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## LETTER

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Assessment of an air quality surveillance network through passive  
pollution measurement with mobile sensorsEdgar Lorenzo-Sáez<sup>1</sup> , Jose-Vicente Oliver-Villanueva<sup>1</sup> , Lenin-Guillermo Lemus-Zúñiga<sup>1</sup> ,  
Eloina Coll-Aliaga<sup>1</sup> , Carolina Perpiñá Castillo<sup>2</sup> and Carlo Lavalle<sup>2</sup> <sup>1</sup> Universitat Politècnica de València, Information and Telecommunication Research Institute—ITACA, Camino de Vera s/n, 46022 Valencia, Spain<sup>2</sup> European Commission, Joint Research Centre (JRC), Ispra, ItalyE-mail: [edlosae@upv.es](mailto:edlosae@upv.es)**Keywords:** air quality, air pollution, passive dosimetry, mobile sensors, NO<sub>2</sub>Supplementary material for this article is available [online](#)**Abstract**

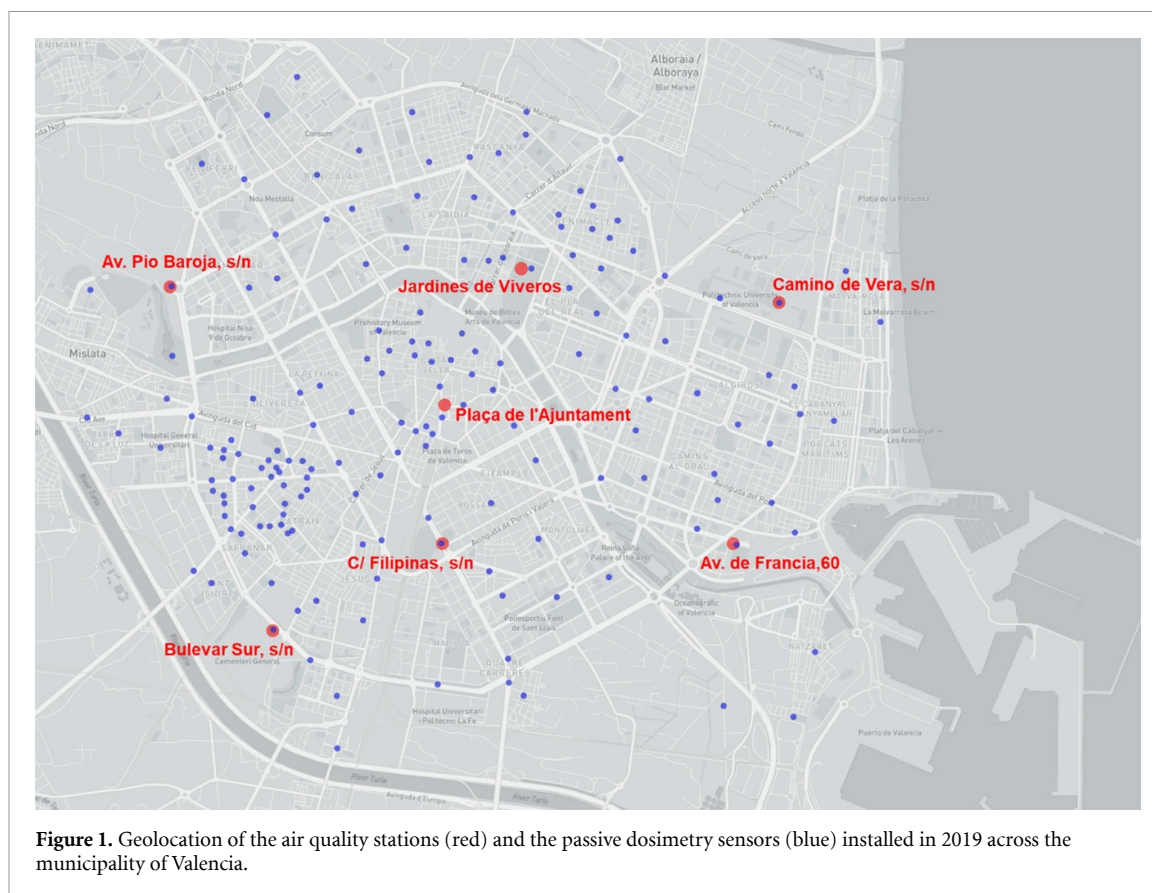
Today, about 55% of the world population lives in cities and this is foreseen to increase to 68% by 2050. The urban activities of such a large number of people in relatively small spaces can make the air quality levels in cities harmful to human health. For this reason, the European Union (EU) has established a regulatory framework to control and improve air quality levels in cities (Directive 2008/50/EC) by defining a number of fixed stations and other requirements. The aim of this work is to evaluate the air quality reported by the official fixed stations via the installation of a complementary mobile network of air quality based on passive dosimetry of NO<sub>2</sub> measurement during the period 2017–2019. In this study, Valencia (Spain) is selected as a representative European city with seven fixed stations and a network of 424 passive dosimetry sensors distributed throughout the city. In addition, an index of impact of pollutant on population is developed to optimize the locations of air quality stations among neighbourhoods across the city based on the levels of pollution measured by mobile sensors and the population directly affected. The results obtained show that 43.7% of mobile sensors in Valencia exceeded the limit value established by the EU Directive as well as by the World Health Organization during the assessment period. This indicates that the air quality levels offered by the fixed stations are neither representative nor reliable for the air quality monitoring of the city. Thus, the fixed stations currently operating do not provide reliable information on the areas of the city where the majority of the population breathes air with the highest level of pollution. Specifically, the results show that 34.6% of citizens live in areas with an average annual value above the limit recommended for the protection of human health.

**1. Introduction**

Every year, more than 400 000 people in the European Union (EU) prematurely die due to the negative consequences of air pollution (European Court of Auditors 2018). About 6.5 million people fall sick due to air pollution that causes different types of diseases (EEA 2017). Currently, several studies are demonstrating the significant influence of air pollution on the severity of pneumonia derived from the COVID-19 pandemic (Conticini *et al* 2020, Fattorini and Regoli 2020, Frontera *et al* 2020, Wu *et al* 2020). These facts and evidence have made it necessary to consider

common official guidelines and standards to ensure effective protection against harmful effects on human health and the environment by measuring, monitoring and assessing the compliance with air quality limit values.

Air quality is measured by the concentrations of primary and secondary pollutants in the air (Reich *et al* 2006). Primary pollutants are emitted by emission sources directly into the atmosphere. The most prominent are nitrogen oxide and nitrogen dioxide (NO<sub>x</sub>), particulate matter in suspension (PM<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>) and volatile organic compounds. Secondary pollutants are formed in the



**Figure 1.** Geolocation of the air quality stations (red) and the passive dosimetry sensors (blue) installed in 2019 across the municipality of Valencia.

**Table 1.** Description of air quality stations and pollutant measurements. Source: Ministry of Agriculture, Rural Development, Climate Emergency and Ecological Transition, Generalitat Valenciana (2020a).

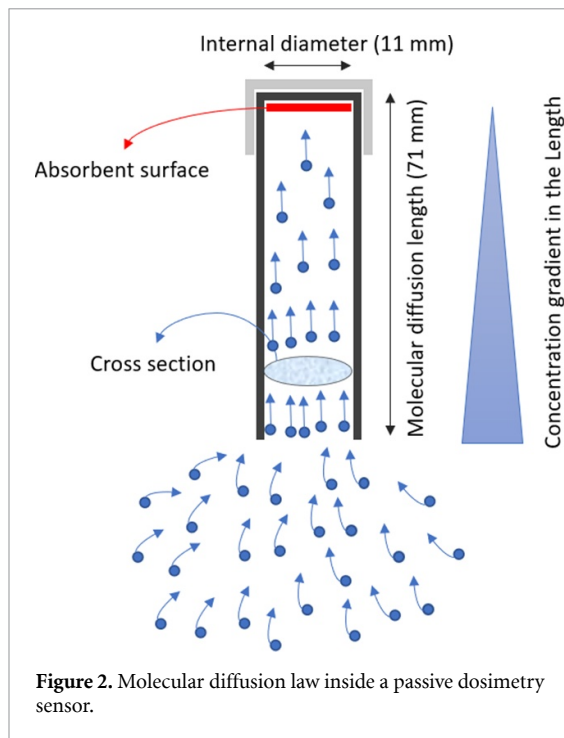
Air quality station description	Pollutants measured	Description of the surroundings
ID 46250048 (Molí del Sol) Municipality Valencia Address Av. Pio Baroja, s/n Code 46250048 Longitude 0° 24' 30" W Latitude 39° 28' 52" N Altitude 15 m Classification: street	Nitrogen dioxide Carbon monoxide Nitrogen monoxide Total nitrogen oxides Ozone Particulate matter (<1 $\mu\text{m}$ ) Particulate matter (<10 $\mu\text{m}$ ) Particulate matter (<2.5 $\mu\text{m}$ )	Located in a parking adjacent to cropland and other green areas and close to a low-traffic road.

atmosphere through oxidation and reaction between primary pollutants (Kibble and Harrison 2005). The most prominent are carbon dioxide ( $\text{CO}_2$ ), carbon monoxide (CO), ozone ( $\text{O}_3$ ), benzene[a]pyrene and benzene, polycyclic aromatic hydrocarbons, and methane ( $\text{CH}_4$ ) (EU Directive 2008/50/EC). Among all these pollutants, the two major outdoor air pollutants in European cities are  $\text{NO}_2$  and  $\text{PM}_{2.5}$  (Costa *et al* 2014) and their exceedances of current air quality limits of World Health Organization (WHO) guidelines and EU Directive values remain major policy challenges (Carnell *et al* 2019).

Exposure to elevated concentrations of  $\text{NO}_2$  in the air is linked to a range of respiratory diseases such as bronchoconstriction, increased bronchial reactivity, airway inflammation and decreases in immune defence leading to increased susceptibility to respiratory infection (COMEAP 2011), and others that

overlap with the impacts from  $\text{PM}_x$  (Jonson *et al* 2017). In recent studies, adverse health effects were identified when the annual average  $\text{NO}_2$  concentration complied with the established limits by the EU Directive 2008/50/EC (European Commission 2008, COMEAP 2011). This directive on ambient air quality and cleaner air for Europe defines the regulations for air quality assessment, establishes the criteria for the surveillance network according to the affected population, and defines the limit values and thresholds for pollutants.

The management of air pollution in cities is particularly challenging, as policy decisions must be based on reliable measurements to change culturally and locally established citizen patterns and mobility needs (Anagnostopoulou *et al* 2018). To guarantee the wellbeing of citizens by ensuring air quality, it is necessary to evaluate and control air pollution with



rigorous and reliable air quantification systems (EU Directive 2008/50/EC). Air quality surveillance networks are an essential tool to provide a diagnostic in urban settings and, at the same time, give information about contamination problems in an area, allowing decision making or corrective measures to be taken to improve air quality. Following EU Directive 2008/50/EC, the objective of a surveillance network is to avoid, prevent and reduce the harmful effects of pollutants on human health and the environment. In particular, the EU Directive officially defines a minimum number of fixed stations according to population thresholds and implantation requirements. The EU Directive also offers the possibility to complement the network of official stations with other methods in order to provide more precise information on air quality measurements and an optimal geographical location.

Currently, it is being used a type of mobile sensor (understanding mobile sensors as part of a temporary sensor network) that can be distributed throughout a city to complement measurements from the official stations (Chang *et al* 2008, Mead *et al* 2013). An example of this complementary technology is the passive dosimetry sensors for  $\text{NO}_2$  measurement, called Palmes tubes, that were introduced for occupational exposure monitoring by Palmes *et al* (1976). Passive samplers are based on the diffusion principle described in Fick's law (Krupa and Legge 2000) and they provide cost-effective spatial distribution information on pollutant concentrations (Chang *et al* 2008). The passive sensor approach has been widely used and validated for the evaluation of atmospheric  $\text{NO}_2$  pollution (Smith *et al* 1997, Chang *et al* 2008, Hagenbjörk-Gustafsson *et al* 2010, Khuriganova *et al*

2019, CEAM 2019a) with correlations of 0.97–0.99 and 0.95, respectively, of measurements of  $\text{NO}_x$  by passive sensors with respect to measurements by the chemiluminescence method, which is the reference method of the official air quality stations.

The main objective of this work is to compare and assess the adequacy and representativeness of the established air quality network based on fixed stations with a newly designed and complementary network using  $\text{NO}_2$  mobile sensors during the period between 2017 and 2019. This will allow analysis of whether the current locations of the fixed air quality stations (FAQS) offer measurements that represent the quality of the air that the citizens breathe. Then, a redesigned network with strategic locations of the air quality stations is proposed based on the development and application of an index that reflects the impact of pollutants on population-dense areas. In this study, Valencia (Spain) is selected as a mid-sized representative European city for validating the accuracy of the surveillance network, following the specifications of the EU Directive 2008/50/EC.

## 2. Materials and methods

### 2.1. Selection and description of a pilot city for air quality assessment

The city of Valencia is located in the Valencian Community in the eastern part of Spain. Currently, Valencia has 787 266 inhabitants and is the centre of a large metropolitan area with more than 1.5 million people. The city of Valencia represents 16% of the total population of the Valencian Community and is the third most important city in Spain. It is part of the Valencian Network for Monitoring and Control of Air Pollution (RVVCCA)<sup>3</sup>. Figure 1 shows the locations of the seven FAQS (fixed network)<sup>4</sup> and the 424 passive dosimetry sensors (mobile network) within the municipality for the measurement of the air pollutant concentrations considered in the analysis.

### 2.2. Main criteria for the locations of fixed air quality stations and mobile sensors according to the Directive 2008/50/EC on ambient air quality and cleaner air for Europe

#### 2.2.1. Main characteristics and measurements from air quality stations

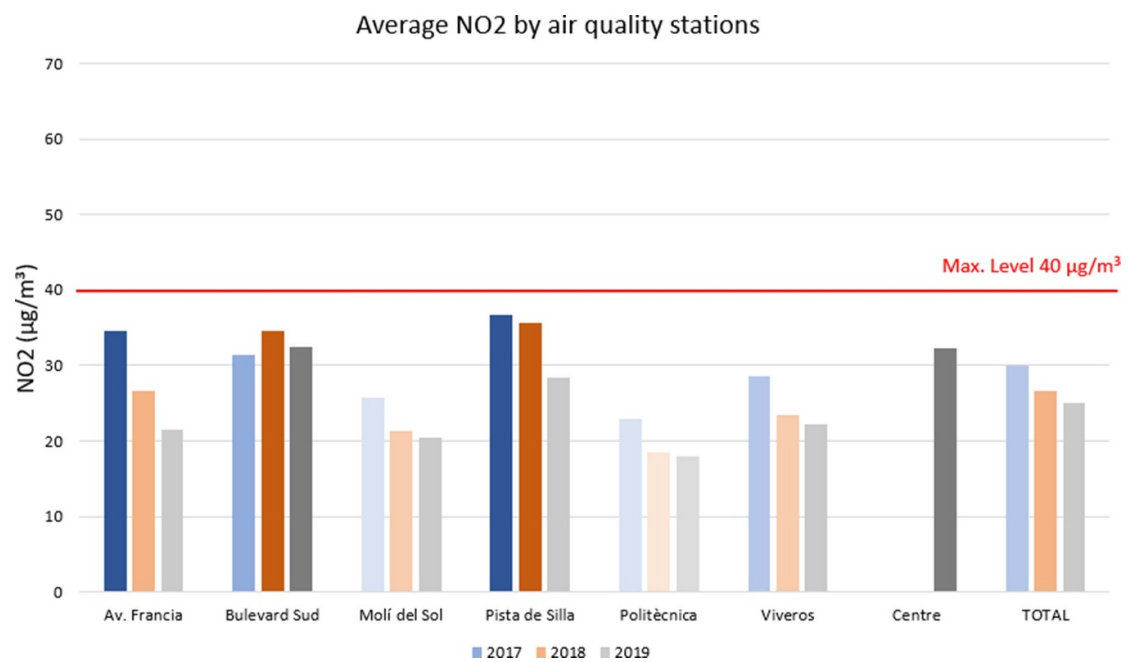
Each air quality station is equipped with automatic continuous measurement monitors as established in the EU Directive 2008/50/EC. In particular, the

<sup>3</sup> [www.agroambient.gva.es/es/web/calidad-ambiental/datos-online](http://www.agroambient.gva.es/es/web/calidad-ambiental/datos-online)

<sup>4</sup> The information on the seven FAQS is provided by the Ministry of Agriculture, Rural Development, Climate Emergency and Ecological Transition (Generalitat Valenciana 2020b). Descriptions of every air quality station in Valencia and the EU limit values of the pollutants measured are shown in the annex of the supplementary material.



**Figure 3.** Left: Palmes tube to passive measurement of  $\text{NO}_2$ ; right: north entrance and exit of the city. Photographs by José Manuel Felisi Herrero. Reproduced with permission.

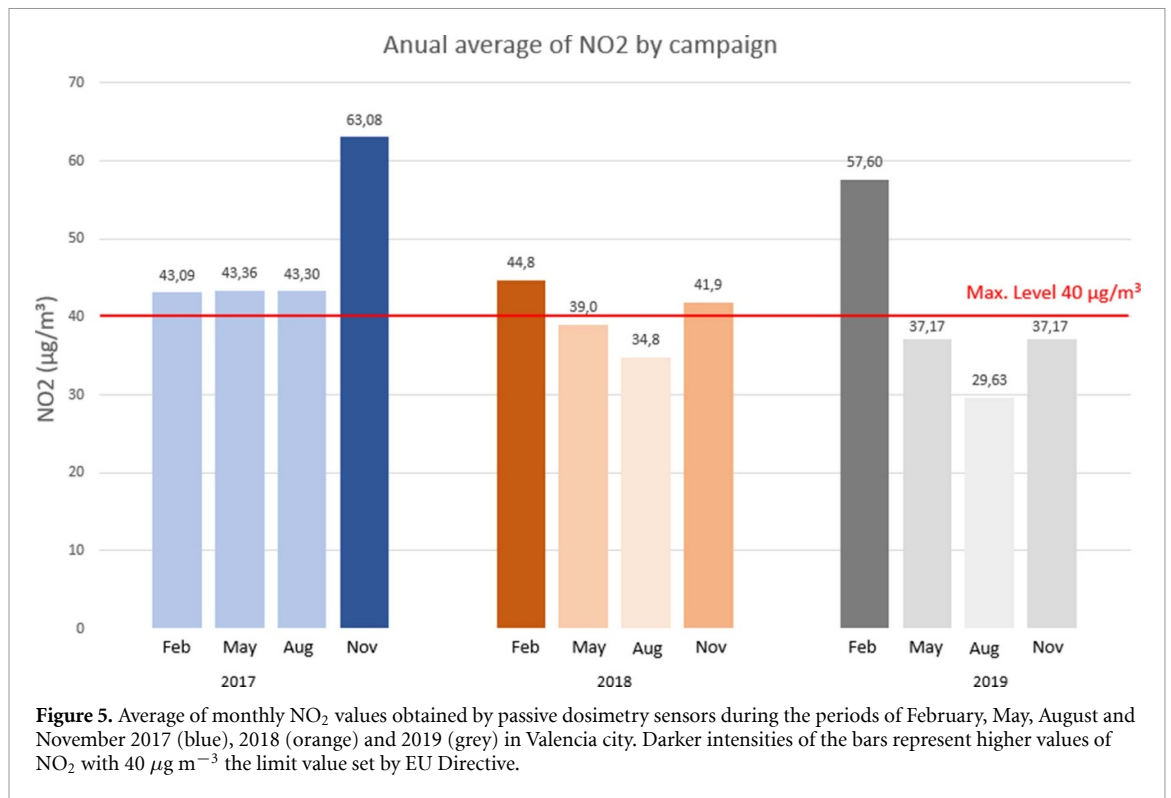


**Figure 4.** Average of daily  $\text{NO}_2$  values recorded in the seven air quality stations of the city of Valencia and the average of all, in 2017 (blue), 2018 (orange) and 2019 (grey). Darker intensities of the bars represent higher values of  $\text{NO}_2$  with  $40 \mu\text{g m}^{-3}$  the limit value set by the EU Directive.

method of measurement of  $\text{NO}_2$  is chemiluminescence, based on the reaction with  $\text{O}_3$  in the gas phase. The rapid gas phase reaction between  $\text{NO}$  and  $\text{O}_3$  produces excited  $\text{NO}_2$  molecules, which can be de-excited by light emission (chemiluminescence) to obtain the  $\text{NO}_2$  concentration (EN 14 211:2012). In table 1 the main characteristics of an individual air quality station, as well as the different measured pollutants, are shown. According to annexes III and V of the Directive, the implementation of the FAQS must follow certain criteria concerning macroimplantation, microimplantation and minimum number of FAQS necessary for the protection of human

health. In terms of macroimplantation, the locations of the sampling points (stations) are determined by the highest pollutant concentrations and the exposed population in a representative agglomeration area in a specific period of time.

Similarly, FAQS must follow the requirements for microimplantation described in the EU Directive, including technical aspects such as the height of the sampling, minimum distances to obstacles, distances to the road and major junctions, etc, ensuring no obstructions affect airflow at the sampling points. Finally, according to annex V of the same Directive, the minimum number of FAQS is set by



**Table 2.** Comparison of annual mean and sampled months mean (February, May, August and November) of official air quality stations (units: µg NO<sub>2</sub> m<sup>-3</sup>).

	2017	2018	2019
Mean of sampled months (Feb, May, August, and November)	30.42	27.82	24.54
Annual mean	29.97	27.34	25.04

the criterion of population (thousands) for the protection of human health and alert thresholds.

The FAQS are: (a) Vivers (location: Jardines de Viveros); (b) Politécnico (location: Camino de Vera, s/n); (c) Molí del Sol (location: Av. Pio Baroja, s/n); (d) Bulevard Sud (location: Bulevar Sur, s/n); (e) Pista de Silla (location: C/Filipinas, s/n); (f) Av. Francia (location: Av. de Francia, 60); and (g) Centre (location: Plaça de l'Ajuntament).

### 2.2.2. Main characteristics and measurements from mobile sensors

The mobile sensor network is implemented by the installation of passive dosimetry sensors across the studied area. These sensors consist of a Palmes tube<sup>5</sup> with an open downside allowing ambient air to enter towards the topside. The pollutant gas is transported to the upper part through the tube by molecular diffusion and it is absorbed by a surface placed on the top

<sup>5</sup> The dimensions of the Palmes tube used in the analysis (TDS 1 / DIF 100 RTU—NO<sub>2</sub>) are 71.0 mm (length) by 11.0 mm (internal diameter), following the EN 13528-1 (2002), EN 13528-2 (2002) and EN 13528-3 (2003) standards.

part. This effect causes a linear concentration gradient from the air value to the absorbent surface (figure 2).

This physical relationship between the amount of pollutant mass in the absorbent and the air concentration produced during a sampling period can be expressed, in quantitative terms, by Fick's second law. This law describes the flow of the pollutant gas through another gas (air) due to the concentration gradient as shown by equation (1):

$$F = -D \frac{\partial C}{\partial L} \quad (1)$$

where  $F$  is the flow of the pollutant gas through the tube section,  $D$  is the coefficient of molecular diffusion of the pollutant gas in the air and  $\partial C / \partial L$  is the concentration gradient ( $C$ ) along the diffusion length ( $L$ ).

A total of 424 measurements of pollutant concentrations were taken in three consecutive annual sampling series using passive dosimetry sensors during the years 2017 (39 measurements), 2018 (208 measurements) and 2019 (177 measurements). These measurements were recorded considering the seasonality, in particular during the months of February, May, August and November for a sampling time of 2–3 weeks each month. The rationale behind this was to minimise biases due to atmospheric factors. The locations of passive sensors were maintained in the four sampling periods of the same year to obtain the annual averages for each location, but they were located in different locations between years.

The passive sensor network was set up following the EU Directive criteria. Firstly, the locations of

**Table 3.** Average NO<sub>2</sub> pollutant level measured in each Valencia neighbourhood for the year 2019. More details are in table 3 of the supplementary material (available online at [stacks.iop.org/ERL/16/054072/mmedia](https://stacks.iop.org/ERL/16/054072/mmedia)).

Neighbourhood name	NO <sub>2</sub> ( $\mu\text{g m}^{-3}$ )	Neighbourhood name	NO <sub>2</sub> ( $\mu\text{g m}^{-3}$ )	Neighbourhood name	NO <sub>2</sub> ( $\mu\text{g m}^{-3}$ )
La Seu	27.3	Jaume Roig	33.1	El Cabanyal	24.8
La Xerea	41.8	Ciutat Universi	45.6	La Malvarosa	25.2
El Carme	23.1	Nou Moles	43.8	Beteró	34.6
El Pilar	33.2	Soternes	34.9	Natzaret	35.3
El Mercat	34.0	Tres Forques	33.1	Aiora	30.8
Sant Francesc	38.9	La Fontsa	44.2	Albors	30.3
Russafa	53.2	La Llum	33.8	Creu del Grau	33.1
El Pla del Remei	37.7	Patraix	38.8	Camí Fondo	34.0
El Botànic	39.0	Sant Isidre	18.2	Penya-roja	40.4
La Roqueta	59.1	Vara de Quart	44.2	L'illa Perduda	31.9
La Petxina	42.8	Safranar	32.7	Ciutat Jardí	27.2
Arrancapins	60.0	Favara	31.3	L'Amistat	42.1
Campanar	42.5	La Raiosa	48.8	La Vega Baixa	29.0
Les Tendetes	27.3	L'Hort de Sena	26.8	La Carrasca	25.3
El Calvari	47.5	La Creu Coberta	32.1	Benimaclet	34.7
Sant Pau	30.3	Sant Marcel·lí	43.5	Camí de Vera	38.2
Marxalenes	28.8	Camí Real	38.3	Orriols	40.7
Morvedre	25.6	En Corts	29.5	Torreñiel	34.3
Trinitat	32.7	Malilla	53.0	Sant Llorenç	36.7
Tormos	30.9	Fonteta Sant Llu	46.5	Benicalap	42.0
Sant Antoni	32.7	Na Rovella	46.1	Ciutat Fallera	26.1
Exposició	31.4	La Punta	32.4	Pinedo	41.7
Mestalla	37.4	El Grau	49.2		

the passive sensors were selected under the macroimplantation criteria in strategic points across the city (figure 1), in particular covering green areas and higher/lower-traffic-density areas, road intersections, high-vulnerability areas (schools and hospitals) and other urban areas (parks, squares, etc). Secondly, the implantation was done following annex III of the Directive. Thus, the Palmes tubes were located at a height between 2.90 and 3.10 m from the ground and at least 5 cm from the adjacent surfaces, avoiding corners (figure 3)<sup>6</sup>. Furthermore, a Palmes tube sensor was placed in each official air quality station to directly compare the measurements of both systems at the same place and time. After collecting the tubes, nitrite ion concentrations and consequently the chemically absorbed NO<sub>2</sub> were quantitatively determined in the laboratory by UV/visible spectrophotometry visible with reference to the calibration curve of the analyses of standard nitrite solutions.

### 2.3. Method for the comparison of NO<sub>2</sub> concentrations

After the analysis of the measurements of NO<sub>2</sub> concentrations from the two systems—air quality stations and passive dosimetry sensors—a comparison of the results is possible only with the recorded values from the seven points where both systems are geolocated in the same position and time. The values obtained by both methods are compared with a Welch

test (t-test) and the number of mobile measurement points that record values above the values of air quality stations is calculated. This gives the number of times that the upper limit values of the Directive have been exceeded in the air quality stations compared with the mobile sensors installed during 2017, 2018 and 2019.

### 2.4. Development of an optimal network design for the locations of air quality stations

The main purpose of the EU Directive is to protect human health in urban settings from air pollutants (EU Directive 2008/50/EC). To measure air pollutants, the Directive established guidance to set sample points in the most effective locations, ensuring the macro- and microimplantation criteria, as well as the minimum possible number of installed air quality stations, are satisfied. To achieve this requirement of effective sample point setting, it is important to identify those neighbourhoods with the highest NO<sub>2</sub> pollution and higher population densities that will show the most populated and polluted locations in the city. For this purpose, an index of the impact of pollutant on population (IIPP) based on the combination of NO<sub>2</sub> pollution concentration and population density by neighbourhood was developed. Integrating the population data provided by the official census (Statistical Office of Valencia 2020), the IIPP index can be applied to the 88 neighbourhoods in the pilot city following equation (2):

$$\text{IIPP} = \text{PV} \times \frac{\text{PSA}}{\text{TPC}} \times 100 \quad (2)$$

<sup>6</sup> These location specifications help to ensure free air circulation inside a Palmes tube.

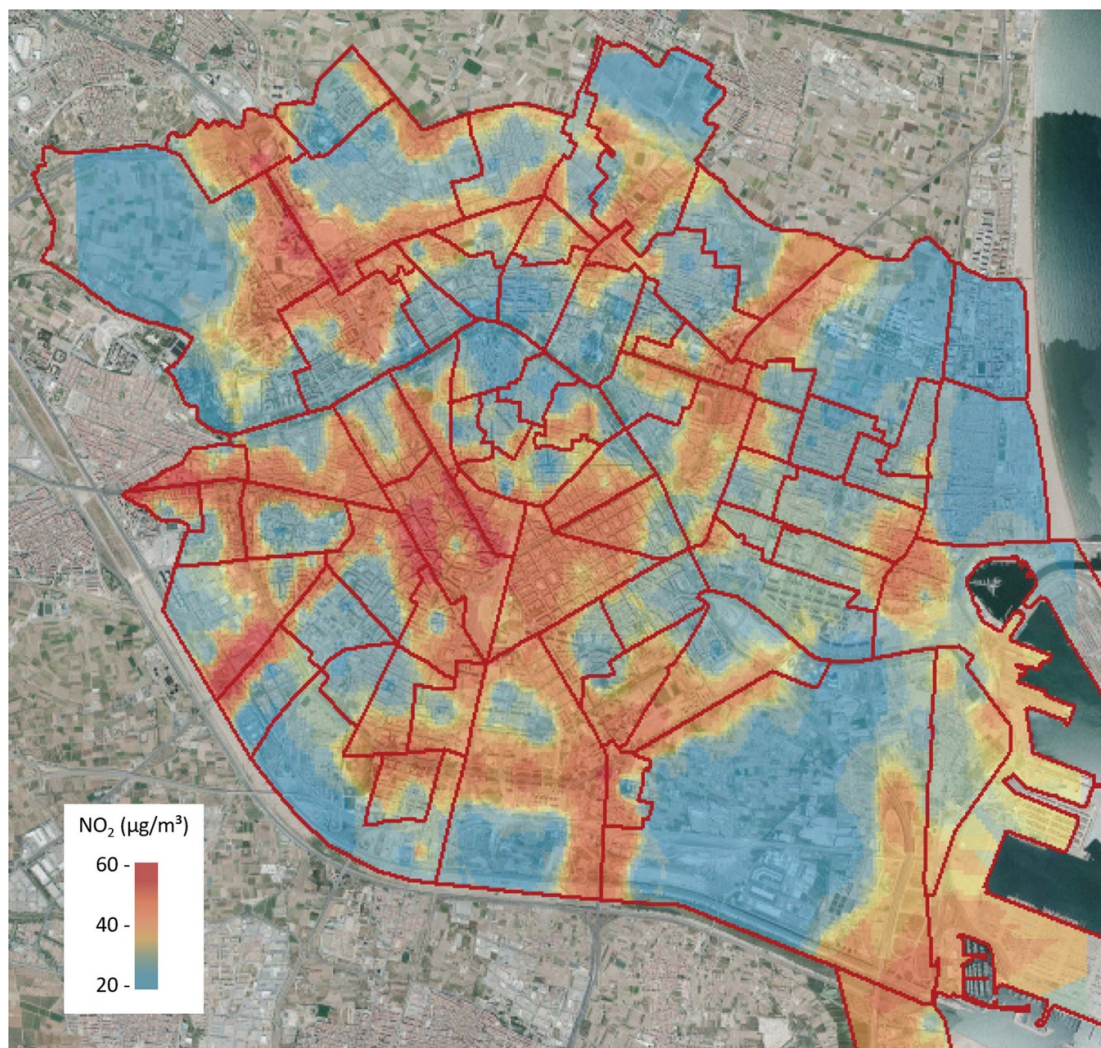


Figure 6. NO<sub>2</sub> pollutant concentration based on mobile dosimetry sensors in Valencia (year 2019).

where IIPP is the index of the impact of pollutant on population; PV refers to pollution value, i.e. the NO<sub>2</sub> amount ( $\mu\text{g m}^{-3}$ ) in each neighbourhood; PSA is the population of each neighbourhood; and TPC is the total population of the city.

### 3. Results and discussion

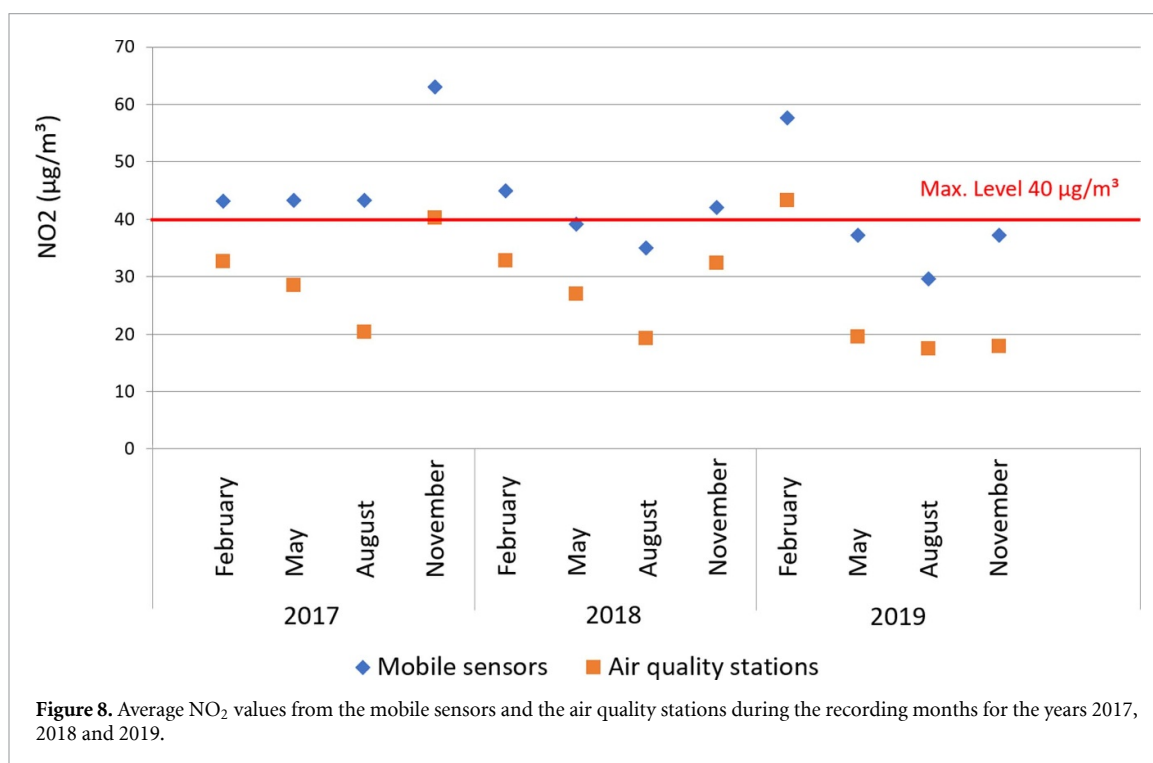
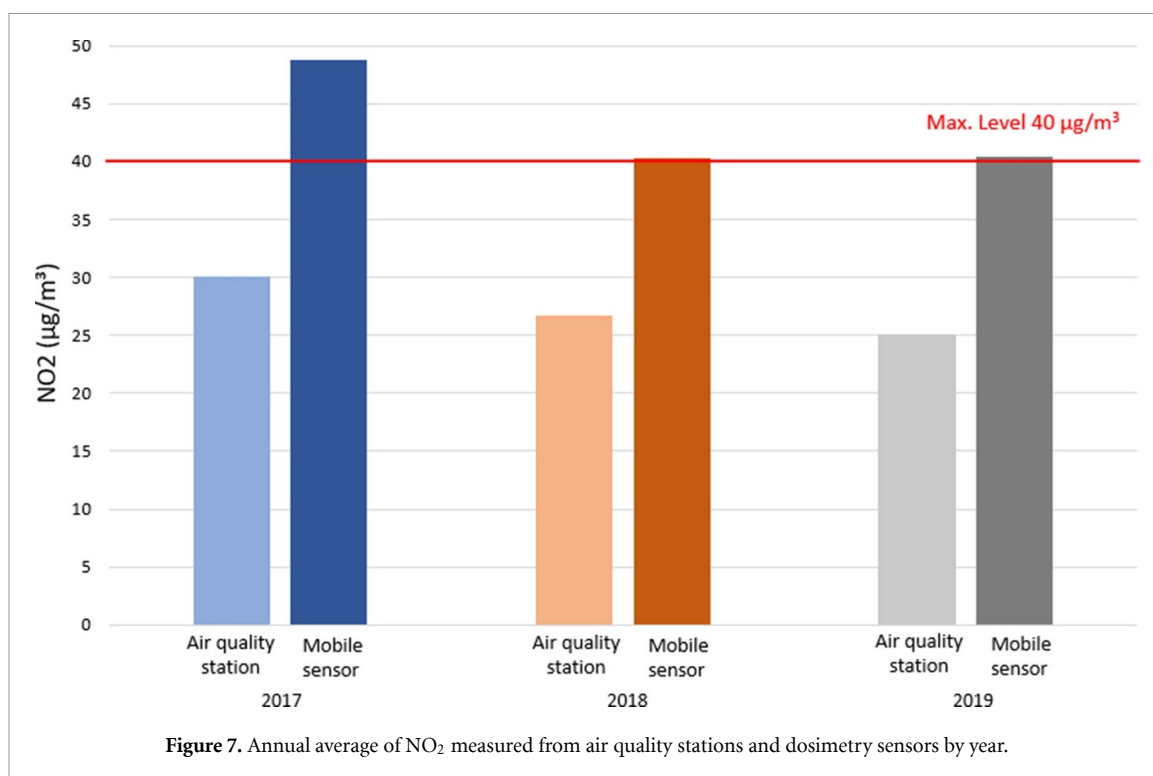
#### 3.1. Accomplishment of EU Directive by the air quality monitoring network in the Valencia municipality (city pilot)

The requirements of annex III regarding macro- and microimplantation of the EU Directive 2008/50/EC are met except for the macroimplantation requirement that the locations of the fixed sampling points are determined by the highest pollutant concentrations and the exposed population (sections 3.2–3.4). Concerning annex V of the EU Directive, the number of air quality stations also fulfils the minimum number established for the measurement of NO<sub>2</sub> concentrations. Owing to the mentioned limitation, a redesign of the current locations of the FAQS is

needed, displacing some of the stations to the most polluted zones where most people live.

#### 3.2. NO<sub>2</sub> measurements from the air quality stations

Figure 4 represents the average daily NO<sub>2</sub> values in  $\mu\text{g m}^{-3}$  measured by the seven FAQS of the city of Valencia and their average. The results from these stations show that the average daily values are systematically below the limit value of  $40 \mu\text{g m}^{-3}$  set by the EU Directive and the WHO for the years 2017, 2018 and 2019. The highest NO<sub>2</sub> concentrations are recorded in the air quality station of ‘Pista de Silla’ during the years 2017 and 2018 and the air quality station ‘Bulevard Sud’ in 2019. These levels are coherent because of the main road entrances of traffic to the city. These results show that the air quality in Valencia does not exceed the limit value set by the Directive and WHO. However, this statement would only be correct in the case that the air quality stations were representative of the air that most citizens breathe.



### 3.3. NO<sub>2</sub> measurements from the passive dosimetry sensors

The installation of the 424 dosimetry passive sensors allowed analysis of the NO<sub>2</sub> levels during the years 2017, 2018 and 2019 in Valencia. Considering the four seasonal periods (February, May, August and November) for each year, a total of 1696 NO<sub>2</sub> measurements were recorded during the analysed period. From these measurements, 1.1% (18) are considered nulls due

to the disappearance of the sampling Palmes tubes. From the rest, 43.7% (733) exceed the limit value established of 40 µg m<sup>-3</sup> while 12.8% (215), 2.4% (41) and 1.3% (21) exceed the values of 60, 80 and 90 µg m<sup>-3</sup>, respectively (figure 5). The average value disaggregated by location type presents the following NO<sub>2</sub> levels: (a) entrances to the city: 79.3 and 74.3 µg m<sup>-3</sup> for 2018 and 2019, respectively; (b) road intersections: 55.9, 55.7 and 53.1 µg m<sup>-3</sup>; (c) squares:



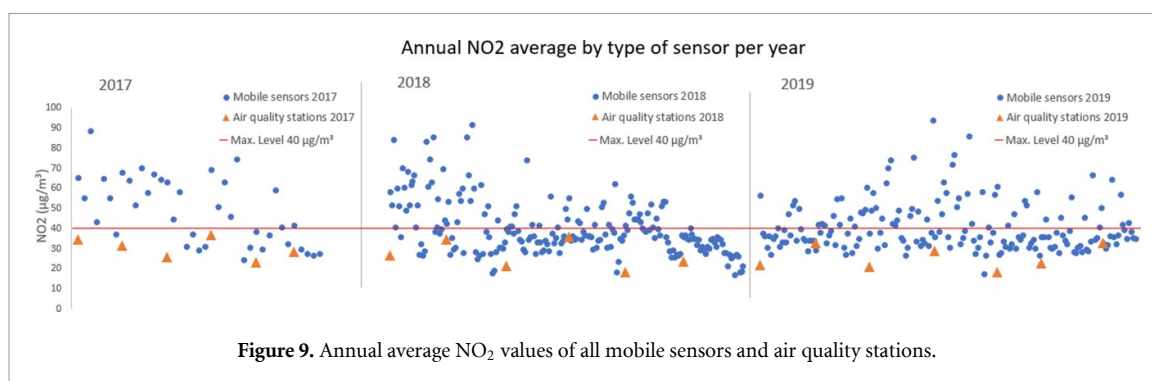


Figure 9. Annual average NO<sub>2</sub> values of all mobile sensors and air quality stations.

Table 4. Characteristics of neighbourhoods with current air quality station locations in relation to NO<sub>2</sub> values of mobile sensors, populations and IIPP index values. More details are in table 3 of the supplementary material.

Air quality station	Neighbourhood	Sorted by IIPP index	Sorted by NO <sub>2</sub> pollution	Sorted by population density
ID: 46250030—Pista de Silla	Russafa	3rd	3rd	6th
ID: 46250047—Avd. Francia	Penya-Roja	16th	22nd	20th
ID: 46250048—Molí del Sol	Sant Pau	17th	54th	13th
ID: 46250043—Vivers	Trinitat	41st	45th	41st
ID: 46250054—Centre	Sant Francesc	44th	24th	54th
ID: 46250050—Bulevard Sud	Camí Real	59th	26th	65th
ID: 46250046—Politècnic	La Carrasca	66th	65th	69th

Table 5. Characteristics of the proposed new air quality station network locations in relation to NO<sub>2</sub> PVs, population density and IIPP index results by neighbourhood. More details are in table 3 of the supplementary material.

Neighbourhood	Sorted by IIPP index	Sorted by NO <sub>2</sub> pollution	Sorted by population density
Benicalap	1st	18th	1st
Arrancapins	2nd	1st	8th
Russafa	3rd	3rd	6th
Malilla	4th	4th	9th
Nou Moles	5th	13th	3rd
Patraix	6th	25th	5th
Torreïel	7th	35th	2nd

51.3, 49.0 and 45.83  $\mu\text{g m}^{-3}$ ; and (d) green urban areas (parks): 31.27, 32.47 and 31.86  $\mu\text{g m}^{-3}$  for 2017, 2018 and 2019 respectively.

The measurements from the sampling months (February, May, August and November) can be used to calculate the annual mean. As can be seen in table 2, the average NO<sub>2</sub> values of the sampled months have a variation of only  $\pm 0.5 \mu\text{g m}^{-3}$  with respect to the annual average based on official air quality station measurements.

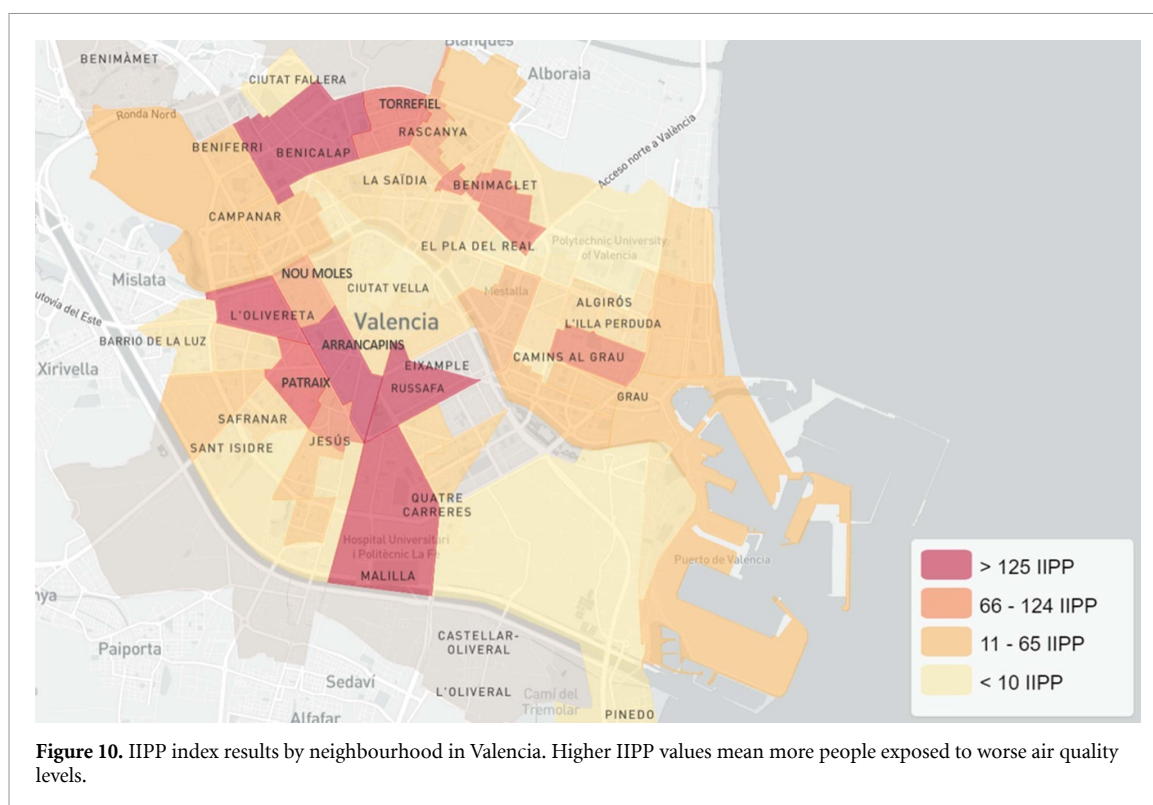
The average NO<sub>2</sub> levels of each neighbourhood are calculated based on the arithmetic mean of measuring points located in the 88 neighbourhoods and 69 points with measuring data of mobile sensors. The limit of the NO<sub>2</sub> average value (40  $\mu\text{g m}^{-3}$ ) is exceeded in 22 of the 69 analysed neighbourhoods (table 3). These figures reveal that only 75% of the neighbourhoods are below the NO<sub>2</sub> limit value, which means that the populations living in

those neighbourhoods are less exposed to harmful health effects than the others. In terms of NO<sub>2</sub> levels registered by the mobile sensors and the population in each neighbourhood, more than 34% of the total population is living in neighbourhoods where the NO<sub>2</sub> concentration in ambient air is higher than the limit value (40  $\mu\text{g m}^{-3}$ ). In particular, this percentage represents 272 571 inhabitants of the total (787 808 inhabitants). The NO<sub>2</sub> average value of all neighbourhood sampling points is approximately 36.4  $\mu\text{g m}^{-3}$ , with maximum and minimum values assigned to the neighbourhoods of Arrancapins (60  $\mu\text{g m}^{-3}$ ) and Sant Isidre (18.2  $\mu\text{g m}^{-3}$ ), respectively. This difference can be explained because Arrancapins is located in the centre of the city with more traffic intensity and less wind exposure than Sant Isidre, hindering the dispersion of contaminants.

Finally, a spatial interpolation using the 177 sampling points of the NO<sub>2</sub> concentration is made using the Kriging method (figure 6). Notice that the zones with high pollution are focused on the main entrances to the city (in the northwest, west and south), the city centre and the east of the city. This is mainly due to the influences of traffic intensity at the main entrances, traffic jams in the centre and on the main roads of the city, and emissions from the Valencian port in the east of the city.

### 3.4. Comparison of the NO<sub>2</sub> values from the two air quality measurement systems

At neighbourhood level, figure 10 shows the spatial distribution of the redesigned air quality station network. In particular, two air quality stations should be placed in the northern neighbourhoods (Benicalap



**Figure 10.** IIPP index results by neighbourhood in Valencia. Higher IIPP values mean more people exposed to worse air quality levels.

and Torrefiel), four quality stations in the central city neighbourhoods (Arrancapins, Nou Moles, Russafa and Patraix) and one station in the southern part of the city (Malilla). A Welch test (t-test) is applied for comparison of the  $\text{NO}_2$  values analysed from the fixed and mobile sampling points. This statistical test demonstrates significant differences ( $p$ -value 0.01) between the  $\text{NO}_2$  annual and daily average values from the mobile sensors and air quality station measurements in the reference years. In contrast, significant differences are not found between the measured values from those mobile sensors that were placed directly at the FAQs and the values recorded by each station itself. It can be assumed, therefore, that both measuring technologies can be comparable and that the differences between mobile sensors and air quality stations are due to differences in the locations of the measurements. In terms of limit values, the annual  $\text{NO}_2$  average values from the air quality stations are below the threshold of  $40 \mu\text{g m}^{-3}$ , while the values from the mobile sensors are above it ( $48.7$ ,  $40.3$  and  $40.4 \mu\text{g m}^{-3}$ , respectively) in the three reference years (figure 7 and in the supplementary material annex).

Figure 8 illustrates the seasonality of the mobile sensors in comparison with the measurements from the FAQs during the months of February, May, August and November. The results show that both measurement systems follow parallel trends, although a systematic gap between the values offered by the FAQs and the mobile sensors can be observed due to the different locations.

Looking at each individual  $\text{NO}_2$  sampling point, figure 9 represents the annual average value from

the mobile sensors (passive dosimetry) in comparison with the FAQs in 2017, 2018 and 2019. Roughly 43.7% of mobile sensors are located in places where the  $\text{NO}_2$  concentration is higher than the limit value set by the EU Directive and the WHO for the protection of human health. It is important to emphasize that the purpose of air quality monitoring stations in urban agglomerations is to control the most polluted zones. However, from figure 9, it can be concluded that the air quality station locations do not correspond with the highest  $\text{NO}_2$  concentration zones in Valencia.

### 3.5. Optimisation of the air quality station network locations

As described in section 2.4, the optimal locations of FAQs are obtained from the application of the IIPP index, composed of  $\text{NO}_2$  concentration values and the population density in each selected neighbourhood (69 in total). Thus, analysing the application of the IIPP index to the specific locations of the seven air quality surveillance network stations in Valencia, only one of them, ID: 46250030—Pista de Silla, is located in one of the ten neighbourhoods with the highest IIPP index. Specifically, the ‘Pista de Silla’ air quality station is located in the third neighbourhood position according to IIPP index, being located at the third most polluted and sixth most densely populated neighbourhood of Valencia (table 4). The second best-located air quality station is in the 16th neighbourhood position, being the 22nd most polluted and 20th most densely populated. Hence, only the station placed in the ‘Russafa’ neighbourhood

(ID: 46250030—Pista de Silla) fulfils the purpose of official air quality surveillance stations described by the EU Directive of providing information from the most polluted zones where most people live. The others are located in neighbourhoods that do not meet the purpose of the Directive. Due to the high volatility and contaminant dispersion, pollutant measurements recorded from only one station are not representative for a mid-sized city.

This situation, therefore, requires a redesign of the current location of the FAQs. With this aim, the IIPP index is used to identify the neighbourhoods with the largest populations highly affected by NO<sub>2</sub> concentrations. Table 5 describes the main characteristics regarding pollution measurements and population density of the newly proposed neighbourhood locations.

The EU Directive 2008/50/EC regulation includes a defined number of FAQs according to the population as well as a set of requirements in terms of macroimplantation and microimplantation of this air quality network surveillance. The most appropriate location of the FAQs determines the correct measurement of air quality that the population breathes, as well as the activation of the protocols for exceeding the pollution limit values to mitigate high pollutant concentration levels.

#### 4. Conclusions

The design and installation of a complementary air quality monitoring network with 424 mobile sensors based on passive dosimetry has allowed analysis of NO<sub>2</sub> levels over three years (2017, 2018 and 2019) in the city of Valencia (Spain) and comparison of their results with those reported from the fixed official air quality surveillance network. This study reveals that while the seven official air quality stations do not exceed the annual average limit of NO<sub>2</sub> concentration values (40 µg m<sup>-3</sup>), the annual average values of NO<sub>2</sub> from the complementary mobile network in the city exceed this limit in almost half of the total mobile sampling locations during all the analysed periods. Based on these results, it can be stated that more than one third of the citizenship of Valencia (272 571 inhabitants) lives in areas with NO<sub>2</sub> pollution levels above the value limit set by both the WHO and EU Directive.

In order to evaluate the representativeness of PVs provided by the FAQs, the IIPP index identified and ranked 69 neighbourhoods based on the level of contamination and the population exposure to NO<sub>2</sub> concentration. In European cities, such as Valencia, air quality stations are not well located according to the real exposure of the population to pollution in the city. The EU Directive should include strict specifications or validation systems based on alternative measurements to optimize the locations of FAQs.

In particular, of all the official air quality stations, only one is located in a representative area (covering 3% of the total population) to establish mitigation protocols when the limit levels are exceeded. Thus, it can be concluded that contamination levels measured from the official air quality stations are not representative for assessing the air quality in the city as they do not provide reliable information from highly polluted areas where, at the same time, the majority of the population lives.

The lack of representativeness of the current official air quality network in Valencia has made it necessary to propose a redesign of the station locations based on IIPP index. Finally, in future works, the relationship between pollutant distribution and socio-cultural and economic characteristics of neighbourhoods should be analysed to study environmental justice along with a further analysis of relevant air pollutants in Valencia.

#### Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.


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