retrieved from https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20200507/oCTuTXeIUTsZKCvKOJOP/cli_20200401_20200430_pcl_mm_co_pt.pdf.

IPMA; Instituto Português do Mar e da Atmosfera (2020b). Dezembro 2020 Portugal Continental. Retrieved from https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20210111/UwuDMONSgntiZjWYKOcP/cli_20201201_20201231_pcl_mm_co_pt.pdf.

IPMA; Instituto Português do Mar e da Atmosfera (2020c). Novembro 2020 Portugal Continental. Retrieved from https://www.ipma.pt/

resources.www/docs/im.publicacoes/edicoes.online/20201207/DsfTVWwbcqCqLwluIAAv/cli_20201101_20201130_pcl_mm_co_pt.pdf.

IPMA; Instituto Português do Mar e da Atmosfera (2020d). Resumo climatológico Março 2020. Retrieved from https://www.ipma.pt/pt/media/noticias/documentos/2020/resumo_clima_mar2020.pdf.

IPMA; Instituto Português do Mar e da Atmosfera (2021a). Boletim Climático Portugal Continental Abril 2021. Retrieved from https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20210507/URlRamBfRUsvkSWMGywb/cli_20210401_20210430_pcl_mm_co_pt.pdf.

IPMA; Instituto Português do Mar e da Atmosfera (2021b). Boletim Climático Portugal Continental Março 2021. Retrieved from https://www.ipma.pt/resources.www/docs/im.publicacoes/edicoes.online/20210409/rnppiqrUQoYFEKmGCyBZ/cli_20210301_20210331_pcl_mm_co_pt.pdf.

Kumari, P., & Toshniwal, D. (2020). Impact of lockdown on air quality over major cities across the globe during COVID-19 pandemic. *Urban Climate*, *34*, 100719. https://doi.org/10.1016/j.uclim.2020.100719

Kumari, S., Lakhani, A., & Kumari, K. M. (2020). Covid-19 and air pollution in indian cities: World's most polluted cities. *Aerosol and Air Quality Research*, *20*(12), 2592–2603. https://doi.org/10.4209/aaqr.2020.05.0262

Kutralam-Muniasamy, G., Pérez-Guevara, F., Roy, P. D., Elizalde-Martínez, I., & Shruti, V. C. (2021). Impacts of the COVID-19 lockdown on air quality and its association with human mortality trends in megapolis Mexico City. *Air Quality, Atmosphere and Health*, *14*(4), 553–562. https://doi.org/10.1007/s11869-020-00960-1

Liu, F., Wang, M., & Zheng, M. (2021). Effects of COVID-19 lockdown on global air quality and health. *Science of the Total Environment*, *755*(Pt 1), 142533. https://doi.org/10.1016/j.scitotenv.2020.142533

Macedo, C. (2020, March 19). APA alerta para ocorrência de fraca qualidade até esta sexta-feira. *Ambiente Magazine*. Retrieved from https://www.ambientemagazine.com/apa-alerta-para-ocorrencia-de-fraca-qualidade-ate-a-esta-sexta-feira/.

Mesquita, S (2013). Reavaliação da Delimitação das Zonas para Avaliação e Gestão da Qualidade do Ar na Região de Lisboa e Vale do Tejo. Retrieved from http://www.ccdr-lvt.pt/pt/avaliacao-da-qualidade-do-ar-na-rlvt/8085.htm.

Neves, A., Sorte, S., Russo, M., Monteiro, A., Lopes, M., & Borrego, C. (2019). Mitigação de emissões marítimas e portuárias: Linhas orientadoras. (U. E.-U. d. Aveiro Ed.).

Ordóñez, C., Garrido-Perez, J. M., & García-Herrera, R. (2020). Early spring near-surface ozone in Europe during the COVID-19 shutdown: Meteorological effects outweigh emission changes. *Science of the Total Environment*, *747*, 141322. https://doi.org/10.1016/j.scitotenv.2020.141322

Piccoli, A., Agresti, V., Balzarini, A., Bedogni, M., Bonanno, R., Collino, E., Colzi, F., Lacavalla, M., Lanzani, G., Pirovano, G., Riva, F., Riva, G. M., & Toppetti, A. M. (2020). Modeling the effect of COVID-19 lockdown on mobility and $NO_2$ concentration in the lombardy region. *Atmosphere*, *11*(12), 1–18. https://doi.org/10.3390/atmos11121319

Porto Business School (2020). O impacto da COVID-19 no setor do turismo. Retrieved from https://www.pbs.up.pt/pt/artigos-e-eventos/artigos/o-impacto-da-covid-19-no-setor-do-turismo/.

QGIS (2021). QGIS Geographic Information System (2021). Retrieved from http://www.qgis.org.

QualAr (2019). Estações. Retrieved from https://qualar.apambiente.pt/qualar/estacoes.

República Portuguesa (2020a). Comunicado do Conselho de Ministros de 9 de junho de 2020. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=351.

República Portuguesa (2020b). Comunicado do Conselho de Ministros de 19 de março de 2020. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=334.

República Portuguesa (2020c). Comunicado do Conselho de Ministros de 30 de abril de 2020. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=344.

República Portuguesa (2020d). Comunicado do Conselho de Ministros eletrónico de 16 de março de 2020. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=332.

República Portuguesa (2020e). Comunicado do Conselho de Ministros extraordinário de 7 de novembro de 2020. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=380.

República Portuguesa (2021a). Comunicado do Conselho de Ministros de 1 de abril de 2021. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=412.

República Portuguesa (2021b). Comunicado do Conselho de Ministros de 11 de março de 2021. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=407.

República Portuguesa (2021c). Comunicado do Conselho de Ministros de 13 de janeiro de 2021. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=394.

República Portuguesa (2021d). Comunicado do Conselho de Ministros de 21 de janeiro de 2021. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicado-de-conselho-de-ministros?i=397.

República Portuguesa (2021e). Comunicados de Conselho de Ministros. Retrieved from https://www.portugal.gov.pt/pt/gc22/governo/comunicados-do-conselho-de-ministros.

República, P. d (2020). Decreto do Presidente da República n.° 14-A/2020. Diário da República 1.ª série, 55 (março), 13-(12) a 13-(14). Retrieved from https://dre.pt/home/-/dre/130399862/details/maximized.

Sahoo, P. K., Chauhan, A. K., Mangla, S., Pathak, A. K., & Garg, V. K. (2021). COVID-19 pandemic: An outlook on its impact on air quality and its association with environmental variables in major cities of Punjab and Chandigarh, India. *Environmental Forensics*, *22*(1–2), 143–154. https://doi.org/10.1080/15275922.2020.1836082

Sahraei, M. A., Kuşkapan, E., & Çodur, M. Y. (2021). Public transit usage and air quality index during the COVID-19 lockdown. *Journal of Environmental Management*, *286*, 112166. https://doi.org/10.1016/j.jenvman.2021.112166

Sannino, A., D'emilio, M., Castellano, P., Amoruso, S., & Boselli, A. (2021). Analysis of air quality during the covid-19 pandemic lockdown in Naples (Italy). *Aerosol and Air Quality Research*, *21*(1), 1–15. https://doi.org/10.4209/aaqr.2020.07.0381

Silva, A. C. T., Branco, P. T. B. S., & Sousa, S. I. V. (2022). Impact of COVID-19 pandemic on air quality: A systematic review. *International Journal of Environmental Research and Public Health*, *19*(4), 1950. https://doi.org/10.3390/ijerph19041950

Slezakova, K., & Pereira, M. C. (2021). 2020 COVID-19 lockdown and the impacts on air quality with emphasis on urban, suburban and rural zones. *Scientific Reports*, *11*(1), 21336. https://doi.org/10.1038/s41598-021-99491-7

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., & Ngan, F. (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system. *Bulletin of the American Meteorological Society*, *96*, 2059–2077.

Tsai, K. (2021, March 19). Boat sales took off during the pandemic and now dealer can't keep up with demand. *CNCB*. Retrieved from https://www.cnbc.com/2021/03/19/boat-sales-took-off-during-pandemic-dealers-cant-keep-up-with-demand.html.

UA; Universidade de Aveiro (2019, October 17). Poluição do tráfego marítimo é preocupante e pode vir a aumentar. Retrieved from https://www.ua.pt/pt/noticias/0/61265.

Vultaggio, M., Varrica, D., & Alaimo, M. G. (2020). Impact on air quality of the covid-19 lockdown in the urban area of Palermo (Italy). *International Journal of Environmental Research and Public Health*, *17*(20), 1–12. https://doi.org/10.3390/ijerph17207375

Weather Underground (2021). Vila Nova da Telha, Porto, Portugal Weather History. Retrieved from https://www.wunderground.com/history/daily/pt/vila-nova-da-telha/LPPR/date/2020-5-2.

WHO; World Health Organization (2018). Ambient (outdoor) air pollution. Retrieved from https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

Wong, D. W., Yuan, L., & Perlin, S. A. (2004). Comparison of spatial interpolation methods for the estimation of air quality data. *Journal of Exposure Science & Environmental Epidemiology*, *14*(5), 404–415. https://doi.org/10.1038/sj.jea.7500338

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Silva, A. C. T., Branco, P. T. B. S., Ferrini Rodrigues, P., & Sousa, S. I. V. (2022). Sustainable policies for air pollution reduction after COVID-19 pandemic: Lessons learnt from the impact of the different lockdown periods on air quality. *Sustainable Development*, 1–17. https://doi.org/10.1002/sd.2432