Environmental Pollution 323 (2023) 121203

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Potential ambient NO_2 abatement by applying photocatalytic materials in a Spanish city and analysis of short-term effect on human mortality[☆]

Jaime Fernández-Pampillón [a,b], Magdalena Palacios [a], Lourdes Núñez [a,*], Manuel Pujadas [a], Begoña Artíñano [a]

[a] Research Centre for Energy, Environment and Technology (CIEMAT), Madrid, 28040, Spain
[b] The National Distance Education University (UNED), Madrid, 28232, Spain

ARTICLE INFO

Keywords:
Air pollution
NO_2
TiO_2-based photocatalytic materials
Mortality

ABSTRACT

Road traffic is the main contributor to NO_2 emissions in many European cities, causing that the current limit values for the protection of human health are exceeded. The use of photocatalytic compounds that incorporate titanium dioxide (TiO_2) is frequently proposed as abatement technology but its depolluting effectiveness on a real scale is still being investigated.

In this work, the potential removal capacity of NO_2 that selected TiO_2-based materials would have if they were implemented in a street in the municipality of Alcobendas (Community of Madrid, Spain) has been evaluated. The number of avoided NO_2-related deaths over the locality across the period 2001–2019 have been inferred. Moreover, the saving associated with the estimated removal of ambient NO_2 due to the use of photocatalytic materials and costs generated by their acquisition and implementation in the selected urban environment were briefly studied.

Attributable mortality due to NO_2 concentrations for Alcobendas has been estimated in 289 deaths, being 9241 the total deaths due to natural cause. This presents a monthly variation associated with the evolution of both mortality due to natural causes and the average concentrations of NO_2.

The reduction in mortality via the hypothetical implantation of photocatalytic materials throughout the municipality, assuming ideal conditions for their optimal performance, would be a maximum of 3%.

In addition, a saving of €5708 yr^{-1} km^{-2} related to NO_x damage costs of transport was obtained. A total cost of k€4750.5 km^{-2} was associated to the purchase of photocatalytic materials and their application to all surfaces in that area.

This technology has a big elimination potential in controlled conditions but a low reduction of ambient NO_2 is provided when implemented in real outdoor urban scenarios. Its use can be recommended incorporated into engineering designs and applications, complementing other abatement measures, to reduce NO_2 mortality in urban areas.

1. Introduction

Air pollution is one of the biggest environmental health risk factors worldwide and increases the whole diseases burden (World Health Organization, 2016), (Health Effects Institute, 2020), (European Environment Agency, 2021). Global assessments of ambient air pollution suggest between 4 and 9 million deaths annually (World Health Organization, 2021), (Murray et al., 2020).

Nitrogen dioxide (NO_2) is an air pollutant for which the evidence of short-term health effects is increasing. Several studies point a causal relationship between short-term NO_2 exposure and respiratory effects and with cardiovascular effects and total mortality (European Environment Agency, 2021), (Environmental Protection Agency, 2016), (World Health Organization, 2013a), (Chen et al., 2018), (Linares et al., 2018). Additionally, there is some evidence supporting a role for long-term NO_2 in increasing all non-accidental and, especially, respiratory mortality (World Health Organization, 2021) or even in causing cardiovascular mortality (Schneider et al., 2018).

[☆] This paper has been recommended for acceptance by Pavlos Kassomenos.
[*] Corresponding author.
E-mail address: lourdes.nunez@ciemat.es (L. Núñez).

https://doi.org/10.1016/j.envpol.2023.121203
Received 14 December 2022; Received in revised form 20 January 2023; Accepted 1 February 2023
Available online 2 February 2023

The road transport sector is the principal source of nitrogen oxides ($NO_x = NO + NO_2$) emissions (39% in the EU-27 in 2019) where high NO_2 concentrations above the annual limit value (Directive, 2008/30/EC) are frequently observed specially at traffic stations located in densely populated urban environments. Even though during the last decades a slight decrease in the annual means of NO_x pollution in European cities has become evident, NO_2 concentrations remain and are still a problem to be solved (European Environment Agency, 2021), (Municipality of Madrid, 2017). The reason is twofold. On the one hand, the ratio of NO_2/NO_x emissions from road traffic has increased (mainly due to the introduction of certain types of diesel particulate filters in buses and the high penetration of diesel passenger cars in the market) (Carslaw et al., 2007). On the other hand, secondary NO_2, formed from directly emitted nitric oxide (NO) and, partially, ozone (O_3) or peroxide radicals (RO_2), does not decrease substantially due to the strongly non-linear dependence of NO_x levels with the already mentioned reactions and the photolysis of NO_2 (Leighton balance) (Palacios et al., 2002), (Kurtenbach et al., 2012). This makes it difficult to reduce ambient NO_2.

In particular, road traffic is the main source of anthropogenic NO_x emissions in the Madrid region (57%) (Palacios et al., 2001) and 78% of local sources concerning NO_2 annual average concentration in the metropolitan urban area (Borge et al., 2014). Both the city and other agglomerations of the region frequently exceed the hourly and annual limits for NO_2 (mainly from October to February) (Ministry of Agriculture and Fishing and Food and Environment, 2017). The Madrid region, located in the centre of the Iberian Peninsula, is frequently under the influence of high pressures that cause poor atmospheric ventilation and favour significant episodes of air pollution, especially in winter and, in general, with moderate ambient concentrations of NO_2 and particulate matter (Martín et al., 2001), (Pujadas et al., 2000). On the other hand, the advection of polluted air masses from the Madrid metropolitan area, which are added to the local emissions of certain municipalities, complicate the problem of improving air quality in some areas near Madrid city (for example, the North agglomeration) (Community of Madrid, 2021).

The need to decrease the contribution of NO_x to air pollution in urban areas has favoured the introduction and evaluation of different mitigation strategies. In addition to the measures adopted to reduce NO_x emissions, it is necessary to implement other control measures that eliminate the NO_2 present in the air (Vedrenne et al., 2015). Among the available air pollution control options with potential success in eliminating ambient NO_x, it is worth highlighting the use of construction materials that incorporate photocatalyst compounds such as titanium dioxide (TiO_2). It is has been proved in numerous laboratory tests that this kind of materials, activated by sunlight, allow the elimination of those pollutants by heterogeneous photocatalysis (Mendoza et al., 2015), (Martinez et al., 2011), (Ballari et al., 2010), (Laufs et al., 2010), (Sikkema et al., 2015), (de Melo and Trichês, 2012), (Zouzelka and Rathousky, 2017), (Ângelo et al., 2014), (Mothes et al., 2018), (Bengtsson and Castellote, 2010), (Karapati et al., 2014). In recent decades, the development of this technology has led to the commercialization of different building materials that have found a field of application for ambient air depollution in European urban environments (Maggos et al., 2008), (Ballari and Brouwers, 2013), (Guerrini and Peccati, 2007), (Moussiopoulos et al., 2008), (Boonen and Beeldens, 2014), (Chen and Chu, 2011), (IPL, 2010), (TERA environment, 2009), (Gallus et al., 2015a), (Gallus et al., 2015b), (Barratt et al., 2012), (Cordero et al., 2021).

Heterogeneous photocatalysis applied to air pollution mitigation implies the interaction between a solid catalyst and the gas phase. The pollutant is transferred to and adsorbed on the photoactive surface TiO_2 centres; next, the absorption of UV-A radiation by TiO_2 promotes the formation of electron/hole pairs; and lastly, adsorbed O_2 and H_2O reacts to form reactive oxygen species that oxidize the nitrogen oxides and the nitrate produced can be finally desorbed. Thus, photocatalytic activity, described in further detail elsewhere, is presented in Fig. 1 (adapted from (Monge et al., 2010), (Dillert et al., 2013), (Ballari et al., 2011), (Herrmann, 2010)).

The latest trends in this technology are aimed at improving performance through greater control of the reaction through new additives, as well as the introduction of different mixtures of photocatalysts. Also, the possibility of extending the useful spectral range from UVA to visible is being investigated (Ochiai and Fujishima, 2012), (Ahmad et al., 2016). On the other hand, research on the kinetics characteristic of the different chemical processes that take place continues, enormously dependent on the substrate to which TiO_2 is incorporated and the additives that are used (Mothes et al., 2018), (Ângelo et al., 2013), (Mills et al., 2016), (Mothes et al., 2016). All this draws an enormous field of experimentation and applicability, referred both to applications in outdoor (urban environment, fundamentally) and indoor. A great piece of information is continually emerging as far as the market launch of new building photocatalytic materials with big potential to reduce NO_x ambient concentrations. These announcements are based on promising laboratory test under controlled conditions but their efficiency to eliminate these pollutants on a real scale is plenty of uncertainties and the possible positive impact in the air quality at real urban areas has to be carefully studied (Air Quality Expert Group of the Department for Environment Food and Rural Affairs, 2016).

Recently, the LIFE MINO$_x$-STREET demonstration project, co-funded by the EU, has had as its first objective to provide evidence from rigorous tests and trials on the physical-chemical properties and the expected efficiency of several commercial photocatalytic materials. Secondly, the depolluting capabilities of the three most promising photoactive products selected to be implemented in three different urban surfaces (road, sidewalk and façade, respectively) in the municipality of Alcobendas (located 10 km northwest of the city of Madrid) were evaluated at real scale (Palacios et al., 2018), (European Commission, 2023).

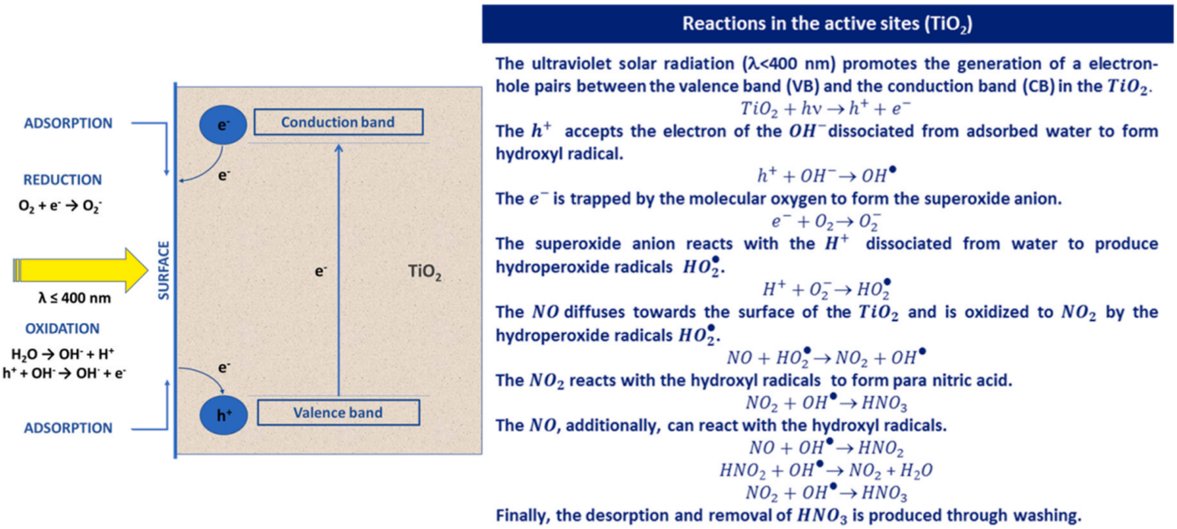
Among the objectives achieved for this project, a characterisation of the sink effect on NO_x levels on different photocatalytic surfaces under controlled ambient conditions was performed (Palacios et al., 2015a, 2015b, 2015c, 2015d, 2015e). This allowed to analyse the potential combined efficiency of several photocatalytic materials when are applied to different elements of the urban environment at street level to improve air quality.

The main contribution of this work refers to the methodology presented to evaluate the capacity of the use of photocatalytic materials to reduce ambient NO_2 concentration in a city of the Community of Madrid and, subsequently, to estimate the decrease in short-term natural cause mortality due to nitrogen dioxide if this technology would have been used during the last two decades, as well as the costs derived from its implementation. Finally, the possible potential benefit has been estimated, in terms of mortality reduction, if the air quality objectives proposed by WHO were achieved.

2. Methodology

First of all, maximum reduction in NO_2 ambient concentration potentially expected as a consequence of the implementation of photocatalytic materials was estimated. The methodology utilized has been based on the different results obtained in the LIFE MINO$_x$-STREET project.

Following short-term association between NO_2 concentrations and natural cause mortality, named as relative risk, referred to the inhabitants of the municipality of Alcobendas during the period 2001–2019, has been used to compute attributable mortality due to NO_2 concentrations in three different scenarios. The first one is considering the city with its actual conditions, the second one is an ideal situation where all roads, sidewalks and facades are treated with photocatalytic coatings and, in the third one, the NO_2 ambient concentration is 20 μg m^{-3}, the AQG level proposed as interim target 3 for annual mean NO_2 concentration by WHO (World Health Organization, 2021), (World



Reactions in the active sites (TiO_2)

The ultraviolet solar radiation (λ<400 nm) promotes the generation of a electron-hole pairs between the valence band (VB) and the conduction band (CB) in the TiO_2.

$$TiO_2 + h\nu \rightarrow h^+ + e^-$$

The h^+ accepts the electron of the OH^- dissociated from adsorbed water to form hydroxyl radical.

$$h^+ + OH^- \rightarrow OH^\bullet$$

The e^- is trapped by the molecular oxygen to form the superoxide anion.

$$e^- + O_2 \rightarrow O_2^-$$

The superoxide anion reacts with the H^+ dissociated from water to produce hydroperoxide radicals $HO_2^\bullet$.

$$H^+ + O_2^- \rightarrow HO_2^\bullet$$

The NO diffuses towards the surface of the TiO_2 and is oxidized to NO_2 by the hydroperoxide radicals $HO_2^\bullet$.

$$NO + HO_2^\bullet \rightarrow NO_2 + OH^\bullet$$

The NO_2 reacts with the hydroxyl radicals to form para nitric acid.

$$NO_2 + OH^\bullet \rightarrow HNO_3$$

The NO, additionally, can react with the hydroxyl radicals.

$$NO + OH^\bullet \rightarrow HNO_2$$

$$HNO_2 + OH^\bullet \rightarrow NO_2 + H_2O$$

$$NO_2 + OH^\bullet \rightarrow HNO_3$$

Finally, the desorption and removal of HNO_3 is produced through washing.

Fig. 1. Photocatalytic reaction mechanism of nitrogen oxides on TiO_2 (adapted from (Monge et al., 2010), (Dillert et al., 2013), (Ballari et al., 2011), (Herrmann, 2010)).

Health Organization, 2013b).

Subsequently, the benefit in terms of mortality that the application of photocatalytic materials would have throughout the city was estimated, as well as what would have been the impact associated with a reduction in the concentration of NO_2 adjusted to certain regulated limits. Furthermore, a rough study of the associated costs saved from removing ambient NO_2 and those derived from the acquisition and arrangement of the materials in the urban environment selected was undertaken.

Such methodology has been applied to Alcobendas, which currently has a population of around 117000 inhabitants (Statistics National Institute, 2023), well below the great European metropolises but similar to many other medium-sized municipalities located in the Community of Madrid. Beyond the prevailing air pollution conditions and regardless of the impact that the reduction of air pollution by NO_2 produces on the number of deaths in this specific location, the methodology presented is applicable to similar studies at any city.

2.1. *Ambient NO_2 reduction due to the implementation of photocatalytic materials*

Even when no available measurements could be used to calculate NO_2 depolluting efficiency, laboratory assays under the ISO 22197–1:2007 international standard method (ISO, 2007) were used to investigate the NO depolluting performance of a variety of commercial photocatalytic materials and select three coatings that finally were implemented in Alcobendas (a water emulsion on a bituminous concrete pavement, a photocatalytic coating on a concrete pavement and a photocatalytic mono-component paint on a brick-facade), because their notable NO purifying efficiency. Additionally, these data were used to estimate the corresponding NO surface deposition velocities by following a first-order kinetic approximation as it is described below (Palacios et al., 2015a, 2015d) and to approximate NO_2 surface deposition velocities needed to compute ambient NO_2 reduction due to the implementation of photocatalytic materials in that city.

Thus, a rate coefficient (k_r, s^{-1}), can be determined from the experimental data:

$$k_r = -\frac{ln\left(\frac{C_{out}}{C_{in}}\right)}{t_r} \tag{1}$$

where C_{in} and C_{out} (ppbv) are NO concentration at the inlet and exit of the photo-reactor and t_r (s) is the reaction time of the gas-phase NO and the sample. k_r is directly related to the activity of the sample, on one hand, but also dependent on the geometry and size of the reactor. Therefore, the dimensionless reactive uptake coefficient, γ, has been introduced in heterogeneous chemistry. The reactive uptake coefficient is defined as the ratio of the number of collisions that lead to reaction over all collisions of the gas-phase reactant with a reactive surface. It can be calculated from k_r as:

$$\gamma = \frac{4 \cdot k_r}{\overline{\upsilon} \cdot S/V} \tag{2}$$

where S/V (m^{-1}) is the ratio of photoactive surface to air volume above this surface and $\overline{\upsilon}$ ($m\ s^{-1}$) is the mean molecular velocity of the gas NO defined by the kinetic gas theory:

$$\overline{\upsilon} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}} \tag{3}$$

where R (8.314 $J\ mol^{-1}\ K^{-1}$) is the ideal gas constant, T (K) is the absolute temperature and M ($kg\ mol^{-1}$) is the molecular mass of NO. Then, an analogue surface deposition velocity V_{surf} ($m\ s^{-1}$) can be defined:

$$V_{surf} = \frac{\gamma \cdot \overline{\upsilon}}{4} \tag{4}$$

which can be useful to estimate surface deposition fluxes in atmospheric models through a surface resistance computed from the inverse of the surface deposition velocity. Further details on kinetic parameters are given elsewhere (Ifang et al., 2014).

On the other hand, NO_2 surface deposition velocities for several TiO_2-based photocatalytic materials, calculated by means of laboratory tests, have given similar values or even one order of magnitude lower than that obtained for NO (Laufs et al., 2010), (Mothes et al., 2018), (Gallus et al., 2015b), (Air Quality Expert Group of the Department for Environment Food and Rural Affairs, 2016), (Ifang et al., 2014), (Engel et al., 2015). Here, NO and NO_2 surface deposition velocities are assumed to have the same value for every one of the photoactive materials under consideration in order to evaluate an upper limit of photocatalytic NO_2 degradation and its impact in the surrounding air of a selected stretch of the Paseo de la Chopera avenue (Alcobendas). For this purpose, it is also presumed that NO_2 photocatalytic decomposition follows a first order kinetics in the street under specific atmospheric conditions, reproducing a plugged flow reactor situation in which the air mass travels longitudinal through the canyon without dilution to the upper atmosphere. Then, assessing the NO_2 potential remediation ((C_{out}-C_{in})/ C_{in}) for the study street is possible by using above expressions (1–4). Finally, this maximum NO_2 removal value was considered to be the same for the whole municipality of Alcobendas.

2.2. Attributable mortality due to NO_2 in real urban scenario

In order to compute the number of deaths attributable to NO_2 concentrations for the municipality of Alcobendas in the whole period considered, the methodology presented by Tobías et al. has been followed (Tobías et al., 2015). Previous studies indicate that in the case of daily mean NO_2 concentrations, the functional relationship established with mortality is linear, thus rendering parameterisation unnecessary for their introduction into the models (Díaz et al., 1999), (Ortiz et al., 2017).

First, it is necessary to calculate the attributable risk (AR), which represents the percentage increase in daily mortality when the mean NO_2 concentration increases in 10 μg m^{-3} and it is computed by using a previously estimated RR associated to this increment, via the expression: $AR = (RR - 1)/RR * 100$ (Coste and Spira, 1991).

The RR for the municipality of Alcobendas is assumed to be the same as that estimated for Madrid, taking into account that this town is located in the northern area of the metropolitan belt of the Madrid city and, as in the case of the capital, the main source of air pollutants, including NO_2, is road traffic. Relative risk is computed by Linares et al. for Madrid (Linares et al., 2018) (see Annex 1 of Supplementary Material). RR calculated for increases of 10 μg m^{-3} in NO_2 levels based on natural cause mortality are found to be 1.009 (1.006; 1.013) (95% CI), in the order of the average given in the systematic review and meta-analysis published by Orellano 1.007 (1.006; 1.009) (Orellano et al., 2020). Consequently, a natural cause AR of 0.89 (95% CI: 0.58–1.28) was adopted with no significant effect found for respiratory or circulatory cause (Linares et al., 2018).

Next, the daily mortality associated with an average daily NO_2 concentration need to be estimated. For that, daily mean NO_2 concentrations are used as the measure of mean population exposure to this pollutant. Hourly available and validated data, as supplied by Ministry for the Ecological Transition and the Demographic Challenge, are taken across the period 2001–2019 at the urban traffic monitoring station of Alcobendas city belonging to the Air Quality Network of the Community of Madrid and, with comparative purposes, also at the air quality stations that constitute the Air Quality Network of Municipality of Madrid (Ministry for the Ecological Transition and the Demographic Challenge, 2022). Subsequently, taking daily mortality data (supplied by the Spanish National Statistics Institute, INE), the percentage increase in daily mortality associated with that given NO_2 concentration is thus calculated by multiplying it by the computed AR and dividing by the reference increase of 10 μg m^{-3}. Afterwards, to go from the percentage increase in mortality to the number of daily deaths attributable to this NO_2 concentration, this percentage increase value in mortality must only be multiplied by the number of daily deaths and divided by one hundred.

Finally, it is possible to estimate the number of deaths associated with ambient concentrations of NO_2 registered during an investigated period by integrating the daily mortalities calculated for that required term.

2.3. Evaluation of attributable mortality due to NO_2 in ideal urban scenarios

In the first ideal scenario addressed, all roads, sidewalks and facades in the municipality of Alcobendas are considered to be covered with photocatalytic coatings and the mean NO_2 ambient concentration reduction is estimated. For this hypothetical scenario with reduced NO_2 ambient concentrations the associated attributable mortality can be computed.

In the second ideal scenario proposed, the ambient conditions correspond to an average annual NO_2 concentration of 20 μg m^{-3} and in this case the attributable mortality is also inferred. This scenario corresponds to the AQG level proposed as interim target 3 for annual mean NO_2 concentration by WHO (World Health Organization, 2021).

2.4. Cost-benefit assessment related to the implementation of photocatalytic materials in urban outdoor scenarios

Beyond the inestimable benefit of saving human lives, a very relevant aspect to consider is the economic viability of the application of photocatalytic materials, associated with both costs due to their implementation and costs saved, mainly related to the health benefits derived from the elimination of ambient NO_2. In this work, a comparative estimate is presented, taking as a case study an area of 1 km^2 in which the street where the experiments were carried out in Alcobendas is embedded.

Recently, damage costs of main pollutants from transport have been presented by the European Commission, covering not only health effects (90% of the total external effect), but also quantifying the side effects of emitted NO_x on materials (e.g. buildings), biodiversity, and crops. Existing studies on external costs have mainly concerned road transport. The evidence shows that road transport has by far the largest share in total external costs of transport. For Spain, a value of 8500 € per tonne of NO_x is given (Essen et al., 2020). This would imply that each tonne of NO_x withdrawn from the atmosphere would save such cost.

In this work, total NO_x vehicle emissions E_{NO_x} (g h^{-1}) in a selected 1 km^2 area were estimated by means of the expression: $E_{NO_x} = EF_{NO_x} \bullet l_{roads} \bullet DMI$, where EF_{NO_x} is the average emission factor taken as representative of the fleet traveling within that area (g km^{-1}), l_{roads} is the total length of the main roads considered (km) and DMI is the daily mean intensity from the traffic counts registered (vehicles h^{-1}).

Having considered that the surface deposition rates of NO and NO_2 are equal the estimated reduction in the ambient concentration of NO_2 is also applicable for NO_x. Additionally, to estimate the potential benefit of reducing the ambient concentration of NO_x in the estimated proportion a numerical model of atmospheric dispersion should be used (Izquierdo et al., 2020). Alternatively, the estimated ambient NO_x reduction could simply be considered a consequence of reducing NO_x emissions by the same proportion. The expected benefit (euros $year^{-1}$) associated with the ambient NO_x removed as a consequence of the application of photocatalytic materials can be calculated by applying the aforementioned external cost referred to road transport.

Moreover, the cost for the acquisition and setup of the products selected for their application on roads, sidewalks and facades surfaces within the area of 1 km^2 studied was estimated taking into account data supplied by manufacturers and public administration responsible.

3. Results

3.1. Ambient NO_2 removal in ideal conditions for the city of alcobendas

Upper limit photocatalytic NO_2-degradation was estimated in a stretch of Paseo de la Chopera (Alcobendas) an urban main street, whose geometry nearly matches the canon of an ideal typical street canyon. The chosen street presented a cross section of 36 m wide by 16 m height. A wind direction parallel to the canyon was considered so that the air mass stream flows at a constant velocity parallel to its longitudinal axis with no back mixing. Fig. 2 shows the municipality of Alcobendas where residential areas with large avenues contrast with other narrow streets that constitute the oldest part of the city.

In the course of the development of the LIFE $MINO_x$-STREET project, modified-ISO 22197–1:2007 laboratory assays were performed for the two different TiO_2-water emulsions and the monocomponent nanopaint selected to be implemented in a road, a sidewalk and a facade of Alcobendas, respectively. NO averaged inlet concentration was set to 140 ppb instead of the standard value of 1000 ppb. The use of a classical first-order kinetic approximation to calculate the surface deposition rates of

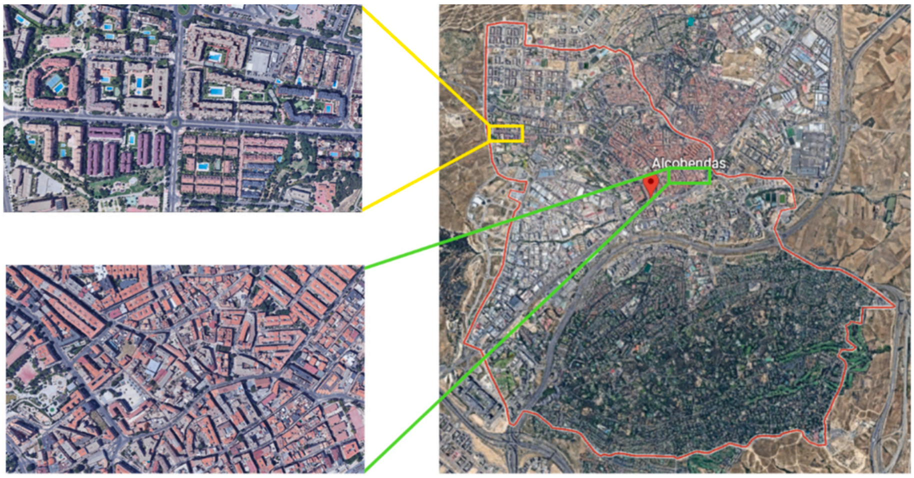


Fig. 2. Map of Alcobendas. Delimitation of the municipality pointed out in red line. Experimental area of the Paseo de la Chopera (LIFE MINO$_x$-STREET project) framed in yellow. A detail of the downtown of Alcobendas indicated in green. Images have been taken from Google Earth geobrowser. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

NO is admissible at concentrations in the range of relevant air pollution levels (Mothes et al., 2018), (Ifang et al., 2014). Thus, the estimate obtained for the selected test condition gave a result for the respective NO surface deposition velocity of 7.2 10^{-3}, 8 10^{-3} and 1.6 10^{-3} m s^{-1}, for the three mentioned products. Interestingly, activity was similar to those obtained for NO by other studies (Mothes et al., 2018), (Gallus et al., 2015a), (Ifang et al., 2014), (Engel et al., 2015). Nevertheless, it is important having in mind that in such ISO bed photo-reactors, transport limitations occur that can lead to underestimation of the activity by possible diffusion limitations (Ifang et al., 2014).

The average wind speed in the street canyon was assumed to be 1.5 m s^{-1}, estimated by using measurement data within the experimental campaign carried out in studied street in the course of the project LIFE MINO$_x$-STREET (Pujadas et al., 2016), (Fernández-Pampillón et al., 2021). It was considered that air polluted mass is transported longitudinal through the canyon, without dilution to the upper atmosphere and traverses 300 m long. Under this condition, the upper limit of NO_2 residence time in the street could be estimated as 200 s. When the air flow is established in other directions, the turbulent mixing in the canyon increases shortening the NO_2 residence time in the canyon.

All the canyon surfaces (roads, sidewalks and facades) were assumed to be active. By taking estimated NO surface deposition velocities for the three mentioned selected photocatalytic materials implemented in real urban areas during the project and considering NO_2 uptakes to be the same as those calculated for NO, a surface reactivity given by an NO_2 average surface deposition velocity of 5.6 10^{-3} ms^{-1} has been used in this study. This gives an NO_2 uptake coefficient of 6.1 10^{-5}. An active surface to air volume above the surface ratio (S_{active}/V) of 0.1 m^{-1} was then taken to calculate a NO_2 first-order rate constant equal to 6.6 10^{-4} s^{-1}. Considering a residence time of 200 s, the NO_2 degradation was estimated, leading to a maximum estimated photocatalytic NO_2 potential remediation of 12%, assuming all surfaces to be totally illuminated.

However, by using this approximation, no transport limitations were considered and only surface activity has been taken into account, neglecting turbulent mixing and quasi molecular-diffusion. If these latest were included, the real NO_2 uptake would decrease more than a factor of two (VDI, 2006). Moreover, surfaces are not active during night time period and assuming half the daytime there is enough UV-A radiation for photocatalysis to take place, a diurnal upper limit of approximately 3% is reached.

Being aware that the difference between the streets that make up the urban network of Alcobendas is enormous, that upper limit of the impact on the concentration of ambient NO_2 potentially generated by the use of photocatalytic materials on roads, sidewalks and facades of the whole urban environment has been adopted intentionally to study the potential benefits of that measures on public health. For it, the estimated reduction percentage for the selected section of Paseo de la Chopera has been extrapolated to the entire municipality.

3.2. *Attributable mortality due to NO_2 in a real urban scenario*

Taking into account the influence of ambient concentrations of NO_2 on the attributable mortality to said pollutant and since the RR taken for the city of Alcobendas has been the same as that previously estimated for Madrid, the hourly average concentration of NO, NO_2 and O_3 has been calculated for the study period both in Alcobendas and in the nearby city of Madrid managing the data from the air quality stations at Alcobendas and Madrid city, for the period 2001–2019. The profiles represented in Fig. 3 clearly reflect the influence of road traffic emissions as the most relevant primary emission source in both locations, with maxima of NO and NO_2 corresponding to peak hours. Likewise, the photochemical generation of secondary NO_2 and O_3 is observed, with a time evolution profile in accordance with the aforementioned primary emission pattern, as reflected in previous studies related to atmospheric pollution in the Community of Madrid (Palacios et al., 2002), (Pujadas et al., 2000) (Borge et al., 2012). It should be noted that, as expected, the concentration levels of nitrogen oxides are higher in the city of Madrid, as well as its ozone levels are lower than those recorded in Alcobendas.

Moreover, the evolutions of the monthly average concentrations of NO_2 calculated for both Madrid and Alcobendas also show similar

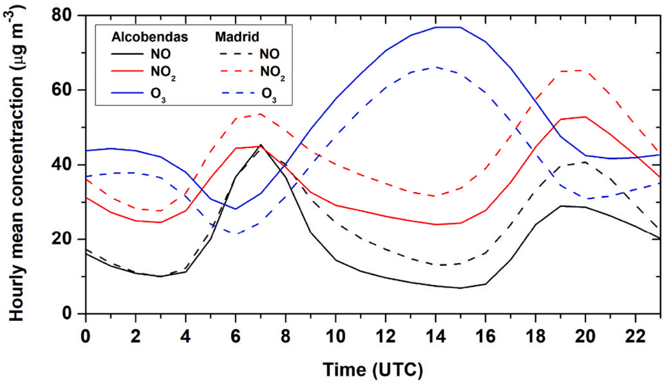


Fig. 3. Hourly mean profile of NO, NO_2 and O_3 for Alcobendas and Madrid city concerning the period 2001–2019.

patterns, although the difference observed between the warmest and coldest months is slightly more pronounced in Alcobendas. Fig. 4 shows related statistics for both locations analysed across the study period.

Fig. 5 shows the average monthly mortality corresponding to natural cause in Alcobendas computed for 2001–2019, with an annual mean value of 486 ± 62 deaths. Furthermore, the attributable mortality due to NO_2, according to the RR assumed for Alcobendas, is presented in the lower panel.

The highest values were observed in the fall and winter seasons. Although the annual evolution of total mortality reflects a slight seasonal influence, meteorology is clearly a determining factor on the recorded levels of NO_2 (Fig. 4). Indeed, during these colder months, the Community of Madrid is frequently under the synoptic influence of high-pressure systems, associated with poor ventilation events and strong surface thermal inversions. All these factors, together with the limited photolysis of NO_2, lead to the accumulation of this pollutant in ambient air and the development of local episodes of urban pollution (Pujadas et al., 2000). This circumstance is reflected in the higher NO_2 attributable mortality found for Alcobendas during the colder seasons. Integrated attributable mortality due to NO_2 concentrations for Alcobendas for the study period was 289 deaths, representing a 3.1% of total attributable mortality due to natural cause for this municipality.

Fig. 6 shows the annual evolution of the two factors that determine the attributable mortality due to NO_2 for the chosen period. Until 2008, the annual average concentration of NO_2 increased, with a mean value around 40 µg m^{-3}, but from that year on it stabilized at lower values, around 30 µg m^{-3}, and even decreased slightly. On the other hand, total mortality due to natural cause normalized to 1000 inhabitants shows a growing trend throughout the period studied, more pronounced as of 2008, which cannot be attributed exclusively to population growth, but probably also to its progressive aging (Fig. 7) and to other influencing factors (Murray et al., 2020).

Clearly, during the period discussed, there has been a progressive increase in the mortality due to natural causes attributed to age groups over 80 years old, which doubled their population in 2019 compared to the value recorded in 2001. Thus, population distribution must therefore be understood as a key factor, determinant of mortality from natural causes and, therefore, of mortality attributable to NO_2 in a specific location.

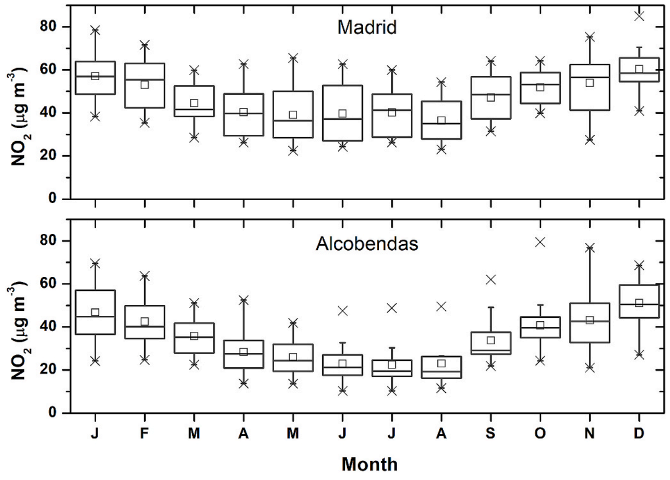


Fig. 4. Box plots for NO_2 concentrations registered by the air quality station at Alcobendas (Air Quality Network of Community of Madrid) and air quality stations at Madrid city (Air Quality Network of Municipality of Madrid) during the period 2001–2019. Box: lower and upper limits are the 25th percentile (Q1) and the 75th percentile (Q3), respectively; median (line); mean (open symbol). Upper/lower bars: the largest/lower observed point from the dataset that falls within the distance of 1.5 times the interquartile range. Cross: maximum and minimum.

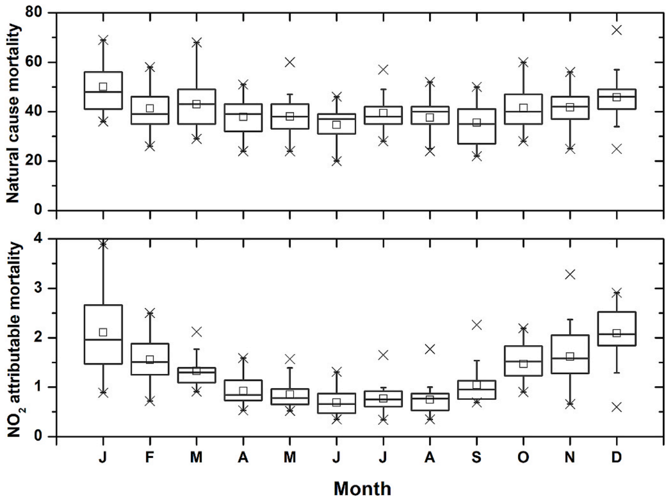


Fig. 5. Upper: Monthly mortality due to natural cause. Lower: Monthly attributable mortality due to NO_2. Box: lower and upper limits are the 25th percentile (Q1) and the 75th percentile (Q3), respectively; median (line); mean (open symbol). Upper/lower bars: the largest/lower observed point from the dataset that falls within the distance of 1.5 times the interquartile range. Cross: maximum and minimum. Figures refer to Alcobendas municipality during the period 2001–2019.

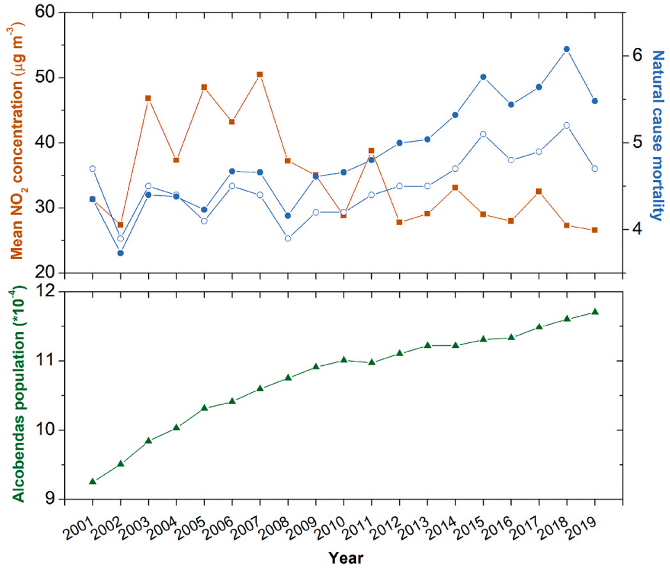


Fig. 6. Upper: Annual mean NO_2 concentration (left axis, square); total mortality due to natural cause*10^{-2} (right axis, solid circle); total mortality due to natural cause per 1000 inhabitants (right axis, open circle). Lower: Alcobendas population (triangle). Data furnished by INE. Figures refer to Alcobendas municipality during the period 2001–2019.

3.3. *Attributable mortality due to NO_2 in an ideal urban scenario*

Considering a 3% reduction in ambient mean NO_2 concentrations due to the hypothetical massive implementation of selected photoactive products on the roadways, sidewalks and facades of Alcobendas city, attributable mortality due to NO_2 concentrations would be 280 deaths. Furthermore, provided that ambient NO_2 values met the 20 µg m^{-3} threshold, a 57% reduction in total number of deaths with respect to that estimated for reference scenario was found (see supplementary material, Table 1). Fig. 8 shows the attributable mortality due to NO_2 concentrations for those latest two cases in which NO_2 concentrations are taken to be reduced with respect to the reference scenario.

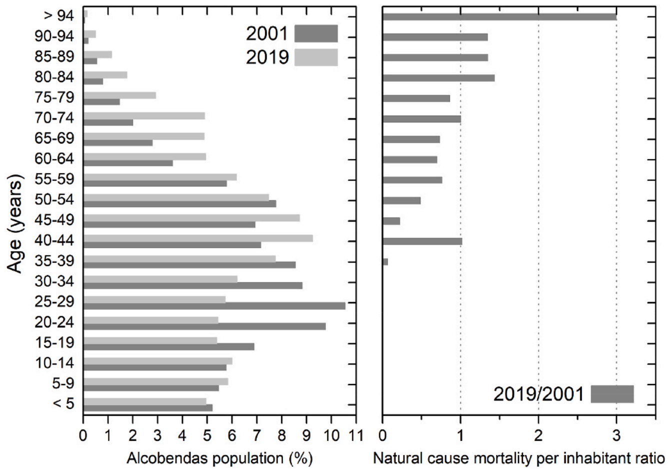


Fig. 7. Age distribution of population in 2001 and 2019 (%) (left) and natural cause mortality per inhabitant ratio 2019 vs. 2001 (right), in Alcobendas.

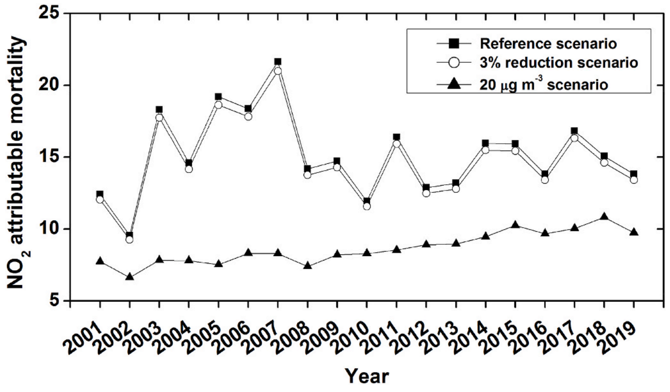


Fig. 8. Attributable mortality due to NO_2 concentrations for Alcobendas during 2001–2019 for the investigated ambient NO_2 reduction scenarios (3% and 20 μg m^{-3} threshold) compared to the reference one.

3.4. *Cost-benefit estimation for the 3% NO_x reduction scenario*

In the course of a NO_x measurement campaign carried out in Alcobendas, traffic volume in the selected stretch of Paseo de la Chopera street was also exhaustively determined on three different days throughout the measurement period (September 29th, October 15th and 22nd, 06:00–17:00 UTC) by using a video camera. An average of 610 ± 113 vehicles h^{-1} was registered at the Paseo de la Chopera. Traffic counts were analysed by category of vehicles (for which passenger cars represents 85.3% of the fleet, with 9% vans, 2% buses, 1.6% trucks and 2.1% motorcycles). An average speed of less than 60 km h^{-1} was found for the 90% of the fleet (data was supplied by the Police of the municipality of Alcobendas) (Fernández-Pampillón et al., 2021). In order to estimate the total NO_x emissions within an area of 1 km^2 around the selected street, an average emission factor for NO_x of 0.544 g $vehicle^{-1}$ km^{-1} (NO_x expressed as NO_2) was used (Ait-Helal et al., 2015). A total length of approximately 8 km was considered taking into account all the main roads enclosed in that area. Finally, a total NO_x emission of 7.1 10^{-7} tonne s^{-1} has been estimated.

The reduction of 3% in the ambient NO_x concentration gives a total of 0.67 tonne NO_x yr^{-1} withdrawn from the atmosphere as a result of the application of the photocatalytic materials. By applying the mentioned damage cost of NO_x from transport, a benefit of 5708 euros yr^{-1} could be derived.

Additionally, the cost for the acquisition and setup of the products selected for their application on roads, sidewalks and facades surfaces within the area of 1 km^2 studied (50000 m^2, 550000 m^2 and 400000 m^2, respectively) (data supplied by municipality of Alcobendas) was estimated. In Table 1, cost of the photocatalytic materials purchase and its application is given. Therefore, a total cost of k€4750.5 can be derived.

Obviously, cleaning should be taken into account in the maintenance costs. However, selected materials do not require additional or different cleaning practices from the usual ones carried out in the municipality, reason why these costs have not been considered in this evaluation.

4. Discussion

The existence of an association between ambient NO_2 and cardiovascular and all-cause mortality has been demonstrated for the population of some Spanish cities (Saez et al., 2002). More recently, Linares et al. (Linares et al., 2018) have updated the impact of daily mean NO_2 concentrations on population mortality at a national level analysing the short-term association between NO_2 concentrations and natural-cause, circulatory-cause and respiratory-cause mortality in all Spanish provinces across the period 2000–2009.

Although the technology implemented in European cities in order to reduce emissions, specially from road traffic, has allowed levels of air pollution to have been progressively decreasing in recent decades (Querol et al., 2014), (Colette and Rouïl, 2020), pollutant sudden increases from their background levels, known as high pollution episodes, continue to occur. These episodes are highly conditioned not only by the intensity of the emissions but also by the highly stable atmospheric conditions produced under specific synoptic meteorological patterns associated with high pressure systems (Artíñano et al., 2003), (Kukkonen et al., 2005), (Reizer and Juda-Rezler, 2016), (Largeron and Staquet, 2016), (Borge et al., 2018). Particularly in the Community of Madrid, these systems, frequently located near the Iberian Peninsula, generate strong atmospheric stability in winter and autumn. And, as a consequence, the development of frequent thermal inversions, with light winds and low turbulent vertical exchange. These conditions give rise to low-dispersion local circulations (Pujadas et al., 2000), (Martilli et al., 2021), (Salvador et al., 2021), (Valverde et al., 2015), that produce episodes, sometimes of several consecutive days, of high NO_2 pollution in urban areas, above of the limit levels established for this pollutant. An analysis of the situation of Alcobendas, taking into account the guideline values for NO_2 levels, across the studied period 2001–2019, has revealed a worrying situation in which mean annual concentrations exceeded the EU annual limit in the 21% of the analysed years. During the months of September to March, the average monthly concentration of NO_2 observed was a factor 1.7 higher than that registered during the period from April to August, due to the different climatic-meteorological (dispersive) and emission conditions (see supplementary material, Table 2).

Given that the susceptibility of the populations to adverse health effects of air pollution may be quite different from one place to another, an adequate choice of dose-response function and appropriate determination of population exposure levels are crucial to quantify the impact of any atmospheric pollutant on health. Spanish values for relative risks calculated for increases of 10 μg m^{-3} in NO_2 levels based on natural cause mortality are in the range from 1.007 (95% CI: 1.005–1.009) to 1.051 (95% CI: 1.016–1.086), showing a wide variability (Linares et al., 2018). In the present study, the relative risk taken for Madrid has been supposed to represent the dose-response function needed to estimate the

Table 1
Materials purchase and application costs of the photocatalytic products selected for their implementation in urban surfaces of the area selected in Alcobendas. Data supplied by the Municipality of Alcobendas (2018).

Cost (€ m^{-2})	Road	Sidewalk	Facade
Material	1.25	1.08	2.38
Application	1.00	4.00	2.23

attributable to NO_2 mortality for Alcobendas, considering that no relevant differences in pollutant mix, concentration levels, disease composition and prevalence levels, and susceptibility of underlying population exist between these two cities.

On the other hand, the seasonal variation factor of total mortality assessed for the coldest versus warmest periods was 1.1 (see supplementary material, Table 3). This fact, together with the variability just mentioned in ambient NO_2 concentrations, is reflected in the annual evolution estimated of the mortality attributable to NO_2 that presents a seasonal variation factor of 2 (see supplementary material, Table 4).

Although a priori the choice of a RR for Alcobendas identical to that for Madrid is reasonable, there are factors that could affect the relationships between observed air pollution and daily mortality (Barceló et al., 2016) that could not be controlled by Linares et al. (Linares et al., 2018). These authors distinguished the effects of NO_2 per se from the modifying effects of PM_{10}, but daily levels of other pollutants such as SO_2 or O_3 were not investigated as possible confounding. Moreover, the effect of certain explanatory variables at the individual level, such as sex, age and residence of the subjects or other confounders such as individual socioeconomic data, lifestyle, and comorbidities, which may differ among people residing in different locations were not considered (Vodonos et al., 2015), (Samoli et al., 2006).

Even when the average daily concentrations of NO_2 were similar for different locations, those mentioned factors will decisively influence daily mortality, so that, for a selected RR, the mortality attributable to NO_2 may differ significantly. In fact, while the annual mean mortality attributable to NO_2 concentrations for Alcobendas during the study period was 1.4 deaths/10000 inhabitants, that corresponding to the city of Madrid was 3.4 deaths/10000 inhabitants. This is due both to the ratio found in the average annual concentration of NO_2 between Madrid and Alcobendas (1.3), and to the fact that the average annual mortality per 10000 inhabitants in Madrid was approximately twice higher than the figure found for Alcobendas (see supplementary material, Table 5).

Concerning the reported efficiency of NO_x reduction on TiO_2-treated surfaces, several field experimental studies have been developed at real scale in outdoor conditions whose results have yielded quite low to non-detectable reductions (IPL, 2010), (TERA environment, 2009), (Gallus et al., 2015a), (Gallus et al., 2015b), (Barratt et al., 2012). Other studies done under unrealistically high S_{active}/V ratios have shown estimated reductions of only ~5% when scaling down to real urban street conditions (Laufs et al., 2010), (Maggos et al., 2008), (Moussiopoulos et al., 2008), (Fraunhofer Institute for Molecular Biology and Applied Ecology, 2009). Similar results (<3%) were found in an urban area of Alcobendas in which a selected photocatalytic TiO_2-based water emulsion was applied on a bituminous pavement (Fernández-Pampillón et al., 2021) in the framework of LIFE $MINO_x$-STREET project. The latest value is in the order of the estimate presented here for the municipality of Alcobendas.

In this study, NO_2 surface deposition velocities utilized to compute the NO_2 potential degradation in Alcobendas have been taken to be equal to NO uptakes estimated for the three selected photoactive materials implemented in this city by using standard 22197–1:2007 test, that applies only for NO remediation. As long as similar uptakes for both NO_x pollutants or even up to one order of magnitude lower for NO_2 have been reported for most studies, this assumption was considered to be valid in order to estimate a maximum NO_2 surface deposition flux. However, the selected NO_2 deposition rate could be obviously overestimated such that if the NO_2 uptake chosen had been an order of magnitude lower, the environmental NO_2 reduction and, consequently the benefits in terms of reduction in mortality due to NO_2 would have decrease, approximately, in the same extent. The evaluation of the NO_2 efficiency in a more realistic way continues to be a research area focused in designing specific laboratory tests that pay special attention to transport phenomena limitations and the NO_2 gas phase relevant photochemistry (Ifang et al., 2014).

Assessing the impact of this technology in the urban air quality has been tackled here by using a first-order kinetic approach that has allowed the estimation of maximum NO_2 expected removal efficiency under particular atmospheric conditions at an urban area. This simplification must be used only when the chosen street behaves as a canyon under specific ambient conditions so that constant air mass flow goes parallel to the longitudinal axis and well-mixed atmospheric situation avoids concentration gradients. Nevertheless, taking into account other atmospheric crucial phenomena, as turbulence or transport limitations, microscale models could be used to better define pollutants dispersion and concentration fields.

It must be emphasized that the estimation of the ambient NO_2 removal capacity of the photocatalytic technology applied to the city of Alcobendas is an ideal upper limit since it has been carried out under optimal conditions (unrealistic) and other factors, which decisively influence the photocatalytic activity, have not been taken into account (orientation of the streets that prevents all urban surfaces from being illuminated simultaneously; width/height relationships of the streets that determine the shadows casted by buildings and obstacles; variation in environmental conditions such as concentration and emission of pollutants, solar irradiance, speed and direction of wind or relative humidity; wetted conditions; aging, soiling or wearing of active areas).

In Alcobendas, the streets of the downtown area, that represent a 7.5% of the whole urban grid (Google Earth Pro tools), have characteristics that would decrease daily photocatalytic activity. They are narrow, which dramatically reduces the potential of the surfaces under consideration to be illuminated. Furthermore, their average S_{active}/V ratio is also low, limiting the heterogeneous NO_2 uptake. In addition, the traffic flow can be increased by the frequent congestions that occur, reducing the potentially active area. Finally, its irregular layout would favour turbulent mixing, reducing the residence time of street air masses and, consequently, their possibility of interaction with photocatalytic surfaces.

Taking into account the low NO_2 removal potential due to the use of TiO_2-based photocatalytic materials in outdoor urban scenarios and that the estimated damage costs potentially saved by the use of this technology could be negligible compared to the expected acquisition and installation costs, this type of strategy alone cannot solve air quality problems. In addition to advance in the research of new photocatalytic materials and new engineering designs, it is key that in those future applications the photocatalytic materials can be used under controlled conditions and with a significant increasing of the S_{active}/V ratio (Huang et al., 2021). Their efficiency should be further investigated in order to determine to what extent their combined use with other abatement measures, targeted to the road traffic sector source and already considered in the urban air quality plans (e. g. definition of low emissions zones, reduction of road capacity and pedestrianized areas in the city centres, renovation of city bus fleets to incorporate clean technologies, promotion of the use of cleaner vehicles and the public transport, etcetera) (Ministry of Agriculture and Fishing and Food and Environment, 2017), (Borge et al., 2018), (Municipality of Madrid, 2019), could contribute achieving the fulfilment of NO_2 air quality standards and noticeably reduce the attributable mortality to NO_2 in urban areas.

5. Conclusions

Within the framework of the European LIFE $MINO_x$-STREET project, the potential usefulness of a variety of commercial photocatalytic materials to act as ambient NO_x sinks when implemented on urban surfaces was evaluated. A wide variety of laboratory-scale experiments were developed in order to select three of the tested materials for their implementation in real urban scenarios in the city of Alcobendas (Community of Madrid). In this work, the results obtained from testing the photocatalytic activity of the selected materials, in outdoor conditions by using a modified standard method, were subsequently utilized to derive the corresponding surface NO_x deposition velocities following a first-order kinetic approximation.

Realistic NO_x surface deposition velocities are essential in order to assess which could be the ambient effect on pollution levels if photocatalytic materials were applied in a particular area or, furthermore, to model the foreseen effects if such materials were implemented in a whole city. Particularly, when upper limit photocatalytic NO_x-degradation was estimated in an urban main street canyon of Alcobendas, based on the NO_x deposition velocities obtained in the present study under optimal ambient conditions, a reduction of only a few per cent was found (3%).

The application to the municipality of Alcobendas of the dose-response function relating NO_2 ambient concentrations and associated mortality for Madrid city, has allowed estimating the mortality attributable to that pollutant in that municipality over an extended period. A marked seasonal dependence has been observed, function of both the climatic-meteorological and air pollutant emission conditions with a minimum in NO_2-attributable mortality in the spring-summer period.

For a more precise study of the benefit that the implementation of the mentioned technology would have in Alcobendas in terms of deaths avoided, it would be necessary to have an individualized estimate of the RR for the municipality and, in addition to the explanatory variables considered in the proposed methodology, it would be necessary to consider other factors as relevant as the characteristics of the distribution of the population and socioeconomic conditions.

Finally, the cost-benefit evaluation associated with the application of photocatalytic materials in Alcobendas yields results that question the profitability of using this technology as a NO_2 depolluting strategy, with the relative cost of acquisition and implementation notably higher than the savings derived from the maximum potential decrease in the calculated atmospheric NO_2 concentration. Additionally, and although it falls outside the scope of this work, it would be highly recommended to carry out a comparative analysis, in terms of both efficiency and cost-benefit balance, of this strategy with other NO_2 remediation options included in urban air quality plans. And, subsequently, to analyse their complementarity and to efficiently help air quality managers to protect the population, specially in particularly sensitive areas.

Credit author statement

Jaime Fernández-Pampillón: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. Magdalena Palacios: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. Lourdes Núñez: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. Manuel Pujadas: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision. Begoña Artíñano: Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This study has been supported by LIFE MINO$_x$-STREET project (LIFE12 ENV/ES/000280) funded by European Commission. We would also like to greatly acknowledge the assistance and useful suggestions of Julio Díaz and Cristina Linares from the Carlos III Institute of Health (Madrid, Spain).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.121203.

References

Ahmad, R., Ahmad, Z., Khan, A.U., Mastoi, N.R., Aslam, M., Kim, J., 2016. Photocatalytic systems as an advanced environmental remediation: recent developments, limitations and new avenues for applications. J. Environ. Chem. Eng. 4 (4), 4143–4164. https://doi.org/10.1016/j.jece.2016.09.009.

Air Quality Expert Group of the Department for Environment Food and Rural Affairs (DEFRA), 2016. Paints and Surfaces for the Removal of Nitrogen Oxides.

Ait-Helal, W., Beeldens, A., Boonen, E., Borbon, A., Boréave, A., Cazaunau, M., Chen, H., Daële, V., Dupart, Y., Gaimoz, C., Gallus, M., George, C., Grand, N., Grosselin, B., Herrmann, H., Ifang, S., Kurtenbach, R., Maille, M., Marjanovic, I., Mellouki, A., Miet, K., Mothes, F., Poulain, L., Rabe, R., Zapf, P., Kleffmann, J., Doussin, J.F., 2015. On-road measurements of NMVOCs and NOx: determination of light-duty vehicles emission factors from tunnel studies in Brussels city center. Atmos. Environ. 122, 799–807. https://doi.org/10.1016/J.ATMOSENV.2015.09.066.

Ângelo, J., Andrade, L., Madeira, L.M., Mendes, A., 2013. An overview of photocatalysis phenomena applied to NOx abatement. J. Environ. Manag. 129, 522–539. https://doi.org/10.1016/j.jenvman.2013.08.006.

Ângelo, J., Andrade, L., Mendes, A., 2014. Highly active photocatalytic paint for NOx abatement under real-outdoor conditions. Appl. Catal. Gen. 484, 17–25. https://doi.org/10.1016/j.apcata.2014.07.005.

Artíñano, B., Salvador, P., Alonso, D.G., Querol, X., Alastuey, A., 2003. Anthropogenic and natural influence on the PM_{10} and $PM_{2.5}$ aerosol in Madrid (Spain). Analysis of high concentration episodes. Environ. Pollut. 125 (3), 453–465. https://doi.org/10.1016/S0269-7491(03)00078-2.

Ballari, M.M., Brouwers, H.J.H., 2013. Full scale demonstration of air-purifying pavement. J. Hazard Mater. 254 (255), 406–414. https://doi.org/10.1016/j.jhazmat.2013.02.012.

Ballari, M.M., Hunger, M., Hüsken, G., Brouwers, H.J.H., 2010. Modelling and experimental study of the NOx photocatalytic degradation employing concrete pavement with titanium dioxide. Catal. Today 151 (1), 71–76. https://doi.org/10.1016/j.cattod.2010.03.042.

Ballari, M.M., Yu, Q.L., Brouwers, H.J.H., 2011. Experimental study of the NO and NO_2 degradation by photocatalytically active concrete. Catal. Today 161 (1), 175–180. https://doi.org/10.1016/j.cattod.2010.09.028.

Barceló, M.A., Varga, D., Tobias, A., Diaz, J., Linares, C., Saez, M., 2016. Long term effects of traffic noise on mortality in the city of Barcelona, 2004–2007. Environ. Res. 147, 193–206. https://doi.org/10.1016/j.envres.2016.02.010.

Barratt, B., Carslaw, D., Green, D., 2012. High Holborn D-NOx Paint Trial – Report 3 (Updated).

Bengtsson, N., Castellote, M., 2010. Photocatalytic activity for NO degradation by construction materials: parametric study and multivariable correlations. J. Adv. Oxid. Technol. 13 (3), 341–349. https://doi.org/10.1515/jaots-2010-0311.

Boonen, E., Beeldens, A., 2014. Recent photocatalytic applications for air purification in Belgium. Coatings 4 (3), 553–573. https://doi.org/10.3390/coatings4030553.

Borge, R., de Miguel, I., de la Paz, D., Lumbreras, J., Pérez, J., Rodríguez, E., 2012. Comparison of road traffic emission models in Madrid (Spain). Atmos. Environ. 62, 461–471. https://doi.org/10.1016/j.atmosenv.2012.08.073.

Borge, R., Lumbreras, J., Pérez, J., de la Paz, D., Vedrenne, M., de Andrés, J.M., Rodríguez, M.E., 2014. Emission inventories and modeling requirements for the development of air quality plans. Application to Madrid (Spain). Sci. Total Environ. 466 (467), 809–819. https://doi.org/10.1016/j.scitotenv.2013.07.093.

Borge, R., Artíñano, B., Yagüe, C., Gomez-Moreno, F.J., Saiz-Lopez, A., Sastre, M., Narros, A., García-Nieto, D., Benavent, N., Maqueda, G., Barreiro, M., de Andrés, J. M., Cristóbal, Á., 2018. Application of a short term air quality action plan in Madrid (Spain) under a high-pollution episode - Part I: diagnostic and analysis from observations. Sci. Total Environ. 635, 1561–1573. https://doi.org/10.1016/j.scitotenv.2018.03.149.

Carslaw, D.C., Beevers, S.D., Bell, M.C., 2007. Risks of exceeding the hourly EU limit value for nitrogen dioxide resulting from increased road transport emissions of primary nitrogen dioxide. Atmos. Environ. 41 (10), 2073–2082. https://doi.org/10.1016/j.atmosenv.2006.10.074.

Chen, M., Chu, J.W., 2011. NOx photocatalytic degradation on active concrete road surface - from experiment to real-scale application. J. Clean. Prod. 19, 1266–1272. https://doi.org/10.1016/j.jclepro.2011.03.001.

Colette, A., Rouïl, L., 2020. Air Quality Trends in Europe: 2000-2017. Assessment for Surface SO_2, NO_2, Ozone, PM_{10} and $PM_{2.5}$. Eionet Report - ETC/ATNI 2019/16. https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-16-2019-air-quality-trends-in-europe-2000-2017-assessment-for-surface-so2-no2-ozone-pm10-and-pm2-5-1/@@download/file/ETC-ATNI. Last accessed: February, 2023.

Chen, R., Yin, P., Meng, X., Wang, L., Liu, C., Niu, Y., Lin, Z., Liu, Y., Liu, J., Qi, J., You, J., Kan, H., Zhou, M., 2018. Associations between ambient nitrogen dioxide and daily cause-specific mortality. Epidemiology 29 (4), 482–489. https://doi.org/10.1097/EDE.0000000000000829.

Community of Madrid, 2021. Statisticians of the Air Quality Network of Community of Madrid (2007-2021). http://gestiona.madrid.org/azul_internet/run/j/InformEvaluacionAccion.icm?ESTADO_MENU=7. Last accessed: February, 2023.

Cordero, J.M., Hingorani, R., Jimenez-Relinque, E., Grande, M., Cutillas, F., Martinez, E., Borge, R., Narros, A., Castellote, M., 2021. Challenges in quantification of photocatalytic NO_2 abatement effectiveness under real world exposure conditions illustrated by a case study. Sci. Total Environ. 766, 144393. https://doi.org/10.1016/j.scitotenv.2020.144393.

Coste, J., Spira, A., 1991. La proportion de cas attribuable en santé publique: définition (s), estimation(s) et interprétation. Rev. Epidemiol. Sante Publique 39 (4), 399–411.

de Melo, J.V.S., Trichês, G., 2012. Evaluation of the influence of environmental conditions on the efficiency of photocatalytic coatings in the degradation of nitrogen oxides (NOx). Build. Environ. 49, 117–123. https://doi.org/10.1016/j.buildenv.2011.09.016.

Díaz, J., García, R., Ribera, P., Alberdi, J.C., Hernández, E., Pajares, M.S., Otero, A., 1999. Modeling of air pollution and its relationship with mortality and morbidity in Madrid, Spain. Int. Arch. Occup. Environ. Health 72 (6), 366–376. https://doi.org/10.1007/s004200050388.

Dillert, R., Engel, A., Große, J., Lindner, P., Bahnemann, D.W., 2013. Light intensity dependence of the kinetics of the photocatalytic oxidation of nitrogen(II) oxide at the surface of TiO_2. Phys. Chem. Chem. Phys. 15, 20876–20886. https://doi.org/10.1039/c3cp54469a.

Engel, A., Glyk, A., Hülsewig, A., Große, J., Dillert, R., Bahnemann, D.W., 2015. Determination of the photocatalytic deposition velocity. Chem. Eng. J. 261, 88–94. https://doi.org/10.1016/j.cej.2014.03.040.

Environmental Protection Agency, 2016. Integrated Science Assessment for Oxides of Nitrogen - Health Criteria (Final Report). EPA/, Washington, D.C.. https://www.epa.gov/isa/integrated-science-assessment-isa-oxides-nitrogen-health-criteria. Last accessed: February, 2023.

Fernández-Pampillón, J., Palacios, M., Núñez, L., Pujadas, M., Sanchez, B., Santiago, J.L., Martilli, A., 2021. NOx depolluting performance of photocatalytic materials in an urban area – Part I: monitoring ambient impact. Atmos. Environ. 251, 118190. https://doi.org/10.1016/j.atmosenv.2021.118190.

Essen, H., Fiorello, D., El Beyrouty, K., Bieler, C., Wijngaarden, L., Schroten, A., Parolin, R., Brambilla, M., Sutter, D., Maffii, S., Fermi, F., 2020. Handbook on the external cost of transport: Version 2019 - 1.1. European Commission - Directorate General for Mobility and Transport. Publications Office. https://data.europa.eu/doi/10.2832/51388.

European Commission, 2023. MonItoring and Modelling NOx Removal Efficiency of Photocatalytic Materials: A STRategy for Urban Air Quality managEmEnT. https://webgate.ec.europa.eu/life/publicWebsite/index.cfm?fuseaction=search.dspPage&n_proj_id=4673. Last accessed: February, 2023.

European Environment Agency, 2021. Air Quality in Europe 2021 Report. https://www.eea.europa.eu/publications/air-quality-in-europe-2021. Last accessed: February, 2023.

Fraunhofer Institute for Molecular Biology and Applied Ecology, 2009. . https://www.ime.fraunhofer.de/content/dam/ime/de/documents/Publikationen/Fraunhofer_IME_Annual_Report_2009_2010.pdf.

Gallus, M., Akylas, V., Barmpas, F., Beeldens, A., Boonen, E., Boréave, A., Cazaunau, M., Chen, H., Daële, V., Doussin, J.F., Dupart, Y., Gaimoz, C., George, C., Grosselin, B., Herrmann, H., Ifang, S., Kurtenbach, R., Maille, M., Mellouki, A., Miet, K., Mothes, F., Moussiopoulos, N., Poulain, L., Rabe, R., Zapf, P., Kleffmann, J., 2015a. Photocatalytic de-pollution in the Leopold II tunnel in Brussels: NOx abatement results. Build. Environ. 84, 125–133. https://doi.org/10.1016/j.buildenv.2014.10.032.

Gallus, M., Ciuraru, R.Ciuraru, Mothes, F., Akylas, V., Barmpas, F., Beeldens, A., Bernard, F., Boonen, E., Boréave, A., Cazaunau, M., Charbonnel, N., Chen, H., Daële, V., Dupart, Y., Gaimoz, C., Grosselin, B., Herrmann, H., Ifang, S., Kurtenbach, R., Maille, M., Marjanovic, I., Michoud, V., Mellouki, A., Miet, K., Moussiopoulos, N., Poulain, L., Zapf, P., George, C., Doussin, J.F., Kleffmann, J., 2015b. Photocatalytic abatement results from a model street canyon. Environ. Sci. Pollut. Res. 22, 18185–18196. https://doi.org/10.1007/s11356-015-4926-4.

Guerrini, G.I., Peccati, E., 2007. Photocatalytic cementitious roads for depollution. In: International RILEM Symposium on Photocatalysis. Environment and Construction Materials, pp. 179–186.

Health Effects Institute, 2020. State of Global Air 2020. Special Report, Boston, MA. https://www.stateofglobalair.org/sites/default/files/documents/2022-09/soga-2020-report.pdf.

Herrmann, J.-M., 2010. Photocatalysis fundamentals revisited to avoid several misconceptions. Appl. Catal. B Environ. 99 (3), 461–468. https://doi.org/10.1016/j.apcatb.2010.05.012.

Huang, M.H., Huang, Y., Cao, J.J., Tao, W.Q., 2021. Study on mitigation of automobile exhaust pollution in an urban street canyon: emission reduction and air cleaning street lamps. Build. Environ. 193, 107651 https://doi.org/10.1016/j.buildenv.2021.107651.

Ifang, S., Gallus, M., Liedtke, S., Kurtenbach, R., Wiesen, P., Kleffmann, J., 2014. Standardization methods for testing photo-catalytic air remediation materials: problems and solution. Atmos. Environ. 91, 154–161. https://doi.org/10.1016/j.atmosenv.2014.04.001.

IPL, 2010. Dutch Air Quality Innovation Programme concluded. Improved Air Quality with Coating of Titanium Dioxide Not Demonstrated. https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/TR010019/TR010019-002594-Dutch%20Air%20Quality%20Innovation%20Programme%20concluded.pdf.

Fine Ceramics (Advanced Ceramics, Advanced Technical Ceramics)—Test Method for Air-Purification Performance of Semiconducting Photocatalytic Materials—Part 1 : Removal of Nitric Oxide, 2007. ISO 22197-1.

Kukkonen, J., Pohjola, M., Sokhi, R.S., Luhana, L., Kitwiroon, N., Fragkou, L., Rantamäki, M., Berge, E., Ødegaard, V., Håvard Slørdal, L., Denby, B., Finardi, S., Oslo, 2005. Atmos. Environ. 39 (15), 2759–2773. https://doi.org/10.1016/j.atmosenv.2004.09.090.

Karapati, S., Giannakopoulou, T., Todorova, N., Boukos, N., Antiohos, S., Papageorgiou, D., Chaniotakis, E., Dimotikali, D., Trapalis, C., 2014. TiO_2 functionalization for efficient NOx removal in photoactive cement. Appl. Surf. Sci. 319, 29–36. https://doi.org/10.1016/j.apsusc.2014.07.162.

Kurtenbach, R., Kleffmann, J., Niedojadlo, A., Wiesen, P., 2012. Primary NO_2 emissions and their impact on air quality in traffic environments in Germany. Environ. Sci. Eur. 24 (1), 21. https://doi.org/10.1186/2190-4715-24-21.

Largeron, Y., Staquet, C., 2016. Persistent inversion dynamics and wintertime PM_{10} air pollution in Alpine valleys. Atmos. Environ. 135, 92–108. https://doi.org/10.1016/j.atmosenv.2016.03.045.

Laufs, S., Burgeth, G., Duttlinger, W., Kurtenbach, R., Maban, M., Thomas, C., Wiesen, P., Kleffmann, J., 2010. Conversion of nitrogen oxides on commercial photocatalytic dispersion paints. Atmos. Environ. 44 (19), 2341–2349. https://doi.org/10.1016/j.atmosenv.2010.03.038.

Linares, C., Falcón, I., Ortiz, C., Díaz, J., 2018. An approach estimating the short-term effect of NO_2 on daily mortality in Spanish cities. Environ. Int. 116, 18–28. https://doi.org/10.1016/j.envint.2018.04.002.

Maggos, T., Plassais, A., Bartzis, J.G., Vasilakos, C., Moussiopoulos, N., Bonafous, L., 2008. Photocatalytic degradation of NOx in a pilot street canyon configuration using TiO_2-mortar panels. Environ. Monit. Assess. 136 (1), 35–44. https://doi.org/10.1007/s10661-007-9722-2.

Martilli, A., Sanchez, B., Rasilla, D., Pappaccogli, G., Allende, F., Martin, F., Román-Cascón, C., Yagüe, C., Fernandez, F., 2021. Simulating the meteorology during persistent Wintertime Thermal Inversions over urban areas. The case of Madrid. Atmos. Res. 263, 105789. https://doi.org/10.1016/j.atmosres.2021.105789.

Martín, F., Palacios, M., Crespí, S.N., 2001. Simulations of mesoscale circulations in the centre of the Iberian Peninsula for thermal low pressure conditions. Part II: Air parcel transport patterns. J. Appl. Meteorol. Climatol. 40 (5), 905–914. https://journals.ametsoc.org/view/journals/apme/40/5/1520-0450_2001_040_0905_somcit_2.0.co_2.xml?tab_body=fulltext-display.

Martinez, T., Bertron, A., Ringot, E., Escadeillas, G., 2011. Degradation of NO using photocatalytic coatings applied to different substrates. Build. Environ. 46 (9), 1808–1816. https://doi.org/10.1016/j.buildenv.2011.03.001.

Mendoza, C., Valle, A., Castellote, M., Bahamonde, A., Faraldos, M., 2015. TiO_2 and TiO_2–SiO_2 coated cement: comparison of mechanic and photocatalytic properties. Appl. Catal. B Environ. 178, 155–164. https://doi.org/10.1016/j.apcatb.2014.09.079.

Mills, A., Burns, L., O'Rourke, C., Elouali, S., 2016. Kinetics of the photocatalysed oxidation of NO in the ISO 22197 reactor. J. Photochem. Photobiol. Chem. 321, 137–142. https://doi.org/10.1016/j.jphotochem.2016.01.010.

Izquierdo, R., García Dos Santos, S., Borge, R., de la Paz, D., Sarigiannis, D., Gotti, A., Boldo, E., 2020. Health impact assessment by the implementation of Madrid City air quality plan in 2020. Environ. Res. 183, 109021. https://doi.org/10.1016/j.envres.2019.109021.

Ministry of Agriculture and Fishing and Food and Environment, 2017. Plan Nacional de Calidad del AIRE 2017-2019 (Plan Aire II). https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/planaire2017-2019_tcm30-436347.pdf.

Monge, M.E., D'Anna, B., George, C., 2010. Nitrogen dioxide removal and nitrous acid formation on titanium oxide surfaces-an air quality remediation process? Phys. Chem. Chem. Phys. 12, 8991–8998. https://doi.org/10.1039/b925785c.

Mothes, F., Ifang, S., Gallus, M., Golly, B., Boréave, A., Kurtenbach, R., Kleffmann, J., George, C., Herrmann, H., 2018. Bed flow photoreactor experiments to assess the photocatalytic nitrogen oxides abatement under simulated atmospheric conditions. Appl. Catal. B Environ. 231, 161–172. https://doi.org/10.1016/j.apcatb.2018.03.010.

Mothes, F., Böge, O., Herrmann, H., 2016. A chamber study on the reactions of O_3, NO, NO_2 and selected VOCs with a photocatalytically active cementitious coating material. Environ. Sci. Pollut. Res. 23, 15250–15261. https://doi.org/10.1007/s11356-016-6612-6.

Moussiopoulos, N., Barmpas, P., Ossanlis, I., Bartzis, J., 2008. Comparison of numerical and experimental results for the evaluation of the depollution effectiveness of photocatalytic coverings in street canyons. Environ. Model. Assess. 13 (3), 357–368. https://doi.org/10.1007/s10666-007-9098-2.

Plan A: Air quality and climate change plan for the city of Madrid, 2017. https://www.madrid.es/UnidadesDescentralizadas/Sostenibilidad/CalidadAire/Ficheros/PlanAire&CC_Eng.pdf.

Madrid 360. Avance de la estrategia de sostenibilidad ambiental, 2019. https://madrid360.es/wp-content/uploads/2021/09/Avance-Estrategia-Sostenibilidad-Ambiental-Madrid-360_baja.pdf.

Murray, C.J.L., 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 396 (10258), 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2.

Ochiai, T., Fujishima, A., 2012. Photoelectrochemical properties of TiO_2 photocatalyst and its applications for environmental purification. J. Photochem. Photobiol. C: Photochem. Rev. 13 (4), 247–262. https://doi.org/10.1016/j.jphotochemrev.2012.07.001.

Orellano, P., Reynoso, J., Quaranta, N., Bardach, A., Ciapponi, A., 2020. Short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ozone

(O_3) and all-cause and cause-specific mortality: systematic review and meta-analysis. Environ. Int. 142, 105876 https://doi.org/10.1016/j.envint.2020.105876.

Ortiz, C., Linares, C., Carmona, R., Díaz, J., 2017. Evaluation of short-term mortality attributable to particulate matter pollution in Spain. Environ. Pollut. 224, 541–551. https://doi.org/10.1016/j.envpol.2017.02.037.

Palacios, M., Martin, F., Cabal, H., 2001. Methodologies for estimating disaggregated anthropogenic emissions—application to a coastal mediterranean region of Spain. J. Air Waste Manage. Assoc. 51 (5), 642–657.. https://doi.org/10.1080/10473289.2001.10464305.

Palacios, M., Kirchner, F., Martilli, A., Clappier, A., Martín, F., Rodríguez, M.E., 2002. Summer ozone episodes in the Greater Madrid area. Analyzing the ozone response to abatement strategies by modelling. Atmos. Environ. 36 (34), 5323–5333. https://doi.org/10.1016/S1352-2310(02)00590-3.

Palacios, M., Palacios, M., Núñez, L., Fernández-Pampillón, J., Germán, M., Sánchez, B. S., Santiago, J.L., Martilli, A., Suárez, S., Cabrero, B.S., 2015a. Estimation of NOx deposition velocities for selected commercial photocatalytic products. WIT Trans. Built Environ. 168, 729–740. https://www.witpress.com/elibrary/wit-transactions-on-the-built-environment/168/34810.

Palacios, M., Núñez, L., Pujadas, M., Suárez, S., Sánchez, B., Gómez-Mancebo, M.B., Fernández-Pampillón, J., Mazarío-Fernández, A., Moral, F., Pérez, J., 2015b. Durability of a photocatalytic coating on a bituminous pavement. In: Proceedings of the International Conference on Sustainable Materials and Science Technology, p. 213.

Palacios, M., Palacios, M., Núñez, L., Suárez, S., Pujadas, M., Sánchez, B., Pujadas, M., Fernández-Pampillón, J., 2015c. Selection of commercial photocatalytic materials based on their air-purifying ability. In: Proceedings of the International Conference on Sustainable Materials and Science Technology, p. 231.

Palacios, M., Núñez, L., Pujadas, M., Fernández-Pampillón, J., Fernández, J.M., Sanchez, B.S., Santiago, J.L., Martilli, A., Cabrero, B.S., Suárez, S., Martínez, C., Vilanova, O., Simón, G., Matesanz, R., Gilaranz, J., Gómez-Mancebo, M.B., Fernández, M., Arias, G., Muñoz, R., Iglesias, J.D., Moral, F., Pérez, J., Cadavid, B., Marrón, J.O., Moral, A., Sánchez, M., Pazo, G., Caballero, G., Seisdedos, B., de la Fuente, J.C., Balsells, I., Mazarío-Fernández, A., 2018. LIFE MINO$_x$-STREET project. FuturEnviro 50, 93–96.

Palacios, M., Suárez, S., Núñez, L., Sánchez, B., Pujadas, M., Fernández-Pampillón, J., 2015d. Influence of parameters on the photocatalytic oxidation of nitric oxide at the surface of titanium dioxide-modified concrete materials. In: Proceedings of the International Conference on Chemical and Biochemical Engineering, p. 294.

Palacios, M., Suárez, S., Núñez, L., Sánchez, B., Pujadas, M., Fernández-Pampillón, J., 2015e. NOx photocatalytic degradation employing concrete surfaces with titanium dioxide. In: Proceedings of the International Conference on Chemical and Biochemical Engineering, p. 258.

Pujadas, M., Plaza, J., Terés, J., Artíñano, B., Millán, M., 2000. Passive remote sensing of nitrogen dioxide as a tool for tracking air pollution in urban areas: the Madrid urban plume, a case of study. Atmos. Environ. 34 (19), 3041–3056. https://doi.org/10.1016/S1352-2310(99)00509-9.

Ministry for the Ecological Transition and the Demographic Challenge, 2022. Datos Calidad del Aire 2001-2019. https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/atmosfera-y-calidad-del-aire/calidad-del-aire/evaluacion-datos/datos/Datos_2001_2019.aspx. Last accessed: February, 2023.

Pujadas, M., Palacios, M., Núñez, L., Germán, M., Fernández-Pampillón, J., Iglesias, J.D., Santiago, J.L., 2016. Real scale demonstration of the depolluting capabilities of a photocatalytic pavement in a real urban area. In: Proceedings of the 17th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, pp. 197–201. In: https://www.harmo.org/Conferences/Proceedings/_Budapest/publishedSections/H17-090.pdf.

Querol, X., Alastuey, A., Pandolfi, M., Reche, C., Pérez, N., Minguillón, M.C., Moreno, T., Viana, M., Escudero, M., Orio, A., Pallarés, M., Reina, F., 2014. 2001–2012. trends on air quality in Spain. Sci. Total Environ. 490, 957–969. https://doi.org/10.1016/j.scitotenv.2014.05.074.

Reizer, M., Juda-Rezler, K., 2016. Explaining the high PM_{10} concentrations observed in Polish urban areas. Air Qual. Atmos. Heal. 9 (5), 517–531. https://doi.org/10.1007/s11869-015-0358-z.

Saez, M., Ballester, F., Barceló, M.A., Pérez-Hoyos, S., Bellido, J., Tenías, J.M., Ocaña, R., Figueiras, A., Arribas, F., Aragonés, N., Tobías, A., Cirera, L., Cañada, A., 2002. A combined analysis of the short-term effects of photochemical air pollutants on mortality within the EMECAM project. Environ. Health Perspect. 110 (3), 221–228. https://doi.org/10.1289/ehp.02110221.

Salvador, P., Barreiro, M., Gómez-Moreno, F.J., Alonso-Blanco, E., Artíñano, B., 2021. Synoptic classification of meteorological patterns and their impact on air pollution episodes and new particle formation processes in a south European air basin. Atmos. Environ. 245, 118016 https://doi.org/10.1016/j.atmosenv.2020.118016.

Samoli, E., Aga, E., Touloumi, G., Nisiotis, K., Forsberg, B., Lefranc, A., Pekkanen, J., Wojtyniak, B., Schindler, C., Niciu, E., Brunstein, R., Dodič Fikfak, M., Schwartz, J., Katsouyanni, K., 2006. Short-term effects of nitrogen dioxide on mortality: an analysis within the APHEA project. Eur. Respir. J. 27 (6), 1129–1138. https://doi.org/10.1183/09031936.06.00143905.

Schneider, A., Cyrys, J., Breitner, S., Kraus, U., Peters, A., Diegmann, V., Neunhäuserer, L., 2018. Quantifizierung von umweltbedingten Krankheitslasten aufgrund der Stickstoffdioxid-Exposition in Deutschland. Umwelt & Gesundheit 1, 172. https://www.umweltbundesamt.de/sites/default/files/medien/421/publikationen/abschlussbericht_no2_krankheitslast_final_2018_03_05.pdf.

Sikkema, J.K., Ong, S.K., Alleman, J.E., 2015. Photocatalytic concrete pavements: laboratory investigation of NO oxidation rate under varied environmental conditions. Construct. Build. Mater. 100, 305–314. https://doi.org/10.1016/j.conbuildmat.2015.10.005.

Statistics National Institute, 2023. Población por municipios y sexo. https://www.ine.es/jaxiT3/Datos.htm?t=2881. Last accessed: February, 2023.

TERA environment, 2009. In Situ Study of the Air Pollution Mitigating Properties of Photocatalytic Coating, Tera Environment. Rep. from ADEME Rhone-Alpes Reg. Fr. (Contract number 0941C0978). https://www.atmo-auvergnerhonealpes.fr/sites/aura/files/content/migrated/publications_import/files/ecocoating_rapport_final.pdf

Tobías, A., Recio, A., Díaz, J., Linares, C., 2015. Health impact assessment of traffic noise in Madrid (Spain). Environ. Res. 137, 136–140. https://doi.org/10.1016/j.envres.2014.12.011.

Valverde, V., Pay, M.T., Baldasano, J.M., 2015. Circulation-type classification derived on a climatic basis to study air quality dynamics over the Iberian Peninsula. Int. J. Climatol. 35 (10), 2877–2897.. https://doi.org/10.1002/joc.4179.

VDI, 2006. Environmental Meteorology, Atmospheric Dispersion Models, Deposition. VDI 3782, Part 5. VDI/DIN Clean Air Manual, Volume 1b.

Vedrenne, M., Borge, R., Lumbreras, J., Conlan, B., Rodríguez, M.E., de Andrés, J.M., de la Paz, D., Pérez, J., Narros, A., 2015. An integrated assessment of two decades of air pollution policy making in Spain: impacts, costs and improvements. Sci. Total Environ. 527 (528), 351–361. https://doi.org/10.1016/j.scitotenv.2015.05.014.

Vodonos, A., Friger, M., Katra, I., Krasnov, H., Zahger, D., Schwartz, J., Novack, V., 2015. Individual effect modifiers of dust exposure effect on cardiovascular morbidity. PLoS One 10 (9), e0137714. https://doi.org/10.1371/journal.pone.0137714.

World Health Organization, 2013a. Review of evidence on health aspects of air pollution – REVIHAAP Project: Technical Report. https://www.euro.who.int/_data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf.

World Health Organization, 2013b. Health Risks of Air Pollution in Europe – HRAPIE Project. http://www.euro.who.int/_data/assets/pdf_file/0006/238956/Health_risks_air_pollution_HRAPIE_project.pdf?ua=1.

World Health Organization, 2016. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. https://apps.who.int/iris/bitstream/handle/10665/250141/9789241511353-eng.pdf?sequence=1&isAllowed=y.

World Health Organization, 2021. WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf?sequence=1&isAllowed=y.

Zouzelka, R., Rathousky, J., 2017. Photocatalytic abatement of NOx pollutants in the air using commercial functional coating with porous morphology. Appl. Catal. B Environ. 217, 466–476. https://doi.org/10.1016/j.apcatb.2017.06.009.