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AMBIENT AIR POLLUTION: A GLOBAL HEALTH CRISIS

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Abstract

Air pollution is a significant environmental and public health threat, contributing to approximately 7 million deaths annually, as reported by the World Health Organization (WHO). Major pollutants such as particulate matter (PM10 and PM2.5), carbon monoxide (CO), ozone (O3), nitrogen dioxide (NO2), and sulfur dioxide (SO2) are linked to severe health conditions such as cardiovascular diseases, strokes, respiratory illnesses, chronic obstructive pulmonary disease (COPD), and cancer. Vulnerable populations - the elderly, children, pregnant women, and individuals with pre-existing conditions - face the highest risks. Long-term exposure to air pollution has been associated with a tenfold increase in health complications compared to short term exposure. While research has clarified many of the biological pathways through which pollutants affect human health, ongoing studies continue to explore the full extent of these effects. This study provides a comprehensive analysis of the latest data on the health effects of ambient air pollution, with a particular focus on Bulgaria. It identifies key trends, examines policy gaps, and evaluates the effectiveness of existing air quality regulations. By incorporating a comparative analysis of WHO, EU, and Bulgarian air quality standards, this research underscores the pressing need for stricter regulatory measures and enhanced mitigation strategies to curb pollution-related morbidity and mortality. The findings highlight the urgency of aligning national air quality policies with WHO guidelines to safeguard public health and drive sustainable environmental initiatives.

Key words: *ambient air pollution, air pollutants, air quality, diseases, health impacts, regulatory policies, WHO guidelines.*

INTRODUCTION

Air pollution is a major environmental factor that affects every individual and is a leading cause of numerous diseases worldwide. Globally, the main sources of air pollution are industry (large enterprises, TPPs, steel plants, petroleum refineries, cement factories), transport (road, air, maritime), households and agriculture. According to the WHO, each year 7 million deaths including 600,000 children are caused by polluted air (4.2 million from outdoor air pollution, and 3.8 million from indoor air pollution). Nine out of 10 people around the world live in regions where air pollution exceeds the WHO guidelines. More than 89% of deaths caused by air pollution occur in low- and middle- income countries (WHO, 2024a; Le et al., 2024). Some scientists believe that this number is even bigger estimating at least 9 million people to die every year from the air they breathe (UNEP, 2021; Vohra et al., 2021). Air pollution has also considerable economic impacts, reducing life expectancy, increasing medical costs and reducing productivity through working days lost across various economic sectors (EEA, 2020). The World Bank estimated global air pollution cost at $8.1 trillion in 2019, equivalent to 6.1% of global GDP. In individual countries, the economic burden of pollution associated with premature mortality and morbidity is significant, equivalent to 5-14% of countries' GDPs (WB, 2023). The Organisation for Economic Co-operation and Development (OECD) reported “that a 1 $\mu g/m^3$ decrease in annual mean $PM_{2.5}$ concentration would increase Europe's GDP by 0.8%, representing around €200 per capita per year as result of increases in output per worker, through lower absenteeism at work or increased labour productivity, due to lower air pollution” (EEA, 2020).

Pollutants with the strongest evidence for public health concern include particulate matter (PM), carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). Health problems can occur after both short- and long-term exposure to these various pollutants (Cesaroni et al., 2014; Schwartz et al., 2017; Burnett et al., 2018; Kermani et al., 2018; Zheng et al., 2021; Dass et al., 2021; Popa et al., 2021; Babu et al., 2022). For some pollutants (VOCs, PAHs, O_3), there are no thresholds below which adverse effects do not occur (Papadogeorgou et al., 2019; Manisalidis et al., 2020). Air pollution usually has a greater impact on people living in urban rather than in rural areas. The bigger air polluting sources (industry, traffic, household burning, etc.) and higher population density in the cities lead to high concentration and retention of the atmospheric pollutants (Olstrup et al., 2021; Kozlov et al., 2022; Carozzi & Roth, 2023; Akomolafe et al., 2024; Kar et al., 2024).

Numerous studies reveal the link between polluted air and human health. Air pollution is associated with many diseases affecting different human body systems and functions - respiratory system (Sierra-Vargas & Teran, 2012; Thurston et al., 2017; Heger et al., 2019; Popa et al., 2021; Lee et al., 2021; Kienzler et al., 2022; Lan et al., 2024), cardiovascular system (Shahrbaf et al., 2021; D'Acquisto et al., 2023; Bhatt, 2024; Sadeghi & Sadeghi, 2024), immune system (Dobreva et al., 2015; Ivanov et al., 2016; Glencross et al., 2020), reproductive system (Popa et al., 2020; Shetty et al., 2023), endocrine system (Saleem et al., 2024), nervous system (Solaimani et al., 2017; Thurston et al., 2017), cognitive functions (Meo et al., 2024), mental health (Keswani et al., 2022; Bai et al., 2024) as well as with increased mortality of the affected people (Turner et al., 2020; WHO, 2024b). Vandyck et al. (2022) point out that health considerations form a strong argument in favor of policy action to concurrently mitigate climate change and control air pollution.

EU's policy and legislation on reducing the emissions of harmful substances through the years give positive results; today the air is cleaner than it was two decades ago. Nevertheless, human health is still threatened by various air pollutants (EEA, 2022, 2023a, 2023b). In 2021, premature deaths attributed to exposure to fine PM decreased by 41%, compared to 2005 (EEA, 2023b). The Zero Pollution Action Plan aims to decrease premature deaths caused by exposure to fine particulate matter (PM) by 55% by 2030, compared to 2005 levels. However, despite continued emission reductions, a significant portion of the EU's urban population remained exposed to harmful concentrations of key air pollutants - $PM_{2.5}$, PM_{10}, O_3, NO_2, Benzo[a]pyrene (BaP), and SO_2 - in 2022 (EEA, 2024). In 2021 in the EU-27, total of 327,000 deaths were attributable to exposure to $PM_{2.5}$ (77.4% of all deaths), NO_2 (15.9% of all deaths) and O_3 (6.7% of all deaths) concentrations above 2021 WHO's guideline levels (EEA, 2023b). In 2020, the EC initiated a revision of the ambient air quality directives, aiming to align the air quality standards more closely with the WHO recommendations. As a result, a new Directive (EU) 2024/2881 of 23 October 2024 on ambient air quality and cleaner air for Europe was accepted. Further efforts will be needed to meet the zero-pollution vision for 2050 of reducing air pollution to levels no longer considered harmful to health.

Following the EU policy and legislation referring to the air quality improvement, Bulgaria reported a significant reduction of the air pollution in the last decades. Positive trends in air quality are attributed to active policies and measures at all levels, including legislative harmonization with European standards. The amendments made in the Air Purity Act (1996) emphasize municipal responsibility for air quality improvement, strengthen central government oversight, and the effective implementation of municipal programs (Zheleva, 2024). In 2022, the emissions of $PM_{2.5}$, SO_2, NO_x and NMVOCs have decreased by 30, 94, 53 and 26%, respectively compared to 2005. However, pollution with PM and partly with BaP continues to be a major problem for the ambient air quality in many settlements in the country. The main causes of excessive particulate pollution are solid fuel heating during the winter season and emissions from road and public transport (ExEA, 2024).

The brief review shows that addressing air pollution, which is the second highest risk factor for non-communicable diseases, is key to protecting public health. Despite the progress made, the problem with air pollution has not yet been solved. The tools for achieving this goal include well-motivated policies, adequate legislation, effective practices (monitoring, control, etc.) and reliable and sustainable results. It turns out that there are differences at global (WHO), regional (EU) and local (individual countries) level, both in the regulation of air pollutant levels and interim targets for a gradual shift from high to lower concentrations and their associated health benefits. This gave us the basis to define the scope of our review: the paper first explores the key air ambient pollutants, then assesses their health impacts, partly in Bulgaria, make a comparative analysis of WHO, EU and Bulgarian standards, and concludes with policy recommendations for air quality improvement.

MATERIALS AND METHODS

This review summarizes and analyses the primary information from databases like Google Scholar, PubMed, ResearchGate, and Science Direct. The keywords used were air pollution, particulate matter, gaseous pollutants, human health risks, morbidity, mortality, and air quality standards. We have reviewed 245 studies, including journal articles, conference papers, WHO, EEA, USEPA and Word Bank reports, and country-specific reports, focusing on ambient air pollution and its impact on human health, respectively morbidity and mortality. After the selection, 104 literature sources (mainly from the recent years), including 88 scientific articles published in a peer-reviewed journals and 16 reports and data from different institutions were used.

RESULTS AND DISCUSSIONS

Classic air pollutants

Since 1987, WHO has periodically issued health-based air quality guidelines (AQGs) to assist governments and civil society in reducing air pollution and its adverse effects on human. Those guidelines are not legally binding standards but are a science-based tool that countries around the world can use to improve their policy and legislation aimed at air quality improvement. The new WHO guidelines, published in 2021 (WHO-AQG, 2021), recommend specific air quality levels regarding six pollutants ($PM_{2.5}$ and PM_{10}, NO_2, SO_2, CO and O_3) with the highest evidence for a negative impact on people's health. The WHO determines those pollutants as "classic" pollutants; briefly, they are characterized as follows:

Particulate matter (PM): PM is a complex mixture of solids and aerosols (organic, inorganic) composed of small droplets of liquid, dry solid fragments, and solid cores with liquid coatings. Particles vary widely in terms of size, shape and chemical composition (Estuardo-Moreno et al., 2022). PM may be either directly emitted from sources (primary particles) – natural (ground surface dust, volcanic activity, salts, etc.) and anthropogenic (industry, transport, energetics, household heating, etc.), or may be formed in the atmosphere through chemical reactions of gases (secondary particles) such as SO_2, NO_x, NH_3 and VOCs. According to their size, PM may be divided in 5 groups – supercoarse PM ($d_{pa} > 10$ μm; d_{pa} – aerodynamic particle diameter), coarse PM ($2.5 < d_{pa} \leq 10$ μm), fine PM ($0.1 < d_{pa} \leq 2.5$ μm), ultra-fine PM ($d_{pa} \leq 0.1$ μm) and nanoparticles (NPs) ($1 < d_{pa} \leq 100$ nm). PMs consist mainly of sulfates, nitrates, ammonia, sodium chloride, black carbon (BC), mineral dust and water (Sierra-Vargas & Teran, 2012; Khan et al., 2019; Manisalidis et al., 2020; Kumari & Sarkar, 2021; WHO, 2024a).

Nitrogen dioxide (NO_2): NO_2 is a reddish-brown, highly reactive water-soluble gas, and a strong oxidant. It results from both anthropogenic and natural processes; the main anthropogenic activity leading to NO_2 emissions being the combustion of fossil fuels from industrial sources (coal, gas and oil), vehicles and power plants (Mesas-Carrascosa et al., 2020; Babu et al., 2022).

Sulfur dioxide (SO_2): SO_2 is a toxic colourless gas with a sharp odour; it mainly originates from burning of fossil fuels that contain sulfur (coal, crude oil) in power stations and refineries. The volcanos and oceans are the main natural source of SO_2; it causes health problems in humans, animals and plants (Babu et al., 2022; WHO, 2024a).

Carbon monoxide (CO): CO is a colourless, odourless and tasteless toxic gas produced by incorrect combustion processes (transport, thermal power plants, combustion installations etc. (Babu et al., 2022; WHO, 2024a).

Ozone (O_3) – tropospheric: O_3 is formed through chemical reactions between hydrocarbons, CH_4 and NO_x under the influence of ultraviolet light; it is a strong oxidant and one of the major constituents of photochemical smog (Popa et al., 2020; Babu et al., 2022).

It is important to note that the new WHO AQGs do not include recommendations about pollutant mixtures as well as the combined effects of pollutant exposures, which is a serious omission as usually the people are exposed to a mixture of air pollutants that varies in space and time. Nevertheless, the achievement of the WHO AQGs permissible levels for all these pollutants is necessary to minimize the health risk for humans.

Impact of air pollution on health

In present days, the air pollution is one of the most serious ecological problems with significant impacts on the human health everywhere in the world, particularly in the urban areas. Some population groups are more affected by air pollution than others, because they are more exposed (lower socio-economic groups) or susceptible (older people, children and those with pre-existing health conditions) to environmental hazards (EEA, 2022). The degree of effect on the body depends on the pollutant composition, source and dose, level and duration of exposure to polluted air (Le et al., 2024). To solve the problem, two aspects must be considered - on one hand, to know how the individual air pollutants influence human health and on the other - how the mixtures of pollutants do that.

Air pollutants – human body effects

PM_{10}, $PM_{2.5}$, SO_2, NO_2, CO, and O_3 are the air pollutants considered most harmful to humans (Manisalidis et al., 2020; Ruwali et al., 2024; Saleem et al., 2024). There is suggestive evidence linking the individual air pollutants with human health status, which could be summarized as follows:

(PM): Exposure to fine particle outdoor air pollution is the largest environmental risk factor for premature death globally. In 2022, 96% of the urban population was exposed to concentrations of fine PM above the health-based guideline level set by the WHO (EEA, 2024). In the same year, around 4.7 million people died from exposure to fine particulate outdoor air pollution (28% of all deaths) and the average global life expectancy was reduced by approximately one year and eight months (UNEP, 2021). New research reveals some of the mechanisms behind PM's harmful effects on human health. Li et al. (2024) analyzed the long-term oxidative potential (OP) of water-soluble $PM_{2.5}$ and found that dust, gaseous pollutants (NO_2 and SO_2), black carbon and biomass combustion are the main sources of the OP of $PM_{2.5}$. It is well documented that short-term and long-term exposure to $PM_{2.5}$, PM_{10} and NPs have a significant influence on the human body. Exposure has been linked to a wide range of adverse health effects, including neurological disorders, exacerbation of asthma, and chronic obstructive pulmonary disease (COPD). It also contributes to reduced lung function, lung cancer, silicosis, and tuberculosis. Furthermore, it impacts the reproductive system and increases the risk of cardiovascular conditions such as cardiac arrhythmias, nonfatal heart attacks, and myocardial infarction. Additional effects include irritation of the eyes, throat, and nose, impairment of mucociliary and macrophage activity, neurodegenerative diseases, cerebrovascular conditions, cognitive decline, dementia, and disruptions in children's brain development (Solaimani et al., 2017; Zaheer et al., 2018; Kermani et al., 2018; Silva et al., 2020; Popa et al., 2021; USEPA, 2024). Hofmann et al. (2015) established a relationship between fine dust exposure and the incidence of stroke. Short, mid-, and long-term pre-exposure can significantly exacerbate small-airway inflammation, particularly in males, children, smokers, and individuals with pre-existing respiratory conditions (Lei et al., 2024). Prolonged exposure to PM10 and PM2.5 has been linked to a higher incidence of acute coronary events, even at concentrations below the EU regulatory limits (Cesaroni et al., 2014), as well as an increased risk of premature mortality (Vohra et al., 2021; Isaifan, 2023). Not only long-term exposure, but also acute increases in PM_{10}/$PM_{2.5}$ concentration (up to 10 $\mu g/m^3$) are associated with cardiovascular hospitalization or death with an increase of 1.63% per PM_{10} and 2.12% for $PM_{2.5}$, the most prominent on the day of exposure (Shah et al., 2013). Heger et al. (2019) suggested that the concentration of PM_{10} in the air was an important predictor of the respiratory diseases. The proportion of deaths attributed to outdoor fine particulate air pollution varied by disease, with chronic obstructive pulmonary disease (COPD) accounting for 48%, lower respiratory infections for 30%, ischemic heart disease for 28%, and stroke for 27%. Additionally, 19% of deaths were linked to tracheal, bronchus, and lung cancer, 18% to type 2 diabetes, and 14% to neonatal disorders (UNEP, 2021).

(SO_2): That toxic gas affects susceptible people with lung disease, old people, and children, who present a higher risk of damage. Exposure to high concentrations of SO_2 in the air is associated with headache, anxiety, respiratory problems (facilitates bronchoconstriction, cough, affects the mucous membranes of the throat, nose and eyes) and cardiovascular diseases (Manisalidis et al., 2020; Popa et al., 2020; USEPA, 2024).

(NO_2): NO_2 creates respiratory problems as affects the mucous membranes of the nose, eyes and throat; increases bronchial reactivity and susceptibility to infections; provokes bronchitis, allergic rhinitis, chronic lung disease and even pulmonary edema and tuberculosis; affects some organs (liver, spleen) and the circulatory system (Lin et al., 2019; Manisalidis et al., 2020; Babu et al., 2022).

(CO): CO in the air penetrates very easily through the alveoli of the lung into the human circulatory system, has effects on hemoglobin by blocking oxygen transport (the affinity of CO to hemoglobin is about 250 times greater than that of oxygen). The result is hypoxia, ischemia and cardiovascular disease, effects on the fetus, headaches, nausea, vomiting, dizziness, weakness, vomiting, tuberculosis and eventually loss of consciousness; also, working with CO may result in fatal poisoning (Lin et al., 2019; To et al., 2020; USEPA, 2024).

(O_3): As a strong oxidant, O_3 affects predominantly the respiratory system, which is manifested with inflammation of the mucous membranes of the respiratory tract, causes coughing, chest discomfort, obstruction of the airways, damage to the epithelium lining the airways. It can also cause cardiovascular diseases (Popa et al., 2020; USEPA, 2024). The European research project APHEA2 found out a correlation between daily fatalities and ozone levels; a short-term rise in ozone concentration was connected to an increase in daily fatalities (0.33%), respiratory deaths (1.1%), and cardiovascular deaths (1.1%), (Babu et al., 2022).

Diseases associated with exposure to air pollution

Air pollution typically consists of a complex mixture of multiple pollutants, which together have a more pronounced impact on human health than individual pollutants alone. To evaluate these effects, two key indicators - mortality and morbidity - are commonly used (Thacker et al., 2006). A widely applied metric for assessing the combined burden of both mortality and morbidity is Disability-Adjusted Life Years (DALY), which quantifies the total number of years lost due to disease, injury, or exposure to harmful risk factors. One DALY represents the loss of one year of healthy life (EEA, 2023b) (Figure 1).

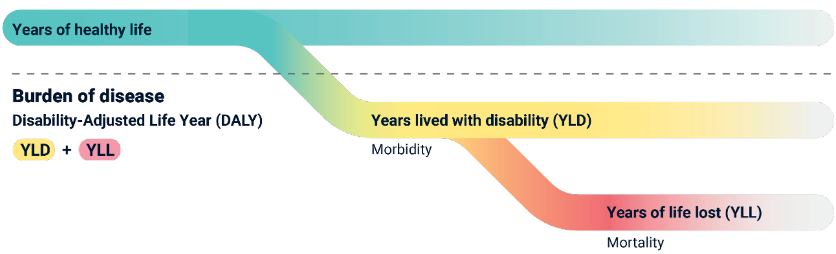

Figure 1. Burden of disease (DALY) as sum of years lived with disability (YLD) and years of life lost (YLL) (Source: EEA, 2023b)

Mortality: This indicator represents the number of deaths resulting from a specific disease or a group of diseases. In scientific studies, reports, and analyses, mortality is commonly expressed as premature deaths (PD) or years of life lost (YLL) to quantify the impact of early mortality.

Schwartz et al. (2017) established a causal association of local air pollution with daily deaths at concentrations below USEPA standards; the increase of the $PM_{2.5}$ and black carbon concentrations was associated with a 0.90% increase in daily deaths; a weaker association was observed for NO_2. In 2021, air pollution led to a significant number of premature deaths in Europe (excluding Türkiye): exposure to concentrations of fine PM above the 2021 WHO guideline level (5 µg/m^3) resulted in 293,000 premature deaths; exposure to NO_2 above the respective guideline level (10 µg/m^3) led to 69,000 premature deaths; acute exposure to O_3 (70 µg/m^3) caused 28,000 premature deaths (EEA, 2023b).

Morbidity: This is a very precise indicator to assess the public health deviation. Morbidity is generally divided in two categories - outpatient care and inpatient care (hospitalization). The morbidity is affected by changes in atmospheric pollutant concentrations (Thacker et al., 2006; Platikanova & Penkova-Radicheva, 2016). Numerous studies have established a strong link between air pollution exposure and morbidity. Platikanova et al. (2018) developed a mathematical model to predict morbidity rates in different residential areas based on correlations between air pollutants (PM10, SO_2, NO_2, and Pb-aerosol) and health outcomes. Short-term exposure to air pollutants and smog is strongly associated with conditions such as COPD, coughing, shortness of breath, wheezing, asthma, respiratory diseases, and increased hospitalization rates. Meanwhile, long-term exposure has been linked to chronic asthma, pulmonary insufficiency, cardiovascular diseases, cardiovascular mortality, and reproductive system impairments in both males and females (Manisalidis et al., 2020; Tran et al., 2023; Saleem et al., 2024). Recently, some researchers suggested that air pollution, especially with $PM_{2.5}$, may be associated with cardiac arrhythmias due to the oxidative stress, autonomic dysfunction, coagulation dysfunc-tion, and inflammation (Shahrbaf et al., 2021). Air pollution (O_3, NO_2, SO_2, and PM) may exacerbate asthmatic symptoms, to increase the morbidity and mortality and risk of hospi-talization associated with respiratory diseases (Lee et al. 2021; Yuan et al., 2024). Data, based on the ETC/HE report (Kienzler et al., 2022), showed that in 2020 in Europe, COPD associated with exposure to $PM_{2.5}$ was on the average 51.6 years lived with disability (YLDs) per 100,000 inhabitants ≥25 years (lowest value 1.2 Iceland - highest value 89.5 Serbia, Bulgaria 70.4); for NO_2 the highest morbidity burden resulted from diabetes mellitus with 54.6 YLDs per 100,000 inhabitants ≥35 years (lowest value 3.7 Estonia - highest value 145.5 Türkiye, Bulgaria 49.0), and for short-term O_3 exposure hospital admissions due to respiratory diseases were estimated at 18 cases per 100,000 inhabitants ≥65 years (lowest value 4 Iceland - highest value 29 Austria). For each specific air pollution-related disease, the relative contribution to poor health (the burden of disease) from mortality and morbidity can vary significantly. For instance, mortality is by far the dominant contributor for ischemic heart disease and lung cancer, while for asthma it is morbidity (EEA, 2023b).

Air quality and human health: a focus on Bulgaria

Bulgaria (111,000 km^2, population 6,440,000) is divided into six regions for atmospheric air quality (AQ) assessment and management: the agglomerations of Sofia (capital, 1,224,000 residents), Plovdiv (325,000 residents), and Varna (314,000 residents), and the North Danube, South-West, and South-East regions. The Bulgarian National Environmental Moni-toring System assesses air quality (AQ) across these regions by 12 air pollutants according to the national and EU legislation, as follows: PM_{10}, $PM_{2.5}$, O_3, NO_2, SO_2, CO, benzo(a)pyrene (BaP), heavy metals (Pb, Cd, Ni), As, and benzene /C_6H_6/ as well as population exposure (ExEA, 2024).

In the last decades Bulgaria has constantly reduced the levels of air pollutants. Bulgaria's commitments under Directive (EU) 2016/2284 and the amended Gothenburg Protocol to the Convention on Long-Range Transboundary Air Pollution (LRTP) for emission levels of SO_2, NO_x, NMVOCs and $PM_{2.5}$ for 2022 have been fulfilled. Unfortunately, these changes occur slowly and despite improvements, pollutant levels still have significant adverse impacts on human health and the environment. The effects of air pollution are felt most strongly in urban areas, where lives 73.3% of the population and the people experience significant health problems (ExEA, 2024; Zheleva, 2024). Large anthropogenic sources of air pollution are electricity and heat production, industry, domestic heating, road transport and agriculture. Thermal power plants (TPPs), including refineries, are the largest sources of SO_2 - 66% of the total amount emitted in the country; the main sources of NO_x are road transport - 38%, TPPs - 25%, agriculture - 18%, combustion processes in industry – 6%, and other transport - 4%; domestic heating is a major source of PM (47% of the total PM_{10} and 69% of total $PM_{2.5}$ emissions), other sources are the agriculture and road transport (ExEA, 2024).

Nowadays, PM air pollution continues to be a major problem for the air quality at the national level (Naydenova et al., 2018; Georgieva et al., 2021; Zheleva, 2024), especially during the winter months in the big cities– Sofia (Dimitrova & Velizarova, 2021), Plovdiv (Ivanov et al., 2023), Ruse (Takuchev et al., 2018; Nikolova et al., 2023), Stara Zagora (Stoykova et al., 2023; Ivanova et al., 2023), Pernik (Ivanov, 2016), and Vidin (Minkova et al., 2023; Kostova-Ivanova, 2024). In 2020, fine particle pollution caused the death of 71 per 100,000 people, a rate higher than that in Slovenia - 16, Croatia - 38 and Romania - 46, and lower than that in Serbia - 79 and North Macedonia - 120 (UNEP, 2021). In 2022, the population share exposed to excessive PM_{10} levels was substantially higher than the EU countries average (10-19% for 2015-2020), reaching 41% (2,640 million people). About 60% of the population in Bulgaria lives in areas with pollution levels above the target norm for benzo(a)pyrene (in EU countries it is 15-17% of the population for the period 2017-2021), and about 0.5% of the population lives in the areas with above-average annual NO_x levels (for EU it is between 0.8-8.0% of the population for the period 2015-2021). The others key pollutants - $PM_{2,5}$, O_3 and SO_2 did not exceed the relevant norm, while in EU up to 8.0% of the population was exposed to O_3 levels above the norm for the period 2015-2021. Notably, individuals in rural areas are exposed to higher levels of O_3 compared to urban residents. In cities, ozone levels are lower due to its depletion through the oxidation of NO to NO_2, which reduces its concentration (ExEA, 2024). Exposure to outdoor air pollution is associated with a broad spectrum of acute and chronic health effects ranging from irritant effects to death. Ivanov et al. (2016) observed an increase of the respiratory diseases, reduced immune defense and activation of the cardiovascular diseases among the population of Pernik town (81,700 residents) in the period 1980-2010, when the levels of PM and SO_2 in the air were over the standard. Platikanova and Penkova-Radicheva (2016) reported that the air pollution (PM, SO_2, NO_2, H_2S and Pb) of Stara Zagora (142,000 residents), one of the industrial centers in the country, located near the Maritsa-Iztok energy complex (4 TPPs), affects human health directly through pathological changes in the human organism. Epidemiological studies of Dobreva et al. (2015) demonstrated that the exposure to different air pollutants, including PM_{10} and $PM_{2.5}$ has been related to adverse effects on the immune system (modulate cytokine production and change the balance between pro-inflammatory TNF-α and anti-inflammatory IL-10 production) of adolescents, living in the cities of Stara Zagora, Kazanlak, and Chirpan. Takuchev et al. (2018) established statistically significant positive correlations between the concentrations of the investigated air pollutants (PM_{10}, $PM_{2.5}$, NO_2, SO_2, O_3, CO, CH_4, benzene and BC) in the town of Ruse and the health status of the patients in 73 of the 125 clinical pathways; the pollutant with the greatest impact on the health was the CH_4, often in combination with benzene and fine PM. Georgiev et al. (2025) found a general increase in hospital admissions for respiratory diseases, ischemic heart disease and cerebral infarction associated with higher pollution levels ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, and CO) in the cities Sofia, Plovdiv and Vidin during 2009-2018.

According to data of the European Environment Agency (EEA), in 2021 the estimated number of attributable deaths in Bulgaria resulting from $PM_{2.5}$ pollution (15.1 μg/m^3 annual mean value) was 10,800; resulting from NO_2 pollution (17.5 μg/m^3 annual mean value) - 2,200 and resulting from O_3 pollution (2,668 annual sum of daily maximum running 8-h average concentrations over 70 μg/m^3) was 460. The values for the absolute number of the attributable deaths resulting from $PM_{2.5}$, NO_2 and O_3 pollution are calculated based on the number of the population of the different countries and because of that, they could not be compared. Logically, countries with larger populations (Poland, Italy and Germany) had a higher number of deaths than countries with smaller populations (Estonia, Finland and Sweden). A suitable indicator for between-countries comparison of deaths resulting from air pollution is years of life lost (YLL). In 2021 in Bulgaria, the YLL per 100,000 inhabitants attributable to exposure to $PM_{2.5}$ was 1,443, to NO_2 - 294 and to and to O_3 - 63. Those data were higher than the average values for EU-27 - by 2.47 times for $PM_{2.5}$, by 2.45 times for NO_2 and by 1.19 times for O_3. Referring to the neighboring countries, similar data were reported for Romania (1,111, 275 and 60, respectively) and higher for Serbia (1,938, 212 and 99, respectively) and North Macedonia (2,115, 169 and 88, respectively), (EEA, 2023). The comparison of the new WHO guidelines (2021) with the standards applicable in Bulgaria (Regulation No.12/2010) and with the new EU Directive (Directive /EU/ 2024/2881) revealed that the WHO AQGs are more stringent than the standards in Bulgaria and EU (Table 1).

Table 1. Comparison of WHO, Bulgarian and EU standards regarding air quality

Pollutant	Unit	WHO AQG, 2021		Bulgarian standard[a]	EU AQS, 2024[b]	
		Reference period	Recommendation		Target by 11.12.2026	Target by 01.01.2030
$PM_{2.5}$	μg/m^3	24-hour[c]	15	-	-	25[k]
		calendar year	5	20	25	10
PM_{10}	μg/m^3	24-hour[c]	45	50[e] (20%)[l]	50[e]	45[k]
		calendar year	15	40 (50%)[l]	40	20
O_3	μg/m^3	peak season[d]	60	-	-	-
		8-hour[c]	100	120[f]	120[f]	120[f]
NO_2	μg/m^3	24-hour[c]	25	-	-	50[k]
		calendar year	10	40	40	20
SO_2	μg/m^3	24-hour[c]	40	125[j]	125[j]	50[k]
		calendar year	-	-	-	20
CO	mg/m^3	8-hour	-	10[i] (60%)[l]	10	10
		24-hour[c]	4	-	-	4[k]

Notes: a - Bulgarian standard, Regulation No.12/15.07.2010; b - EU Air Quality Standard (AQS), Directive (EU) 2024/2881; c - 99[th] quantile range (e.g., exceeding 3-4 days/calendar year); d - the highest average O_3 concentration over 8 hours daily for 6 consecutive months; e - not to be exceeded on more than 35 days per calendar year; f - not to be exceeded on more than 25 days/calendar year, averaged over 3 years; j - not to be exceeded on more than 3 days per calendar year; i - maximum 8-hour average value within 24 hours; k - not to be exceeded more than 18 times per calendar year; l - permissible deviation (%).

The permissible annual levels for $PM_{2.5}$, PM_{10} and NO_2, and for O_3 (8-hour exposure) in the Bulgarian standard, in force since 2010, are higher than those in the 2021 WHO AQGs by 4.0, 2.67, 4.0 and 1.2 times, respectively; for the 24-hour norms – by 1.11 times for PM_{10} and by 3.12 times for SO_2. In fact, a similar picture can be observed in other EU countries, as the EU legislation is mandatory for all member-states. For example, Góra (2024) made the same conclusion when comparing WHO AQGs with the Polish standard. The norms of the classic air pollutants in the new EU standard (2024) are also higher than those in the 2021 WHO recommendations: for 2026 (the first target) the EU annual permissible levels exceed the WHO norms by 5.0 times for $PM_{2.5}$, by 2.67 times for PM_{10} and by 4.0 times for NO_2 (for a calendar year), and by 1.2 times for O_3 (for 8-hour exposure); for the 24-hour norms – by 1.11 times for PM_{10} and by 3.12 times for SO_2. The EU norms of the pollutants that must be reached in 2030 (the second target) are closer to those of the 2021 WHO recommendations, but remain higher: for the annual norms – by 2.00 times for $PM_{2.5}$ and NO_2, by 1.33 times for PM_{10}, and by 1.20 times for O_3 (8-hour exposure); for the 24-hour norms – by 1.67 times for $PM_{2.5}$, by 2.0 times for NO_2 and by 1.25 times for SO_2. Only the PM_{10} 24-hour norm is equal to the WHO standard (45 μg/m^3). In the EU 2026-first target/Bulgarian standard there neither average daily norms for $PM_{2.5}$, NO_2 and CO, nor average annual norms for SO_2 and O_3 (peak season). In the EU standard for 2030-second target, norms are included for all reference periods with one exception, there is no standard for O_3 (peak season). However, the new EU Directive makes a serious progress in gradually reducing the permissible levels of classic air pollutants, comparable to the levels proposed by the WHO. According to the EU Zero Pollution Action Plan, the first goal must be reached until 11.12.2026, the second – until 01.01.2030, and the last one – until 2050 ("zero pollution"), when air pollution must be reduced to levels safe to human health and ecosystems (EEA, 2024).

Policy recommendations

There are many examples of successful policies that reduce air pollution (WHO, 2024a). Below, we present some well-addressed, specific and feasable solutions to improve the air quality and reduce the health risk to people.

For citizens: It all depends on the people, that's why, the civil society play a key role in achieving better air quality as it can pose a constant pressure on the authorities to improve the environment, respectively, the quality of life. To be able to carry out this activity, the people must be well informed about the air quality in the regions where they live, work or travel. Along with the traditional sources of information - TV, radio, internet, etc., a very reliable source is the European Air Quality Index (EAQI), available online in the internet. It reflects the potential impact of air quality on health, based on the lowest safety concentrations for five key pollutants - PM_{10}, $PM_{2.5}$, O_3, NO_2 and SO_2. The EAQI indicates the short-term air quality situation; it does not reflect the long-term (annual) air quality state, which may differ significantly (EEA, 2025).

For the industry: implementation of cleaner technology that reduce industrial smokestack emissions; stricter rules and control of the industrial emissions (Mahala, 2024).

For power generation: the promotion of clean energy use; increase the use of low-emissions fuels and renewable combustion-free power sources (solar, wind or hydropower); co-generation of heat and power.

For urban planning: improving the energy efficiency of buildings and making cities greener and more compact, thus energy-efficient; improving the management of urban and agricultural waste, including capture of methane gas emitted from waste sites as an alternative to incineration (for use as biogas); street sweeping and washing as methods for urban PM control - those practices are very effective for reducing the near-ground levels of fine PM and related pollutants (Bogacki et al., 2018; Lin et al., 2023; Das & Wiseman, 2024).

For the transport: promotion of the use of electric vehicles; prioritizing rapid urban transit, walking and cycling networks in cities; shifting to cleaner heavy-duty vehicles with low emissions and fuels with reduced sulphur content.

For the households: ensuring access to affordable clean household energy solutions for cooking, heating and lighting (electricity or gas instead of briquettes, pellets, etc.).

For health-care activities: putting health services on a low-carbon development path, which leads to a decrease in environmental health risks for patients, health workers and the community.

For future research directions: the use of artificial intelligence (AI) for air quality monitoring and prediction (Li et al., 2022; Awasthi et al., 2024; Rautela & Goyal, 2024; Olawade et al., 2024) as well as for the long-term impact of climate change on pollution patterns (Kaur & Pandey, 2021; Pinho-Gomes et al., 2023; Afifa et al., 2024; Ofremu et al., 2024; Stanisci et al., 2024; Ayyamperumal et al., 2024) is very promising and should be encouraged. Having in mind that air pollution is a pervasive public health issue with major economic consequences; it should remain a key target for global, regional and national health policy and standards.

CONCLUSIONS

In this review, we presented a detailed overview about the main ("classic") ambient air pollutants ($PM_{2.5}$, PM_{10}, SO_2, NO_2, and O_3,) and their influence (individually and in combination/ mixtures) on human health, expressed by two keys indicators - morbidity and mortality. Despite the reduction of the harmful emissions and improving the air quality in EU countries, including Bulgaria, the concentrations of some air pollutants (PM_{10}, $PM_{2.5}$, BaP) remain over the standard levels. In 2022, 96% of the urban population was exposed to concentrations of fine particulate matter ($PM_{2.5}$) above the 2021 WHO annual guideline of 5 $\mu g/m^3$. To meet the WHO goals, the annual reduction of the levels of the individual air pollutants must be between 1.2 times for O_3 to 5.0 times for $PM_{2.5}$ up to 2026

- the first target of 2024 EU standard and between 1.2 times for O_3 to 2.0 times for $PM_{2.5}$ and NO_2 up to 2030 - the second target of 2024 EU standard. For Bulgaria, the respective figures range from 1.11 times for PM_{10} to 4.00 times for $PM_{2.5}$ and NO_2. To curb the harmful effect of the air pollutants and to improve the health status of people, the policy, legislation and standards of air quality must follow the WHO guidelines. In this sense, the efforts of monitoring and decreasing the industrial/urban pollution in Europe and in the world must be continued, the European Green Deal must be joined, as initiatives and policies on reducing pollution and reaching environmental sustainability must facilitate the transition to sustainable, low-carbon economy. Some of the successful policies that can reduce air pollution, and consequently improve the health status of humans, refer to stricter rules and emission control; implementation of cleaner technology; promotion of clean energy (solar, wind or hydropower); expansion of the urban green spaces; street sweeping and washing; more extensive use of electric vehicles.

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