Air quality: advances and best practices

New opportunities in the face of a systemic challenge

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Production method

Reports C are brief documents on subjects chosen by the Bureau of the Congress of Deputies that contextualise and summarise the available scientific evidence on the analysed subject. They also inform about areas of agreement, disagreement, unknowns, and ongoing discussions. The preparation process for these reports is based on an exhaustive bibliographical review, complemented with interviews of experts in the field who subsequently conduct two review rounds of the text. Oficina C conducts this process in collaboration with the management team of the Spanish Parliament's Lower House Documentation, Library and Archive service.

To produce this report the Oficina C referenced 530 documents and consulted 21 experts in the subject. Of this multi-disciplinary group, 43% of the experts were from the field of life sciences (medicine, geology, chemistry, chemistry, biology, environmental sciences and engineering), 48% from physical sciences and engineering (chemical, industrial, environmental and civil engineering, physics) and 10% from social sciences (sociology, political sciences and public administration). 57% work in Spanish institutions or centres, whereas 43 % have affiliations with at least one institution outside Spain..

Oficina C is the editorial supervisor of this report.

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Summary C

The report in 5 minutes

Relevance

The loss of air quality derived from atmospheric pollution is one of the main public health problems facing Europe and Spain. Scientific evidence highlights the serious impact of air quality on human health, the environment and the economy, which has an unequal effect on the population. The general public has expressed concern about this threat but, in most cases, people have limited options to protect themselves. The last decade has seen a wide range of public policies, in Spain and Europe, aimed at reducing atmospheric pollution and its adverse effects. Such policies can be a useful tool, as the progressive improvement of air quality in Spain and other EU countries shows but, based on the evidence available, they are insufficient. The European Union highlights this and is currently working on modifying and improving the regulatory framework.

This report offers an overview of the status, impact and main challenges facing ambient air quality in the Spanish context and covers the main mitigation strategies that could bring about improvements in the different areas that constitute the wide-ranging intersectionality of this challenge.

Air quality

The pollutants that determine air quality are legally defined. These pollutants or their precursors are released into the atmosphere due to daily activities. The major sources include road traffic and transport, the residential, commercial and institutional sectors, energy production, industrial and agricultural and livestock farming activities, and waste management.

Among the multiple pollutants that define air quality, suspended fine particulate matter, followed by nitrogen dioxide and ozone are those that cause the most adverse effects on human health. In Spain, as in other European countries, they reduce life expectancy and they are responsible for some 17,000, 4,800 and 2,400 premature deaths, respectively, each year. They also increase morbidity because they cause cancer and worsen or cause many other diseases. The people most affected are minors, older people and those in situations of socioeconomic disadvantage, which heightens social inequality. Due to its phytotoxic nature, bad air quality also implies a loss of biodiversity, since these pollutants can alter ecosystems, for instance, by means of processes such as eutrophication. This is particularly the case for nitrogen oxides, sulphur, ammonia and ozone. The estimated economic impact by 2030 is calculated to be between 40,000 and 50,000 million euros, although there are many limitations and difficulties when it comes to quantifying these figures.

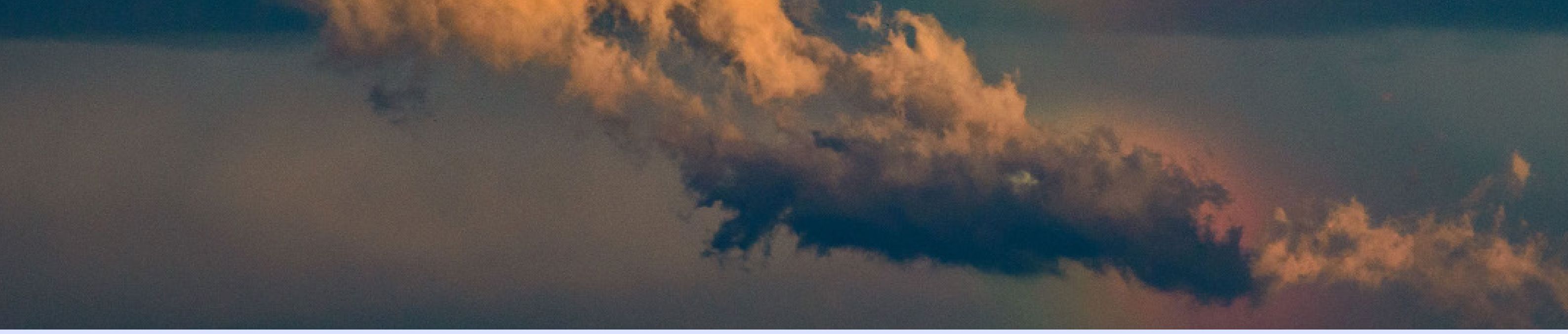
Air quality management is based on a regulatory framework that defines legally acceptable conditions and long-term objectives as well as a system for monitoring the status and evolution of air quality that assesses risk and degrees of compliance. The legal framework determines the presence or acceptable levels of each pollutant in the air. On the other hand, it sets out progressive reductions for emissions until 2030. Working towards emissions ceilings is based on strategic policies that define actions designed to achieve the reduction objectives established for each sector, from road traffic and transport, or the residential, commercial and institutional sectors to the energy, industrial and agricultural sectors, among others. In terms of monitoring, a set of networks monitor the presence of pollutants using various measurements. In addition, air quality models are employed for monitoring, which also enable future projections. The Spanish network meets the requirements of EU directives and is in line with international standards.

Although the greatest challenges focus on towns and cities, this is a subject that has implications at all levels of governance (local, regional, national and international). Moreover, air quality is inextricably linked with other challenges of profound social importance such as the issue of climate, public health or social justice and the economy.

Focal point

Given its transversal nature, experts highlight the need for a systems approach in air quality management. This should reinforce strategies that integrate actions across all levels of governance in a coordinated way and enhance measures that generate co-benefits for all of the challenges and sectors involved. Research is essential to identify and develop this type of approach.

In the last decade, Spain, in common with other European countries, has seen isolated cases of non-compliance with levels of nitrogen dioxide and particulates in air. This is also more generally the case for ozone, the pollutant that represents a key challenge in the Spanish context. Forecasts based on specific measures proposed by the General State Administration predict a general improvement in the situation by 2030, although certain problems prevail. However, the panorama is less favourable if the current situation or forecasts are compared to the WHO standards for protecting health, which are markedly stricter than those enshrined in current regulations. A large part of Spanish and European territory exceeds these safe thresholds for one or several pollutants.



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On the horizon

Technical and regulatory aspects exist that could redesign air quality management in the medium term; there are also advances in the development of mitigation strategies that can be incorporated into public policies.

Among other ways, monitoring could be strengthened by broadening its physical scope, including measurements of pollutants considered of interest or of growing concern, or by applying new developments in measurement, modelling and satellite technology. Monitoring could also be enhanced with the use of new features or developments in the types of sensors available. In turn, the scope of protection can be increased with the support of structural, contingency measures to minimise the impact of heavy pollution episodes (increasingly common in Spain) with effective communication on this subject and its associated risks, and, in more general terms, by modifying acceptable threshold levels for pollutants. The new European directive on air quality, which is currently undergoing the approval process, addresses many of these questions. The directive aims to strengthen public health protection, reinforce monitoring, improve citizen access to justice that promotes the right to clean air and boost the potential of civil society information mechanisms. A key aspect, which is highly complex given the major challenge achieving it would represent, is the proposal to limit the tolerable presence of air pollutants by setting levels that are closer to or the same as -still to be defined- the maximum levels proposed by the WHO.

In order to do this, experts indicate that it would be necessary to combine technological measures that primarily focus on reducing the emissions of an activity, with others that are social in nature, associated with reducing the incidence of contaminating activities. As an example, this might involve, on one hand, proposing technical measures to reduce the emissions of the vehicles that are manufactured, and mobility or other plans that contribute to reducing the use of cars, on the other.

This report covers the main actions in key sectors, highlighting:

•Road traffic: the general goal is to reduce the number of vehicles and the emissions of those that remain on the roads. This is based on a change in the means of transport, with public and active transport becoming the preferred options, the application of restricted access zones for vehicles, and the introduction of technological alternatives in order to reduce emissions. Such alternatives could include complementing the existing fleet with low-emissions vehicles, the redesign of goods delivery and urban spaces, acting on mobility, or the presence of green spaces.

•Domestic and residential sector: the focus here is on measures aimed at increasing energy efficiency and the use of suitable heating and combustion systems in the sector.

•Industry: despite a general improvement in emissions levels in this sector, certain problems of a regional scope persist and there is still room for improvement.

•Agriculture and Livestock Farming: mitigation actions focus on ammonia emissions associated with liquid manure and the particulates and other pollutants associated with burning agricultural waste.

Best practices to improve air quality are always conditioned by a proper diagnosis of the problem's causes and the potential effectiveness of the measures to be applied, in order to effectively act on the main sectors responsible. It is also essential to consider the general public: social information and perceptions as well as their behaviour are key factors to mitigate air pollution causes and effects. Effective communication strategies exist that can help citizens protect themselves and reduce their emissions at the same time as reinforcing their commitment to and collaboration in the development and achievement of public policies.

Air quality: advances and best practices

Introducción

Atmospheric pollution is the cause of bad air quality, which is one of the main public health problems in Europe and Spain

The loss of air quality derived from atmospheric pollution is one of the main public health problems in Europe and Spain[1-6]. Estimates suggest it is the main environmental cause of premature deaths on the continent7 and also has considerable impact worldwide[8]. Additionally, it involves major negative ecological repercussions[9,10]. The estimated economic impact[11,12] for the year 2030 is around 4% of Spain's annual GDP[11].

Air pollution is a matter of concern for the majority of the population[13,14]; however, its effects are unequa[l15-17] and in many cases, people have limited options in terms of self-protection[18]. Increasingly, people affected by this problem take their cases to court and many have received favourable judgements in different European countries (France, Germany, the United Kingdom, Italy or the Czech Republic)[14,19], which have sparked off debate about the right to clean air[20-22]. While the primary issues manifest in large cities due to their concentrated population and pollution sources[23], air quality is the result of complex phenomena. There are many root causes associated with different economic sectors (energy, transport, town planning, industry, agriculture and livestock farming, etc.), and of different, interconnected geographic scopes, from street level to pollution that is transported over long distances. This situation calls for effective coordination between the different levels of government[19,24] and requires public policies in the areas involved[23,25,26].

The Spanish Constitution enshrines the right to enjoy a suitable environment[27]. Accordingly, the last decade has seen the consolidation of a wide range of public policies aimed at reducing atmospheric pollution and its adverse effects. The European Commission indicates that these have been useful, albeit insufficient, tools[7]. Despite a general improvement, Europe and Spain still face major challenges in this area[4, 28-32].

Main pollutants

The pollutants that determine air quality are legally defined. Among these, suspended particulate matter, especially fine particulates, followed by nitrogen dioxide and ozone constitute the principal challenges because they are responsible for the most adverse effects on health.

Air quality refers to the presence of atmospheric pollutants that have a particularly serious direct effect on health **(Box 1)**[6,33-37]. Due to their higher impact, particulate matter, nitrogen dioxide and ozone are priority concerns. In addition to local sources, ozone and particulates can be transported over long distances, which necessitates evaluation of their possible impacts far from the zones where these compounds or their precursors are released[38].

Particulate matter is formed from a set of solid and liquid particulates in suspension. Their danger depends both on their size[52] -with fine particulates (**Box 1**) causing the greatest adverse effects- and in their composition, which is complex and variable. They may contain mineral dust, ash, soot, organic compounds, metals, cement or pollen, among other components[53]. Likewise, their origin may be natural (such as Saharan dust) or derived from human activity. According to the national informative inventory report on emissions, the main activities that cause emissions of fine particulates in Spain are waste management (41%), particularly from open burning of pruning waste (40% of the total), the energy sector (27%; mainly non-industrial combustion in the domestic, commercial and institutional sector), industry (12%) and road transport (10%)[54]. In addition, fine particulates can have a secondary source, and be formed in the atmosphere from precursor gasses and pre-existing particulates. Some examples of

· Informative inventory report: quantification of the emissions of diverse pollutants for all of the sectors involved in a given region. The national inventories reported to the EU base their estimations on a standardised methodology validated at EU level that guarantees comparability between countries. Air quality modelling in future (projections) or past emissions scenarios are based on these data, and scientists use adapted, optimised inventories for the specific purposes the models aim to achieve.
· Secondary pollutant: one that is formed in the atmosphere from other pollutants or the precursors found there.

these are ammonia (96.8% of which originates in agricultural and livestock activities[54]) and a wide range of organic compounds, among others[55,56].

Air quality is determined by the presence of atmospheric pollutants, which include numerous chemical substances and other forms of pollution, such as noise. There are thousands of synthetic pollutants created by humans, the possible effects of which are in many cases unknown.

Box 1. Atmospheric pollution

This refers to the presence of gasses, particulates, radiation, noise, pollen or pathogens, among others, with prejudicial effects on health and the environment. As some of these, such as those connected with air quality or noise, cause high mortality[3,36,39,40], they have garnered public and scientific interest.

Air quality is a dimension of atmospheric pollution with a legal definition, based on compliance with limit and threshold values for the presence of the following compounds[41–43]: sulphur dioxide (SO_2), nitrogen dioxide (NO_2), suspended particulate matter with a diameter less than 10 microns (PM_{10}) and fine particulates with a diameter less than 2.5 microns ($PM_{2.5}$), carbon monoxide (CO), heavy metals (lead, arsenic, cadmium, nickel, benzene, polycyclic aromatic hydrocarbons (benzo(a)pyrene) and ozone (O_3). Additionally, European and Spanish regulations provide for other regulatory measurements, with recommended or obligatory target values, such as those for other nitrogen oxides, hydrocarbons, mercury, ammonia, carbon and organic carbon, or volatile organic compounds[32,44,45].

In addition to the pollutants already covered by legislation, a high number of others exist that represent potential risks for health and the environment, especially the thousands of chemicals synthesised by humans (for industrial use, pesticides, cosmetics, medicines, etc.)[46]. Experts warn of the need to broaden our knowledge about the toxicity, impact and public management of these pollutants[47,48]. It is also necessary to monitor and control the environmental quality of interiors (homes, workplaces, educational centres, etc.) where we spend most of our time (which may be as high as 100% in the case of dependency). As is the case for ambient outdoor air quality, bad air quality in indoor spaces has serious effects on health, so it is essential to improve our knowledge of this subject to develop mechanisms and legal measures that protect the population[49–51].

The pollutants -or their precursors- that are the cause of bad air quality are the result of daily activities: road traffic, the residential sector, commerce and institutions, industrial activity or livestock farming and waste management.

Nitrogen oxides are generated in combustion processes, above all in road traffic[57] -which, in Spain, accounts for 37% of emissions- followed by industry (18%), agriculture and livestock farming (12%) and waste management (9%)[54].

Ozone does not have any significant direct sources. This gas is formed completely in the atmosphere from complex, diverse photochemical reactions (requiring solar radiation) between different precursors[45,58–60]. Its main precursors are nitrogen oxides and a wide variety of volatile organic compounds. These come from sources that are natural (plant life) and from human activities. In Spain, the foremost of sources are the use and production of solvents (48%; 21% solvents in the domestic context, 10% chemical products, 10% coverings such as paint, etc.), agriculture and livestock farming (13%), industry (10%) and road transport (4%)[54].

Nationally, informative inventory reports allow us to evaluate the main sources of pollution[54,57]. However, percentages of emissions do not necessarily represent the levels of exposure or the origin of the pollutants we find in urban ambient air or at a specific site[61,62]. Among other reasons this happens because the sources of emissions are not evenly distributed, and atmospheric creation/elimination processes may alter their presence and relative impact[62–64]. A clear example of this is road traffic, with emissions that are higher in the proximity of the general public than other sources, which significantly increases public exposure to pollutants from this sector[63–66].

· Nitrogen oxides: known as NOx, this generic term refers to a group of highly reactive gases that contain oxygen and nitrogen in different proportions, principally nitric oxide (NO) and nitrogen dioxide (NO2). Other gases exist that are compounds of O and N that are not grouped in the NOx category, but could be of interest (NO_3, N_2O_5 etc.)
· Volatile organic compounds: compounds which have a gaseous state at room temperature and are formed of carbon structures. They include other elements such as oxygen, fluorine, chlorine, bromine, sulphur and nitrogen. They may be of natural or anthropogenic origin, and the ones most abundant in the air are methane, toluene, n-butane, isopentane, ethane, benzene, n-pentane, propane, isoprene and ethylene. They are classified into three groups according to the hazard they represent (the most harmful include benzene, vinyl chloride and dichloroethane) and their potential to generate ozone, which varies considerably. These two factors must be considered when managing them.
·

Impact

Air pollution generates environmental and public health problems, causes inequality and constrains the economy worldwide.

In Spain, as in other European countries, bad air quality reduces life expectancy, since fine particulate matter, nitrogen dioxide and ozone cause some 17,000, 4,800 and 2,400 premature deaths each year, respectively. They also increase morbidity since they cause cancer and worsen or cause many other conditions and diseases.

The World Health Organisation (WHO) the European Environment Agency (EEA) and its American equivalent, the US EPA, and other organisations, have established scientific methodologies to identify the effects of pollutants and/or quantify their impact on people's health.

Effects on humans

The British justice system was the first of a European country to establish the precedent of air pollution as the official cause of death of a minor[67]. There is scientific consensus on the serious effects on health caused by bad air quality, and on the validity and robustness of the methods used to quantify and identify the mechanisms that cause these effects[1,6,8,36,68-70]. This knowledge is based on epidemiological, toxicological and medical information. Adverse effects occur at low concentrations, particularly among minors as indicated by studies[17,71]. Indeed, in the case of pollutants such as atmospheric particulate matter, there is no safe lower limit below which there are no effects[63,72]. Moreover, fine particulate matter is the pollutant attributed with the highest number of adverse effects[36,73-75].

Air pollutants generate and exacerbate many diseases, in addition to being carcinogenic[70,76-79]. This is why they cause an increase in morbidity and mortality, reduce life expectancy and increase the number of years that people live in conditions of bad health or with disability[8,11,33,63,69,80]. The evidence about these effects is robust[70], both at national and international levels[1,81-86], which means the scientific challenge of establishing causal relationships can be addressed[9,36,68,73,74,87,88] (**Box 2**).

Box 2. Causality and effects

Causality refers to the possibility of establishing a cause-and-effect relationship between the presence of a pollutant and its health consequences. The World Health Organisation (WHO) assesses the scientific evidence available in order to establish the effects of pollutants, and offers quantitative recommendations to assess and prevent them[36,63,89-94]. The European Environment Agency (EEA) method to assess the disease burden (effect) among the population broadly follows WHO recommendations[95] and calculates the mortality caused (as the number of premature deaths and as years of life lost) and morbidity (expressed as years living with disease and disability)[96,97]. The United States Environmental Protection Agency establishes a causal relationship gradient between the presence of a pollutant and its effects by assessing the weight of evidence, which it then classifies as a "causal relationship"; " likely to be a causal relationship"; "suggestive of a causal relationship" requiring further evidence to clearly establish a relationship; "inadequate to infer a causal relationship", and "unlikely to be a causal relationship"[73-75]. With reference to the three highest levels of causality, the main effects of atmospheric particulate matter, nitrogen dioxide and ozone taken as a whole are:

•An increase in short- and long-term morbidity and mortality[73-75], cause or worsening of cardiovascular diseases (haematologic diseases, ischaemia, heart failure and stroke)[36,73,89,91], cause or worsening of respiratory conditions such as childhood asthma[17,74,75], impaired pulmonary function in children and adults[17,74,75] and general inflammation of the respiratory tract and lungs[74].

•Long- and short-term effects on the respiratory system. These include the cause or worsening of chronic obstructive pulmonary disease (COPD)[73], respiratory tract infections, impaired lung development in children and asthma in adults[73-75]. Other effects include disorders of the nervous system (cognitive loss, neurodegenerative diseases and impaired development of the nervous system)[1,73,75,98-100], disorders in metabolic function (obesity, hypertension, etc.)[74] and lung cancer[73,75] with major recent developments in findings for the latter[78,101].

•Type II diabetes[73], low quality sperm[73,74], effects on the immune system[102], effects on pregnancy (premature births, low weight)[17,73-75] the cause of other types of cancer (breast[77,81], bladder[77], digestive system[81]) and others.

· Epidemiology, toxicology and clinical research: Epidemiology relates the presence of pollutants with diseases and mortality. Toxicology essentially focusses on the biological mechanisms that trigger the observed effects. Clinical research is based on assessing the effects of controlled exposure in humans.
· Morbidity: refers to the degree or level of disease or ailment that an individual or a group of people experience. In general terms, morbidity refers to the proportion of people in a population who are ill or suffer a medical condition.

Studies currently estimate that for 2020 alone, fine particulate matter, nitrogen dioxide and ozone were responsible for 238,000, 49,000 and 24,000 premature deaths, respectively, in Europe[103], of which 17,000, 4,800 and 2,400, respectively, were Spain[103]. Mortality for cardiovascular causes accounts for the highest number of deaths, followed by respiratory diseases[1,85,104]. On the other hand, if we only consider short-term mortality in Spain, i.e., death that occurs within the 15 days after a peak in pollution, some studies estimate 10,000 deaths per year[105].

Despite extensive evidence in the field of health, it is important to progress in research on subjects such as combined, changing exposure to multiple substances[69] , including the so-called contaminants or pollutants of emerging concern[106] (**Box 3**) and the mechanisms that determine the toxicity of pollutants[69,72,90].

Certain pollutants have been identified which, despite not being included in the regulatory framework, require particular attention and scientific, administrative and social monitoring due to their danger or relation to other pollutants.

Box 3. Air pollutants of emerging concern

Evidence highlights the danger and abundance of these substances which have the potential to change the climate (short-lived climate pollutants), and their role as precursors or indicators of other pollutants. Although they are not yet on the list of legally controlled pollutants (**Box 1**), scientific research into them is progressing[106,107] and scientists highlight the need to pay them more attention[19,106].

- Some progress is the result of a better understanding of the factors that determine the toxic potential of particulate matter:
  - Ultrafine particles (UFP), or $PM_{0.1}$, smaller than 0.1 microns) have an outstandingly high toxic potential. We still need to improve our knowledge about them[108–110].
  - Black carbon: fine to ultrafine particulate matter ($PM_{2.5}$–$PM_{0.1}$) formed of pure carbon in several forms, such as soot. It has a remarkably toxic potential (it is strongly related to the adverse effects of particulate matter and its action on climate warming)[108,111–113]. Experts highlight the importance of improving our knowledge in this area, and of harmonising and improving methods to determine these particulates[114–116].
- Others are compounds like ammonia (in addition to being a precursor of fine particulates, it is currently rarely subject to monitoring[113] and reducing its emissions represents a major challenge for Europe[118]), volatile organic compounds (VOC – the precursors of ozone and fine particulates)[45], methane (acts as a precursor of ozone and is a greenhouse gas about which we need more information[119]) and levoglucosan (a tracer for biomass burning).

Social inequality

There is an unequal distribution of the adverse effects of the main air pollutants on the public, with most harm to minors, older people and people in situations of socioeconomic disadvantage.

There is clear inequality in terms of the effects of air pollution on the population[6,15,16,120–124]. Minors, older people and people with underlying health conditions are the main vulnerable groups; they more frequently suffer the effects and experience more severe consequences[34]. These effects begin during pregnancy and continue throughout development into adulthood, with data indicating some 1,200 deaths per year of people under the age of 18 in Europe[17]. Among other aspects, brain development[125,126] and cognitive performance[127] are affected, which is why measures are in place to protect the areas surrounding schools from atmospheric pollution[128–130]. It is anticipated that the vulnerability of older people will rise in the future, considering the ongoing demographic trends[131,132]. Data also suggest that people in situations of socioeconomic disadvantage are more vulnerable to air pollution[15,16,34,36,122,133–135]. These differences (in related mortality, among other factors) can be seen between neighbourhoods, cities and countries[16,124,136]. Experts highlight not only the lack of specific actions in European policies to address this problem, but also the need for standardised data and methods in this field[16,123,124,137]. Recent studies therefore propose mechanisms and new tools to act on and broaden the development of environmental justice[121,124,133,138,139].

Environmental effects

Because of their phytotoxicity and their capacity to alter ecosystems, nitrogen oxides and sulphur, ammonia and ozone cause the loss of biodiversity and harm plant life, which also involves a loss of agricultural productivity.

Bad air quality alters environmental processes and the development of plant life, which is prejudicial to biodiversity and ecosystem services[9,10] reduces agricultural productivity[11,140,141], and affects natural areas[10,32,142]. Nitrogen oxides, sulphur and ozone are phytotoxic, causing harm to plant life[9,10,143-145]. In addition, deposits of sulphur, and above all of nitrogen, which form part of the compounds involved in pollution[143], alter ecosystems and affect organisms through processes of acidification and eutrophication. Ammonia, one of the pollutants of emerging concern (**Box 3**), is also of particular importance due to the effects described and the risk it entails for the environment[10,146,147].

Despite this, roughly one-fifth of Spain's territory exceeds the established pollutant levels designed to protect plant life and ecosystems, with a particular emphasis on ozone[30,148-150]. Various studies in this field have found that the indexes for calculating damage caused by ozone, which are based only on concentration levels, underestimate its impact on Mediterranean areas[151,152]. To conduct a more exact assessment, experts suggest using indexes which include the environmental and physiological factors that explain the level of ozone's effect on plant life. In terms of acidification, national data on the pH in rain suggest that this is not a significant problem[153], unlike eutrophication, which has significant effects both in Europe and Spain[32,147]. Various areas in Europe exceed the critical load for eutrophication, with the most affected areas being the Po Valley (Italy), frontier areas between the Netherlands, Germany and Denmark and the northeast of the Iberian Peninsula[147]. Experts highlight the importance of coordinating and strengthening both monitoring of and scientific knowledge about the effects of these pollutants on Mediterranean ecosystems, which have not been characterised as well as other bioclimatic zones[154].

Cost and effects on the economy

In Spain, some estimates indicate that bad air quality will cost the country between 30,000 and 40,000 million euros (2030) mainly in expenditure on healthcare. Among other effects, this problem also generates a loss of workforce productivity, causes damage to materials, goods or crops, and reduces economic activity.

Atmospheric pollution affects, among other areas, wellbeing[155,156] and the economy[11,12,157,158] (reduced GDP[159], workforce productivity[160-162], and damage to materials and goods[73]). The estimated cost solely related to the impact on health in Europe is over 900,000 million euros/year (2020)[11], and between 30 billion and 40 billion euros for Spain[11,105]. In the European cost ranking based on normalized data for GDP, Spain occupies the middle ground[11,163], with the highest costs[11,155] associated with reduced life expectancy, followed by morbidity, and degradation of the environment and plant life[141]. For a Spanish autonomous community, the costs derived from hospital admissions associated with nitrogen dioxide alone can reach 120 million euros per year[86]. Per inhabitant, the cost related to health impacts in Spain ranges between 400 and 3,000 euros/year, depending on the city studied[155]. These cost estimates constitute a useful tool to evaluate and develop public policies, although they should be interpreted with caution. Experts indicate the importance of improving our knowledge regarding the economic impact of pollution, in the light of a lack of data and the methodological difficulties involved (monetisation of socio-environmental factors, like the loss of biodiversity, among others)[11,136,155,158,159].

- Ecosystem services: Nature's services or eco-services are the resources or processes of natural ecosystems that benefit humans. These include products such as clean drinking water, wood, foods, etc. and processes such as the breaking down of waste.
- Sulphur and nitrogen deposition: nitrogen oxides, sulphur or even particulates undergo processes that involve their deposition on areas of land or water. They represent extra amounts of nitrogen and sulphur that change the balance of ecosystems and have serious consequences for the affected systems.
- Acidification: the process in which the acidity of the medium (land, water, atmosphere) increases due to the release of acid compounds, particularly sulphur dioxide (SO_2) and nitrogen oxides (NOx) into the atmosphere.
- Eutrophication: the excessive enrichment of an aquatic or terrestrial ecosystem with nutrients, principally nitrogen and phosphorus, which contributes to changes in the ecosystem's specific composition, and which may have serious consequences for it (lack of oxygen in bodies of water, proliferation of unwanted species in land areas, etc.)
- Critical load: the maximum amount of a pollutant that an ecosystem can tolerate without suffering significant adverse effects.

Towards a systems approach

Mitigation of bad air quality requires a systems approach, centred on measures that generate co-benefits in all of the challenges related to air quality (climate change, health, inequality, etc.) and for the sectors involved.

Multiple interconnected sectors: co-benefits

Air quality has implications for and is interconnected with diverse areas such as health, the economy, wellbeing or social justice, and a wide range of sectors such as industry, town planning, housing, commerce, agriculture or mobility[24,37,71,164]. At the same time, it is also strongly related to other environmental problems, particularly the issue of climate. All of these interconnections require a high degree of coordination in governance, as highlighted in Spain's first National Air Pollution Control Programme (*Programa Nacional de Control de la Contaminación Atmosférica*)[37] and its recent review[164], or the Environmental Health Strategy (*Estrategia de Salud Ambiental*)[71]. These also lay the foundations to apply systems approaches (on the parts and their interconnections). This would facilitate identification of measures that present co-benefits in several areas and the redesign of areas/sectors connected to the cause of the problem[26,165,166]. For instance, the redesign of urban areas (green spaces, environments that enable active transportation, etc.) can reduce emissions of pollutants and the greenhouse gases related with road traffic at the same time as acting on public health (see the Road Traffic section)[167]. Actions or mitigation measures that do not consider this perspective can have counterproductive results; indeed, several methods exist to evaluate possible undesired impacts1[8,26,168,169].

Air quality and the climate issue are heavily interrelated in their causes, effects and solutions, which makes integrated policies necessary.

Climate and air quality

Although they are closely related, climate change and bad air quality are different phenomena[25,170-173]. On one hand, many of the sources of emissions are common to both problems (mainly due to the use of fossil fuels)[8,171,174,175]. Whereas climate change includes global warming due to greenhouse gas emissions (above all, carbon dioxide), air quality covers another group of pollutants (**Box 1**)[41]. Some of these also contribute to the greenhouse effect (such as ozone, black carbon and other short-lived climate pollutants, **Box 3**). Others have the opposite effect (particulates, with the exception of black carbon, minimise warming as they reflect incident radiation)[171,172,174,176,177]. On the other hand, the environmental conditions derived from climate change (prevalence of anticyclones, higher temperatures, less wind, more radiation, higher frequency of heatwaves and fires)[170,178] will promote the presence of particulates[179], emissions of volatile compounds and the formation of ozone[180,181]. In addition, the effects that pollutants have on health and the environment (mortality, damage to plant life, etc.) worsen in the context of climate change[25,170,180,182-191].

This explains the need for integrated public policies aimed at mitigating climate change and bad air quality[185,186,189,192]. Such policies include simultaneous strategies to prevent an impact on health (heatwaves, pollution, drought, fires, new diseases, etc.). Integrated approaches offer a better overall balance than one-way approaches[173,177,192,193] since they provide benefits for health or the economy that go beyond the simultaneous reduction of polluting emissions[173,174,194]. However, interrelations are complex and not always linear. For instance, some experts highlight that measures considered beneficial for the climate issue, such as the use of diesel or biomass vehicles, may compromise the aims of improving air quality (by increasing emissions of nitrogen dioxide in the case of the former, and of particulates, polycyclic aromatic hydrocarbons and volatile organic compounds in the latter)[195-198].

In this context, the EU's environmental strategy centres on transversal public policies, which aim at climate neutrality, but also integrate and address the improvement of air quality, acting as systemic instruments. At the forefront of these strategies are the European Green Deal[199], the Net-zero Emissions Strategy[200], the mission for climate-neutral cities[201] and more specifically, the Clean Air Policy Package for Europe[5,202].

· Co-benefits: this concept arose in the international context related to mitigation of climate change. It refers to benefits obtained from mitigation measures that go beyond their intrinsic aim of reducing greenhouse gas (GHG) emissions.

Protection and management of air quality

Although both Spain and Europe have broad, consolidated legal frameworks, the European Commission has highlighted the need to modify the current European directive on air quality to increase the protection of public health and strengthen monitoring, environmental justice and the role of citizen information mechanisms, among other aspects.

Legal framework

In Spain, 75% of citizens state that they have no knowledge of regulations governing air quality13. However, in terms atmospheric pollution and people's health, the EU bases its protection on four lines of action which, alongside other types of instrument[203] aim to reduce the public's exposure to pollution.

- **Limitations on pollutants in the air.** Spanish[41-43] and European[44,204-206] frameworks set limits on the tolerable presence of pollutants, standardising parameters in methodology and communication in this area. When levels rise above the limit values, a mitigation plan must be developed, which is communicated to the European Commission through the European Environment Agency. In unresolved cases of non-compliance, the European Commission may initiate an infringement proceeding against a Member State. The EU is working on approval of the new air quality directive[7,207] which aims to bring in more demanding parameters. The European Parliament has currently accepted the European Commission's proposal and added several amendments that the Commission is in the process of reviewing[208,209]. Some experts highlight this may be the greatest action in public health undertaken in a generation; an intervention which could help prevent disease and premature mortality at levels higher than those of previous steps, such as the ban on indoor smoking[137,210,211].
- **Emissions ceilings.** To maintain pollution levels below the set limits, the EU has established objectives for the progressive reduction of air pollution and emissions until 2030, tailored to the situation of each country[212-215]. For instance, by 2030, Spain will have to have reduced emissions of nitrogen dioxide 39% compared to 1990 levels. The National Programme for Air Pollution Control establishes the instruments to assess, monitor and achieve these ceilings[37] and progress in this field is assessed at EU level[118].
- **Strategic regulations.** Allow the application of measures to adjust emissions ceilings in the sectors where they originate. As an example, for nitrogen dioxide the reduction target for 2030 will be spread over actions on transport, road traffic, urban mobility and any other sectors with potential involvement. In order to act where necessary, it is essential to quantify pollutant emissions by source. Each EU country therefore conducts its own national informative inventory report on emissions. Although Spain's report[216,217] has international recognition[218] there is ample evidence to support ongoing improvement of this tool[219-228] including a recent update of European recommendations[229]. In addition, other inventory reports exist whose methodology is optimised for specific objectives, geographical areas or time periods for the management and research of air quality[230,231].
- **International cooperation.** Given the scope of this problem, we need international agreements and tools[232-236] that enable action on a global scale[237]

In addition to a regulatory framework, recent years have seen Spain develop different plans and strategies to address air quality at national and regional levels[37,71,164,238].

In large parts of Spanish and European territory, air quality does not meet WHO health standards, which are stricter than the levels established by current regulations (which, moreover, are not followed in some parameters).

Guide values for health

The World Health Organisation has recommended levels for pollutants that define air quality in accordance with existing scientific evidence concerning effects on health[36]. With its recent update in 2021, depending on the pollutant considered, between 88% and 98% of European monitoring stations report measurement levels that exceed recommended limits[4,239].

For most pollutants, WHO guide values are markedly more demanding than the limits set both in the European Directive and in current Spanish regulations on air quality, which is one of the reasons why the Directive is under review[7,36]. In this sense, 63% of the Spanish population believes that air quality regulations should be made stricter although, paradoxically, the majority does not know what the regulations are[13].

Assessment of air quality: monitoring and modelling

Spain has an air quality monitoring network that meets EU Directive requirements and is in line with international standards.

The Spanish air quality monitoring network and the use of air quality modelling are two essential instruments to manage this issue. The monitoring network is a key asset for public health protection and is supported by different instrumental methods that determine the presence of pollutants[41]. Modelling enables evaluation of air quality status under different scenarios, which is extremely useful for informing managers when developing public policies.

The monitoring network takes measurements according to criteria of area and possible sources of pollutants, as stipulated in the legislative framework[44,206]. Specifically, it consists of:

- **The EMEP/GAW/CAMP network[240].** Managed by AEMET (the Spanish State Meteorological Agency), which reports nationwide remote background levels[241] and provides information of scientific interest within the scope of this and other networks, and the global programmes that AEMET belongs to[242-246].
- **Autonomous community networks[247].** They manage monitoring at regional level, which includes -among other aspects- rural[76], background, industrial and urban or other areas (urban background, road traffic).
- **Municipal networks[247].** These attempt to reflect the complexity of urban areas in towns/cities and metropolitan areas.

In Spain, the National Reference Laboratory for Air Quality (Laboratorio Nacional de Referencia de Calidad del Aire) provides technical support (data traceability, calibration of ozone transfer patters, sample analysis, etc.), evaluates, and supervises the networks and their quality systems[248]. All networks share their information with the Ministry for the Ecological Transition and the Demographic Challenge (MITERD). MITERD then forwards the data to the European Environment Agency, where it undergoes evaluation and is made available to the European Commission (responsible for evaluating compliance with European regulations), the European Parliament, the general public, NGOs, etc.

On the other hand, air quality modelling allows the estimation of levels in places where no direct measurements are taken, and complements the monitoring network since, for technical and budgetary reasons, measurements cannot be taken at all points of the territory[41]. This enables real-time prediction (e.g., composition of the atmosphere or the ICA, which is the national air quality index)[249,250]. The versatility of modelling also enables future projections, or retrospective assessment of key issues, like the effectiveness of mitigation measures, or their impact on the economy and health. It also allows us to work on scenarios based on different options in public policies related to air quality so as to better understand their implications and effects[37,251-255].

Although air quality modelling and measurement of levels in Spain have both scientific and technical recognition, challenges still exist (**Box 4**). Indeed, the draft of the new ambient air quality directive aims to strengthen aspects that support preventive action, proposing measures and strategies to do so[7,256,257] (**Box 4**).

· Air quality modelling: using mathematical models, we can estimate the amount of a pollutant present in a given area on different time scales (prospective and retrospective) and ranges of area (macro, meso and microscale). Models include the complexity of multiple interrelated factors (emissions, atmospheric dynamics, meteorological variables, orography) that determine the presence of pollutants.
· Instrumental measures: the air quality monitoring network provides standardised measurements based on specific quality and methodological criteria (Royal Decree 102/2011 and amendments) for levels of pollutants in air. Air quality monitoring stations in Spain have instruments that determine the presence (concentration, deposition or other parameters) of pollutants. Instruments may include automatic or real-time measurement systems, ones that need manual input, or sample-taking (filters, adsorbent materials etc.) for lab analysis.
· Background levels: pollution in ambient air, not directly related with a source or sporadic activity. In air quality, reference is made to remote and urban background levels. Remote levels are typical of areas that are far from the source of emissions, such as cities or other urban centres and/or industrial centres. Urban background levels are in cities, not directly associated with a source (traffic or other) and reflect the joint influence of all sources.

Monitoring can improve with advances in measurement systems and with modelling to address key challenges, like those related to spatial representativeness and resolution or monitoring new substances.

Box 4. Trends and state-of-the-art in monitoring and air quality modellingn

Studies of international monitoring exist that highlight the importance of adapting to new challenges in air quality and integrating scientific and technical developments in this field 258,259. Notable examples are:

- **Low cost sensors.** They have the potential to broaden the scope of monitoring (better spatial resolution and accessibility, among other factors) with indicative or qualitative measurements[251,260-263] and have diverse scientific applications (see Section 7). Nevertheless, the data they provide is still not comparable to that of official networks. Despite recent progress[264,265], technological and regulatory developments are necessary to improve the quality of data, their validation (certification, standardisation), and the correct use of these devices[266,267]. The status of development and potential of these devices has been the subject of conferences organised by MITERD[268].

- **Satellite sensors.** The potential and global scope of this technology increases in step with innovations[269,270], in which Spain actively collaborates[271,272]. Europe has its own infrastructure, COPERNICUS, and the corresponding Atmosphere Monitoring Service (CAMS)[273] which provides information about air quality[274-276]. This is a promising field, but exploitation of the data is still in development.

- **Personal exposure.** The combination of data generated by the technologies described above, geolocation of individuals (mobile devices, smart cities, etc.), artificial intelligence, and the use of big data may make this possible in the future[258,275,277-281].

- **Improvement in networks.** The draft of the new ambient air quality directive considers certain changes in the criteria for distribution and classification of stations. Likewise, it proposes tackling mediation of emerging pollutants (ultrafine particles, black carbon, ammonia, among others; **Box 3**) for instance, by means of a network of what are known as super-sites[7,256]; it also raises the requirements for precision in measuring pollutants, and implementation of these aspects may prove a challenge. An increase in automatic measurement systems, human and financial support and constant collaboration and guidance from expert research staff are other aspects under consideration in the international debate[148,259,282-285].

- **Models.** Improving the precision of predictions and standardising comparability and quality criteria so that they are more robust are areas in constant development. The draft of the new European directive includes further requirements to improve the use of air quality modelling and assess its value, above all in areas with low air quality[2,7,256]. In Europe, progress is being made in this field (the FAIRMODE working group)[286], and work is underway on advances and best practices for monitoring, and on formulation of public policie[224,287,288]. Current research into air quality modelling allows evaluation of the situation at a very detailed local level (for each street), and the practical application of this technology is starting to be seen in the management of specific local problems[289-292].

The status of air quality in Spain

Trends over time and compliance

Air quality in Europe and Spain has improved thanks to the public policies applied. Nevertheless, experts warn that progress is insufficient.

There is a broad consensus at both national and European level[4,30,35,150] that there has been a general improvement of air quality in recent decades, which highlights the effectiveness of the public policies applied[190,293,294]. However, experts warn that the advances are neither sufficient to protect public health[7,207] nor can they be extrapolated worldwide[34]. On the other hand, the public has the perception that this problem is constantly worsening[13]. The latest data available for air quality in Europe and Spain confirm the positive trend[4,30,31,148,150], although certain problems persist at national level[30,35,148,295].

In the last decade, Spain has experienced non-compliance with the legal framework, mainly regarding levels of nitrogen dioxide[295-297], atmospheric particulate matter smaller than 10 microns at the local level[35,148,295], and more extensively for ozone[35,45,148,295]. A similar situation can be observed in other European Union countries[298]. Based on the available data, some

In common with other countries in our context, there are isolated instances of non-compliance related to levels of nitrogen dioxide and particulates in air, and more general instances for ozone.

reports of environmental associations estimate that because of this, in 2022, approximately 16% of the Spanish population was exposed to pollution levels that exceeded legal levels for certain pollutants, a figure that would be 100% if WHO guideline values were used[148].

The lockdowns derived from the SARS-COV-2 pandemic offered us an unprecedented global experiment in the variations of air quality over time. Although activities of a large number of air pollution sources came to a halt[239], the presence of emissions did not show homogeneous trends in all cases. The greatest reductions occurred in nitrogen oxides, mainly due to the absence of road traffic[60,299–302]. However, in the case of secondary source pollutants, the trend was less clear[300]. Emissions from the residential and agricultural sectors contributed to the presence of fine particulates, which was also locally the case for ozone, due to changes in the composition of the atmosphere derived from the lack of activity[60,299,303]. This situation reflects the difficulty of achieving effective reductions in secondary pollutants[304] and the need to adopt a holistic approach[60,303] that considers all of the precursors and chemical changes in the atmosphere as a whole[300].

Forecasts based on specific measures proposed by the General State Administration agency (AGE) foresee generally improved compliance by 2030. However, some difficulties are foreseen with persisting ozone concentrations and emissions of volatile compounds or ammonia.

The National Air Pollution Control Programme (Programa Nacional de Control de la Contaminación Atmosférica) comprises a wide-ranging set of measures to improve air quality[37,164]. With its application, the estimates for 2030 indicate that Spain will meet the legally established levels for most pollutants, although it is likely that there will be isolated non-compliance for certain pollutants, which will be more general in the case of ozone[164]. However, bearing in mind the stricter limits for ambient pollution proposed by the EU for 2030[7], the outlook is less encouraging.

To reach the legally established levels for air, the objectives set for cutting emissions must be met. The data regarding trends over time suggest a significant drop in emissions of nitrogen oxides and particulates. However, emissions of volatile organic compounds and ammonia (**Box 3**) remain stable or increase[37,164], a situation that is also seen at European level and has been identified as a challenge[118]. Additionally, some estimates for 2030 suggest difficulties in complying with emissions ceilings, essentially those for volatile organic compounds[164,253], which represent a significant risk for both the environment and health. The European Commission has recently urged Spain and 14 other countries to reduce their emissions of various pollutants so as to respect the commitments derived from the European directive on ceilings (2016/2284)[305].

Challenges: technological and non-technological measures

To reduce emissions and meet WHO recommendations, technological measures must be combined with social change. The reduction of ozone levels in Spain represents a scientific challenge.

The main challenge is to reduce emissions, bringing levels of pollution into line with recommendations for public health and to go further than the legal framework[137,239]. Although this is a complex goal that will require a great effort[60,239], data indicate both the economic advantage and the significant number of premature deaths that could be prevented[11,36,104,210,239,306]. In these terms, some countries with comparatively higher economic activity, such as the USA or Norway, have air pollution limits for certain pollutants, such as fine particulates, which are stricter than those stipulated in current European regulations[307,308].

This objective requires a combination of technological and non-technological measures[197,309,310] that can be grouped into a strategic vision, driving the different sectors towards broad general objectives, as in the case of Europe[199] and the goal of net-zero emissions for 2050[200]. Technological measures generally aim to reduce emissions rates in different sectors of activity and have already been developed (e.g., electric cars). Although necessary, they are not sufficient on their own, and some experts indicate that they may bring fewer inter-sectoral benefits than non-technological measures[18,26,311]. Such measures attempt to reduce the existence of polluting activities, acting on social habits and consumption. These include “hard” coercive measures, such as traffic or parking restrictions etc., and “soft” ones based on voluntary improvements in attitude achieved through information, education and awareness[26,310,312].

We also need a better understanding of the processes that regulate the presence of pollutants in the atmosphere and how they develop as a consequence of changes in the composition of air, even changes derived from mitigation actions themselves[313,314]. This issue is particularly critical in the case of ozone, one of the main problems facing Spain[45,315] and for fine particulates. In the medium term, reducing both requires action on the precursors that enable their formation, several of which are common to both pollutants[45,316]. Experts also highlight the need to improve our knowledge of the characteristics and composition of fine particulates, including their toxicity[317,318]. In addition, it is significantly important to face the challenge posed by heavy pollution episodes, whose frequency is on the rise with climate change[319,320,321] (**Box 5**).

In addition to other considerations, heavy pollution episodes require long-term strategies that reduce background levels of pollution and immediate action measures that limit polluting activities during such episodes. One of the major causes of heavy pollution episodes in Spain is the outbreaks of Saharan dust.

Box 5. Heavy pollution episodes

They may be caused by emissions of pollutants derived from local, regional or transfrontier events (anthropogenic or natural) whose formation, transport or accumulation is significantly worsened by specific meteorological conditions[320]. Forest fires, outbreaks of haze composed of Saharan dust (calima), burning of agricultural waste, high solar irradiance or intense anticyclonic conditions are behind this type of episode[320]. Spain is particularly affected by outbreaks of Saharan dust (particulates)[322-327] that have both a direct and synergistic impact, with socioeconomic consequences and effects on health[322,328-336]. Other episodes occur, such as ozone[337,338] or, in urban contexts, high levels of nitrogen oxides that are either not dispersed or caused by an increase of local emissions[289,339].

Mitigation of the effects of these types of event focuses on applying both long- and short-term strategies[320]. Long-term strategies cover sets of permanent structural measures that attempt to reduce levels of baseline pollutants at local, regional or national level (see Mitigation). Experts believe these to be the most effective group of measures to reduce the impact of atmospheric pollution. Short-term strategies focus on the development and use of precise prediction systems to start up contingency measures for episodes (limits on traffic circulation, industrial activity or biomass burning, among others)[167,289,320,339-341] and limit public exposure (public information, limitations on physical activities, workforce mobility policies, etc.). In this respect, Spain has developed prediction mechanisms (for outbreaks of Saharan dust, chemical composition of the atmosphere, etc.)[247,342-346] and has a short-term action plan framework[238]. The recent Royal Decree 34/2023 also offers a common framework for thresholds and actions to control the impact of heavy pollution episodes[340].

Although large cities represent the main challenge, it is important to move towards a holistic approach and address coordination of the governance system to facilitate management[24,26,347]. This includes the different administrative levels (e.g., national labelling/identification of vehicles enables their regulation in municipal low emissions areas), in addition to the interconnection and cooperation of all actors and sectors involved[23]. On the other hand, the draft of the new European directive contemplates improving access to justice and compensation for damages caused to people's health derived from bad air quality[7,256], which emphasises the importance of a governance system and responsibility for bad air quality.

Mitigation: strategies to improve air quality

The best practices to improve air quality are conditioned by a correct diagnosis of the causes and focus on the main sectors responsible for pollutant emissions.

Mitigation can focus on actions and specific objectives for each polluting sector. It can occur at supranational, national, regional or municipal level, and may respond to the application of a single or several combined measures, depending on the short-, medium- or long-term objectives.

A wealth of information is available about strategies and best practices[224,287,311,348-350]. However, all practices are conditioned by the correct diagnosis of the causes behind the problem that needs solving: target pollutants, local, regional or national sources, and key factors to consider[349,351]. Furthermore, it is advisable to assess the effectiveness and impact[351] of the measures not only in relation to emissions but also considering socio-economic factors, impact on health, cost-effectiveness, simplicity, among others[123,224,252,254,287,349,351].

Although it is a challenge to assess the effectiveness of measures (due to time, resources, technical reasons, etc.) doing so can be useful both for designing public policies and to promote acceptance[69,351,352].

Depending on the main pollutant, actions can be grouped into[24]:

- Nitrogen oxides: strategies focus on road traffic and mobility[37,353,354]. Another important sector of interest is residential, institutional or commercial (non-industrial) and industrial combustion.
- Particulates: require a more transversal approach as various sources and secondary formation processes come into play[355]. Strategies mainly focus on the residential, institutional and commercial sectors, as well as industry, agriculture and livestock farming, and road traffic (both emissions associated with the process of combustion and those not related to exhaust gas)[24,37].
- Ozone: its mitigation still represents a complex scientific and political challenge, given the many factors involved[81,356]. The General State Administration, in conjunction with Spain's Autonomous Communities and scientists are working on the most relevant scientific evidence[110,357,358] to develop an ozone management plan[45]. Although some experts indicate the need to introduce a tougher legal framework to speed up actions that combat this pollutant, there is no clear consensus on this matter[137]. In this respect, some experts propose changing the target values for ozone to mandatory limit values, which has occurred in some countries like the USA[137], and suggest the possibility of amendments to the new Ambient Air Quality Directive presented by the European Parliament[209].

In addition to the areas already mentioned, steps in other sectors could bring benefits in pollution mitigation, in addition to other measures that are not clearly aimed at a single sector. An example of other sectors are port or harbour activities (notably freight management or concentrations of cruise ships in certain cities)[45,197,359,360], air[361] and maritime[45,362,363] transport, construction[311], or waste management. The importance of maritime transport in ozone emission has recently been highlighted[45]. Examples of measures not aimed at a single sector are street cleaning[311,312,364] or the application of chemical dust suppressants[311] to reduce particulates, or the use of photocatalytic products (exterior paints and materials etc.) instead of nitrogen dioxide[365,366]. The findings of studies offer no clear conclusions, and are dependent on application methods, so careful consideration is necessary before their adoption.

Road traffic and mobility

The general objectives of actions to improve air quality related with road traffic are to reduce both the number of vehicles on the roads and the amount of emissions produced by the remaining traffic.

Many strategies exist to achieve the general objective of reducing the number of vehicles and emissions levels of the active vehicle fleet in cities, which is where nitrogen dioxide-related problems are concentrated[352,367-369]. Spain is currently preparing a government bill on sustainable mobility[370].

Modal shifts in transports

Public transport and active transportation are the preferred options as offer co-benefits in diverse areas, unlike private vehicles.

Consolidating public transport so that it becomes the preferred alternative in terms of price, comfort, efficiency, etc. enables other actions on mobility and improves their acceptance[81,351,369,371,372]. Action can also be taken on emissions derived from the use of fossil fuels in public transport (particularly for buses: electrification, hydrogen, gas and others)[373,374]. Active transportation, such as waking or using a bicycle, has a positive effect on both air quality and people's health[167,375,376]. This can be promoted by increasing the network of cycle and pedestrian lanes[377,378], providing access to shared bicycles[377,379] and other vehicles[380] and reviewing the factors that condition their use (safety, distance, age, etc.)[381] as well as town planning (see Town planning). A better understanding of citizen mobility supported by data can help design strategies and mobility alternatives that suit the preferences and needs of citizens[382-385]. Along these lines, progress is being made in modelling data on transport preferences, public mobility patterns and so on, using tools such as artificial intelligence[386] and digital twins among others[387-389].

Zones with restricted vehicle access

Limiting vehicle access to given areas of cities can improve air quality, reduce road traffic and promote renewal of the vehicle fleet.

In Europe, the creation of urban vehicle access regulation schemes or limited traffic zones is one of the most commonly used measures to reduce the number of vehicles or in technical terms, total mileage[287,311,390]. These zones limit or control vehicles access, circulation, or parking using mechanisms like charges or tolls. The criteria for entry may vary, defining the types of vehicles allowed, the extent or hourly patterns of use, conditioned by traffic volume, or a complete ban, etc.[391]. The effectiveness in reducing exposure to and levels of pollution, principally nitrogen dioxide but also particulates, can vary greatly depending on these criteria, making adequate planning essential[287,369,392-395]. Despite this, there are many examples with positive results in other countries[287,311,396-399], and also in Spain[400,401]. In turn, such strategies promote renovation of the vehicle fleet in favour of less polluting models and a change in means of transport311, with benefits that go beyond the zone where the restriction is applied. Experts highlight some difficulties in terms of the social acceptance of low emission zones[287,402] and emphasize the importance of properly communicating measures and addressing the factors that influence their acceptance[310,403,404]. However, data do not suggest that acceptance is generally bad[405,406].

The application of urban tolls and congestion charges is a common mechanism in Europe[407] which is not applied in Spain; the most well-known of such schemes are in London[408] and Stockholm[369,409], although others exist[407]. Spain has implemented low emission zones. The recent legal framework is expected to result in 149 Spanish towns and cities adopting this mechanism by 2023[410]. There are guidelines for the development and introduction of these zones and recommendations aimed at avoiding potentially negative effects, which include inequalities derived from access criteria[87,390,411].

Other measures that act on road traffic circulation are limitations at times of heavy pollution episodes[266,373], speed limits (with positive and negative effects depending on the pollutant and state of traffic)[264,341,374], workforce mobility policies[32] or remote work (also with pros and cons)[275,375,376], shared mobility[32] and higher vehicle occupation (carpooling, car sharing or BUS-HOV lanes) among others[286,339,377].

Technological alternatives to reduce emissions

Technological measures for road traffic (electric vehicles, low emissions, others) can reduce emissions of some pollutants (mainly nitrogen oxides) in the medium to long term.

Experts highlight that to reduce fuel-derived emissions, the goal is to reduce use of fossil fuels. To do so, there are alternatives such as electric, hybrid or hydrogen vehicles, the use of synthetic fuels, particularly biofuel, or other measures like toughening regulations that govern different sectors[32,254,367,412]. The European Commission has already proposed Euro 7[413] to reduce emissions[414] and replace the current Euro 6[415].

The use of electric cars may contribute to significant reductions in local nitrogen dioxide emissions[416]. However, an analysis of emissions and other factors in the value chain of electric cars is necessary. This should include their use of critical materials, the generation of electricity, and their generation of waste or recycling of batteries, in order to avoid additional environmental problems that affect areas other than the ones where these vehicles are used. Another consideration involves the local challenges posed by an increase in non-exhaust gas particulate emissions (heavier cars that increase emissions through re-suspension, wear and tear -brakes, wheels, asphalt-)[287,417,418].

· Digital twins: this refers to a virtual model that exactly reproduces a physical object, process or system. They are used to conduct simulations and observe the performance of a product or system that is the subject study in order to later adopt the solutions or planned changes in real life.
· Urban tolls and congestion charges: systems that allow the access of vehicles after payment of a charge, which varies depending on criteria such as time of day, congestion in the area, type of vehicle and its emissions, etc.
· Low emission zones: zones where it is forbidden to drive certain vehicles depending on the level of their emissions, with exceptions made for justified cause.
· Synthetic fuels: fuels that do not have a carbon-based fossil origin. For instance, methanol, methane, ammonia, biofuel (produced from organic waste and biomass) and other liquid hydrocarbons or green hydrogen.
·

Goods delivery contributes to bad air quality. Experts suggest environmental criteria and low-emissions vehicles to mitigate the impact of this factor.

The redesign of urban spaces and mobility, accompanied by the presence of green spaces could improve air quality and public health.

Currently, the use of electric cars in Spain is low, with a lack of sufficient urban infrastructure to charge them[37], which means their full impact is not expected in the short term. Experts indicate the advisability of implementing incentives to improve this situation, as in the Norwegian model[419]. Despite the potential of hydrogen-powered cars to reduce pollutant emissions, achieving this goal requires scientific and technical developments in the energy sector and regulatory frameworks, making it a long-term option[420-422].

Renewing the active fleet also includes the use of new vehicles based on less contaminating fossil fuels[368] or retrofitting[367]. Renewal efforts should focus on current vehicles that have high emissions, whether due to their technology or their higher mileage. A case in point is diesel vehicles (above all, pre-Euro 6 models)[423,424] and actions on the public service vehicle fleet, the primary sector (highly diesel-reliant) and urban goods delivery[311,369]. On the other hand, there is no clear consensus on the potential use of synthetic fuels or biofuel since, although they are positive from the perspective of climate change, they have limitations or even negative effects, in terms of air quality[254,425-427,428].

Recent studies in Spain and other countries emphasise the importance of combining the different approaches[254] and different types of vehicle[428] in accordance with local characteristics (rural, urban context, etc.) to minimise the possible unwanted effects associated with each alternative.

Low-emission goods delivery

Currently, goods delivery involves a low percentage of vehicles, but a high mileage, which is responsible for a large proportion of road traffic emissions—around 15-30% of nitrogen dioxide or the particulates in a town[369]. Experts highlight the inclusion of environmental criteria for delivery vehicles, along with taking action on logistics and the efficiency of urban distribution (timetables, storage, and fixed or mobile central distribution platforms, etc.). These actions could significantly reduce emissions and avoid heavy pollution peaks[369,429,430].

Town planning: sustainable, healthier towns

The focus here is on holistic approaches that seek improvements in the health of people in urban environments[18,431,432]. From the perspective of air quality, the objective is to achieve urban reorganisation that enables, among other benefits, separating the public from intense road traffic (primarily in sensitive areas, including medical centres, residential areas or schools), reducing traffic, and facilitating access to basic services without the need for road transport. Main actions in this area focus on planning traffic flow-pedestrianisation[166,433,434] and the implementation of blue-green infrastructures associated with the presence of water and plants, among other solutions[435-438]. As well as fostering improved air quality and reducing negative impacts, the co-benefits of such approaches include noise mitigation, promotion of physical activity and personal health or even fighting against the overheating of urban spaces[431,437-439]. Although the balance in favour of health is positive, experts also highlight that green spaces affect allergic response among the population[437] and that bad planning of certain actions could generate local problems (a screen or shade effect derived from trees in streets, moving traffic to new zones, etc.)[440,441].

Despite the challenge represented by its implementation, there are examples in Europe, like London's low emissions areas[398], neighbourhoods without cars in German cities[432] or the 15-minute city in Paris[442]. Of note within Spain are Barcelona's superblocks (*superilles*),[401,443] and "walkable cities" such as Pontevedra's *Metrominuto*[444], among others[445].

· Retrofitting: the application of novel technologies, which did not previously exist, to old vehicles in order to reduce their pollutant emissions.
· ·Biofuel s (biodiesel, bioethanol, etc.): are produced from organic waste and biomass, and -in current development- from microbial sources. Most of these fuels available on the European market come from mixing biodiesel in diesel and bioethanol in petrol.

Domestic and residential sector

Energy efficiency and the use of heating systems or suitable fuels in the residential, commercial and institutional sector can significantly reduce emissions of particulates and other pollutants.

The general aim is to improve the energy efficiency of buildings446 and minimise emissions derived from the combustion of heating systems by optimising them, reducing the use fossil fuels and increasing the spread of renewables and electrification, among other measures37,311. The improvements include public buildings, as well as dwellings in use or under construction (regulations, subsidies, tax incentives, information, etc.)[351].

In this sector, one area of concern is biomass burning (open fires, stoves, pellet burners or similar)[447-450] due to the emission of particulates and other associated pollutants such as polycyclic aromatic hydrocarbons (**Box 1**)[197,451,452]. Although this activity is less common in Spain than in other European countries, it is on the rise in urban contexts, and predominates in rural areas at times when the price of fossil fuels is high[453,454], and above all in winter[448]. Some studies in non-urban areas have found air quality conditions due to biomass burning with a toxicity comparable to that of large cities. It is, therefore, important to address this issue in detail at national level[448,455,456]. In this context, the Norwegian experience[457] or the monitoring of levoglucosan levels in air[454] could be useful references (**Box 3**). Current mitigation measures focus on the use of certified fuels and heating systems, community systems rather than individual ones, and a careful selection of use (burning biomass in certain industrial sectors is not comparable to its extensive use in all dwellings)[197,311]. Countries like the United Kingdom or Norway and regions like Lombardy have set up strategies to restrict this type of activity with controls on the fuels and systems used in private homes. These schemes have met with varying success, and, in some cases, social acceptance has been difficult to achieve[197,447,458,459].

Industry

Despite a general improvement in emissions from this sector, some regional problems exist, and improvements can be made.

Las emisiones del tejido industrial asociadas a la mala calidad del aire experimentaron un marcado descenso (2000-2012)[460] gracias a las políticas estratégicas del sector[461]. Estas conllevan la aplicación de las mejores técnicas y prácticas disponibles al respecto[462–473] y el cambio de combustibles[29,87,251,460,462]. Aun así, la comunidad experta señala problemas de alcance regional que persisten a nivel nacional y requieren atención[474–476]. También destaca, entre otros aspectos, el margen de mejora en las emisiones de algunos contaminantes (como precursores de ozono o partículas)[45,462], ahondar en la caracterización del riesgo que implica para la ciudadanía para favorecer su regulación (composición y distribución temporal de las emisiones)[475,477] o el refuerzo del control en torno al cumplimento de los estándares de emisión[462,476]. Existen experiencias de mitigación eficaces en el contexto nacional que demuestran la importancia de la coordinación de todos los actores implicados[478,479].

Agriculture and livestock farming

Mitigation actions centre on the ammonia emissions associated with liquid manure, particulates and other pollutants associated with burning agricultural waste.

The tools to reduce emissions of ammonia, a precursor of fine particulates, mainly include actions aimed at agricultural practices, and the generation or management of liquid manure and manure[37,480,481]. Actions related to reducing ammonia emissions focus on both the types of manure or fertilizers and on how they are applied[37,482]. In the case of manure generation and management, best practices range from using low-protein feed for cattle, implementing technological advances in livestock housing or in storage and management of manure and liquid manure[37,355,483-485], to measures aimed at public consumption habits, such as reducing meat consumption[355,486-488]. In addition to minimising environmental risk, the reduction of ammonia is a cost-effective way of reducing the presence of fine particulates[56].

On the other hand, scientific evidence indicates the negative effects that burning agricultural waste has on air quality, health, agricultural activities themselves (productivity) and the climate[197,448,455,489-499]. These effects are the same in the case of forest fires[491,495,499-501].

· Burning agricultural waste: any deliberate burning undertaken in the agricultural or forestry sector, including stubble or pasture burning, incineration of pruning (from olive or fruit trees, etc.) or other waste/unwanted elements of trees, and the use of fire to clear fallow land, or unintended fires derived from such practices.

In addition to the emissions of especially toxic particulates (high organic carbon and/or black carbon content, see **Box 3**) this activity also generates ozone precursors, contributing to peaks in its formation[502]. In European countries, legal frameworks vary from a total ban on this practice to temporary permission granted depending on the season, the type of crop and farm, etc.[503]. In Spain, it is permitted to burn plant waste, in specific circumstances, with regional government authorisation[504,505]. The large volume that this sector represents in Spain is significant: estimates for 2020 calculated the open burning of more than 6 million tonnes of agricultural-origin dry biomass[506].

Scientists advise that there should be a complete ban on this activity to avoid the negative impact it produces[197,494]. Alternative practices to burning exist, depending on local characteristics (crop, climate, socioeconomic factors, etc.). Such practices are related with conservation agriculture, strip till, an alternative use of the waste (animal feed, bioenergy for industry and/or residential use, composting, etc.) or other possibilities[494]. For the sector to assimilate these alternatives, it would be necessary (in the following order) to[494]: precisely define the state of agricultural burning (satellite technology can be helpful[494,507,508]); undertake capacity building and training for the sector; and finally, develop regulations and financial support (subsidies, incentives, etc.) to guarantee profitability.

Social change: information, perception and behaviour

Effective communication strategies exist that can foster self-protection, reduce the public's emissions, and gain their commitment to and collaboration in developing and carrying out public policies.

Social sciences, particularly information and behavioural sciences, play a crucial role in air quality management[41,310,509-511]. Although a wide range of public information is available on air quality[511] (historical levels or real-time forecasts, indexes that aim to reduce personal exposure)[512,513] most of the public consider themselves ill-informed[13]. Indeed, the draft of the European directive on air quality contemplates improvements in this area[7,256].

Disseminating information about air quality and on the risks that pollution entails for health has great potential to inspire public attitudes and/or behaviour aligned with combating this challenge. This can act in favour of self-protection, lead to a reduction in public's emissions from daily activities, or influence citizens' attitude to public policies, among other advantages. However, wider availability of information about the problem does not always translate into changes in public habits. Change in this sense depends on a wide set of factors (receptor -personal-, channel, source or characteristics of the message). This complexity makes it difficult to define general patterns in the effect of public communications[310,347,511,514-517].

Studies on public attitudes may contribute to guiding public policies and limiting the set of factors that modify acceptance and public response[310,402,403-405,516,518]. Scientific evidence does exist about communication actions, methods and strategies that encourage changes in behaviour, although this is a field where major advances are still necessary[514,519-521]. Among a wide range of recommendations are to: combine information about air quality with positive messages that motivate action, increase the perceived self-sufficiency or control of the individual regarding this problem, and use prestigious scientific and institutional sources that inspire the general public's trust[310].

Positive messages should emphasize the health and mitigation benefits of personal actions, rather than solely focusing on alerting to risksk[310]. Self-sufficiency can be improved by providing detailed, personalised information about how to carry out effective, specific actions or how to modify an individual's environment to facilitate personal actions[310,405]. Additionally, both in Europe and Spain, different initiatives in citizen science focus on developing and redefining the role of the public to air quality and associated public policies[14,280,522-526] through public involvement in monitoring (low cost sensors, **Box 3**) or the creation of citizen laboratories[527,528] among other initiatives. These experiences can promote collective action, as well as understanding and awareness of the subject, although they do not guarantee a change in social behaviour[263,529,530].

The public represents an essential component that can support or limit the introduction of measures and plans aimed at mitigating the problem of air quality[14]. Therefore, to improve and develop public policies on air quality, it is important to establish committed and trust-based communication and connections between citizens and the government[26,310], engaging the population in the development of mitigation strategies and enhancing understanding of the underlying mechanisms for air quality improvement.

Key concepts

- Air pollution worldwide generates environmental and public health problems, contributes to inequality and constrains the economy. In Spain, only three of the many pollutants that define air quality—fine particulate matter, nitrogen dioxide and ozone—are responsible for 17,000, 4,800 and 2,400 premature deaths each year, respectively. In terms of the environment, bad air quality causes a loss of biodiversity and low agricultural productivity. Estimates place its economic impact around 40,000 million euros by 2030.
- Thanks to the public policies, air quality has improved in both Europe and Spain. Nevertheless, experts highlight that progress is insufficient:
    - The presence of fine particulate matter, followed by nitrogen dioxide and ozone is responsible for the main negative effects on health.
    - High levels of ozone pose a significant challenge in the Spanish context.
    - Large areas of Spain and of EU territory significantly surpass the air pollution level recommendations set by World Health Organisation, which are stricter than current Spanish regulations (certain parameters of which are not complied with).
- Spain has an air quality monitoring network that complies with EU Directive requirements and aligns with international standards. There are scientific developments and technical improvements that may further enhance monitoring and protection.
- Steps to improve air quality focus on the various sectors responsible for pollutant emissions:
    - Noteworthy actions include efforts to reduce the emissions from traffic, the residential sector, commerce and institutions, industry and agriculture and livestock farming..
    - Technological measures exist that could help mitigate the problem in all sectors but are insufficient on their own.
    - Social actions aimed at redesigning urban areas and reshaping the public's role need to be undertaken.
    - Effective communication between the different social actors involved can foster public commitment to and collaboration in developing and carrying out public policies.
- Air quality and the climate change are closely interrelated, necessitating integrated policies. Research is essential to develop mitigation measures that generate co-benefits not only in these two areas but also in others (health, social justice, the economy).
- The revision of the existing EU directive aims to enhance protection of public health, strengthen monitoring, improve access to justice and boost the potential of citizen information mechanisms.

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