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INCREASING THE VISIBILITY AND KNOWLEDGE BASE ON AIR QUALITY WITH BIG DATA AND ITS IMPACT ON THE POPULATION HEALTH

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ADDRESSING AIR POLLUTION IN EUROPE: HEALTH IMPACTS, ENVIRONMENTAL CONSEQUENCES, AND POLICY RESPONSES

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1 INTRODUCTION

Air pollution is a significant environmental issue across Europe, where industrialization, transportation, and urbanization have led to increased emissions of pollutants into the atmosphere. Despite various policies aimed at mitigating air pollution, its adverse effects on health, ecosystems, and climate persist. This literature review delves into the various consequences of air pollution in Europe, focusing on its impacts on human health, the environment, and economy. By synthesizing findings from multiple studies, this review aims to provide a comprehensive understanding of the far-reaching consequences of local and regional air pollution in the European context.

Air pollution is a well-documented cause of a wide range of health problems, particularly in densely populated regions of Europe. Pollutants such as particulate matter (PM), nitrogen oxides (NOx), sulfur dioxide (SO2), and ozone (O3) have been linked to respiratory and cardiovascular diseases, cancer, and premature death.

Particulate matter (PM) is one of the most dangerous air pollutants for human health. It consists of solid and liquid particles suspended in the air, which vary in size. The two most concerning sizes are PM10 (particles with a diameter of 10 micrometers or smaller) and PM2.5 (particles with a diameter of 2.5 micrometers or smaller). Due to their small size, PM2.5 can penetrate deep into the lungs and enter the bloodstream, causing systemic health issues.

Studies have shown that long-term exposure to PM is associated with a higher incidence of chronic respiratory diseases, cardiovascular diseases, lung cancer, and premature mortality (Pope & Dockery, 2006).

Nitrogen oxides, including nitrogen dioxide (NO_2) and nitric oxide (NO), are gases that are primarily emitted from vehicle engines, industrial processes, and power plants. NO_2 is particularly concerning for human health because of its role in forming secondary pollutants

like ozone and particulate matter.

Exposure to NO_2 has been linked to increased respiratory infections, asthma exacerbation, and reduced lung function. Children and elderly populations are especially vulnerable to its effects. A European cohort study by Beelen et al. (2014) demonstrated that long-term exposure to NO_2 was associated with increased all-cause mortality, particularly from respiratory and cardiovascular diseases.

Ground-level ozone (O_3) is a secondary pollutant formed by the reaction of sunlight with pollutants such as volatile organic compounds (VOCs) and NOx. While ozone in the stratosphere is beneficial in protecting the Earth from ultraviolet radiation, ground-level ozone is harmful to human health. Ozone exposure is most prevalent during the summer months and in areas with high levels of traffic and industrial activity.

Short-term exposure to ozone can cause respiratory problems such as coughing, throat irritation, and shortness of breath. It is also known to aggravate pre-existing conditions like asthma and chronic obstructive pulmonary disease (COPD). Long-term exposure to ozone has been associated with increased mortality due to respiratory and cardiovascular diseases (Jerrett et al., 2009).

Sulfur dioxide (SO_2) is a gas produced by burning fossil fuels, particularly coal and oil. It is also released during volcanic eruptions and industrial processes like the extraction of metal ores. SO_2 can cause irritation of the respiratory system and lead to respiratory illnesses, particularly in individuals with asthma or bronchitis.

In Europe, emissions of SO_2 have decreased significantly due to regulations on sulfur content in fuels, but localized pollution from industrial activities remains a concern. Studies have shown that even short-term exposure to SO_2 can exacerbate respiratory conditions and lead to hospital admissions for lung diseases (Schwela, 2000).

Air pollutants affect human health through a variety of biological mechanisms. These mechanisms include oxidative stress, inflammation, immune system impairment, and direct damage to organs and tissues.

2. BACKGROUND

One of the primary ways that pollutants such as PM2.5, NO_2, and ozone cause harm is through oxidative stress. When these pollutants are inhaled, they generate reactive oxygen species (ROS) in the body. ROS are unstable molecules that can damage cells, proteins, and DNA, leading to inflammation and tissue damage (Kelly & Fussell, 2011).

In urban areas with heavy traffic high concentrations of NO_2 and PM2.5 are associated with an increase in asthma prevalence, particularly in children (Anderson et al., 2012). A cohort study conducted in Barcelona found that children exposed to higher levels of NO_2 had significantly reduced lung function and a higher risk of developing asthma later in life (Sunyer

et al., 2015).

Oxidative stress caused by air pollutants has been shown to trigger inflammation in the respiratory system, leading to conditions such as asthma, bronchitis, and COPD. The inflammation can also spread to other parts of the body through the bloodstream, contributing to systemic diseases like atherosclerosis, which can lead to heart attacks and strokes (Brook et al., 2010).

Air pollution can weaken the immune system, making individuals more susceptible to infections, particularly respiratory infections. Several studies have shown that exposure to high levels of PM and NO_2 can impair the body's ability to fight off pathogens, leading to higher rates of hospitalizations for respiratory infections such as pneumonia and bronchitis (Ciencewicki & Jaspers, 2007).

In children, who are still developing their immune systems, long-term exposure to air pollution can lead to increased vulnerability to infections and long-lasting impacts on lung development, potentially reducing lung function later in life (Gehring et al., 2013).

The mechanisms linking air pollution to cardiovascular diseases include systemic inflammation, increased blood pressure, oxidative stress, and changes in heart rate variability. A meta-analysis by Pope et al. (2011) found that long-term exposure to PM2.5 increases the risk of death from cardiovascular diseases by 10-20%.

Cardiovascular diseases related to air pollution are a significant concern in Europe, where aging populations are particularly vulnerable. Long-term exposure to PM2.5 and NO_2 has been linked to higher rates of heart attacks, strokes, and ischemic heart disease (Beelen et al., 2014). A study in Denmark found that individuals living near busy roads, where NO_2 levels are higher, had an increased risk of developing cardiovascular diseases and higher mortality rates (Raaschou-Nielsen et al., 2012).

Studies conducted in Europe have confirmed the strong link between long-term exposure to PM2.5 and the incidence of lung cancer. Raaschou-Nielsen et al. (2013) found that even at levels below current EU air quality standards, PM2.5 exposure was significantly associated with an increased risk of lung cancer.

Air pollution has been recognized as one of the most significant environmental health risks globally. The World Health Organization (WHO) estimates that air pollution contributes to millions of deaths annually, with adverse health effects ranging from respiratory conditions to cardiovascular diseases and cancer. In Europe, air pollution continues to be a pressing public health issue despite improvements in air quality over recent decades.

The World Health Organization (WHO, 2010) reported that environmental issues are also strongly connected to health status and social deprivation. The situation escalated to the levels where "air pollution has overtaken poor sanitation and a lack of drinking water to become the main environmental cause of premature death" (Kelly & Fussell, 2015). Therefore, European Member States are required to take continuous measurements of air emissions

(WHO, 2005). In addition, air pollution also has considerable economic and social implications on household, hospital and public budgets due to increase of medical costs of morbidity and mortality and reduced working productivity (WHO, 2015).

Air pollutants include gaseous pollutants and microscopic particle matters (PMs) that carry various toxic stuffs, such as free radicals, metal and the organic compounds like black carbon and mineral dust (Pope & Dockery, 2006). Within no direct or indirect human activity, PMs could be emitted from natural sources – by volcanos and seismic activities, sea spray aerosols, wild-land fires and wind blow desert dust (EEA, 2012). Studies have shown that long-term exposure to PM is associated with a higher incidence of chronic respiratory diseases, cardiovascular diseases, lung cancer, and premature mortality (Pope & Dockery, 2006). In Europe, the European Environment Agency (EEA) reports that PM2.5 alone is responsible for over 400,000 premature deaths each year (EEA, 2019). However, PM (particulate matter) air pollution results mostly from human activities, such as combustion of fossil fuels, road traffic, residential heating, construction and demolition activities, and industrial processes, primary in urban areas (EEA, 2020). Their half-life is up to several weeks with travel distance more than 1,000 kilometers (Wilson & Suh, 1997). That implies long-distance effects due to the transboundary air pollution (UNECE, 1979), which means that pollutants, such as PM, could travel several thousand kilometers before deposition and damage occurs. Due to the public health implications, the World Health Organization (WHO, 2005) and the EU Ambient Air Quality Directive set the standards of airborne pollutants and guidance on threshold limits that pose health risks. Provisions of the global (UNECE, 1979; WHO, 2005) and European environmental policy related with monitoring and control of ambient air pollution is a highly cost-effective intervention in reducing $PM_{2.5}$-related morbidity and mortality. Air quality data are the basis for rating the exposure of population to $PM_{2.5}$ ambient air pollution. Combining environmental data with the public health data collected from the cohort epidemiological studies is the key element for the estimation of burden of diseases and associated mortality.

As an authoritative source of scientific evidence on cancer-causing substances and exposures, the International Agency for Research on Cancer has classified air pollution in general, as well as PM as a major component of air pollution mixtures, as carcinogenic to humans (IARC, 2013). A growing number of environmental and epidemiology studies have demonstrated that short- (over a few hours or days) and long-term (over months or years) exposure to high concentration of airborne PM are closely related to the incidence of acute and chronic diseases and mortality, mainly related to cardiovascular and respiratory system (Cohen et al., 2006; WHO, 2013; Lelieveld et al., 2015; Yin et al., 2017; GBD, 2017 and 2018;). According to results of the Global Burden Disease Study 2017 (GBD, 2018), 38.44 per 100,000 population all causes of deaths were attributable to ambient PM pollution, and PM identified as one of eight global death risk factors. In 2020, the European Environmental Agency reported that PM alone accounted for around 399,000 of premature deaths in European countries (EEA, 2020).

Many epidemiological studies have shown that susceptible populations like those with prior cardiovascular or pulmonary disease and individuals with obesity and diabetes, are in greater

health risk from elevated $PM_{2.5}$ pollution, including the elderly (>65 years of age) with such comorbidity (Pope et al., 2006: Villeneuve et al., 2012; Burnett et al., 2018).

Ageing is a global phenomenon, since every country in the world is experiencing growth in the share of older people in total population. According to the global United Nation's study (UN, 2019), there were 703 million persons aged <65 years in 2019. According to the same source, the number of elderlies is projected to 1.5 billion in 2050, so that "one in six people in the world will be aged 65 years or over". This demographic structure is expected to put pressure on governments and public expenditures for elderly which require not only long-term medical care but assistance with a number of daily tasks. Therefore, it is obvious that ageing will pose an increasing challenge to the sustainability of public finances in the EU-27.

Significant social inequalities in environmental exposures exist between and within countries (WHO, 2010). It is known that air quality is often worse in locations where socioeconomically disadvantaged residents live, so it is evident that they are disproportionately more exposed to environmental risk factors (US EPA, 2010). Therefore, it is important to address the basic issues for health and wellbeing of elderly, especially those that they cannot affect, such as air pollution. Namely, decision-makers are responsible for solving such challenges. These questions contributed to assessment of the impact of $PM_{2.5}$ air pollution on elderly according to data of premature deaths attributed to airborne $PM_{2.5}$, and related demographic and socio-economic data.

Some population groups are more exposed to the $PM_{2.5}$ air pollution, such as citizens living in the sparse city microenvironments with higher pollution exposures (WHO, 2010; Rajagopalan et al., 2020), and/or some of them are more susceptible like elderly, which mostly have pre-existing health conditions (Chau, et al., 2020). Ageing is an intrinsic process of progressive decline of the body's function that leads to increased sensitivity and vulnerability of elderly. Facing the same level of exposure to $PM_{2.5}$, elderly adults are more susceptible than the general population (Hooper et al, 2018). As they are at higher risk for adverse health effects, the exposure to the $PM_{2.5}$ air pollution may even be fatal, due to comorbidity (Simoni et al., 2014).

Many studies reported morbidity and mortality of the elderly associated to the $PM_{2.5}$ air pollution exposure. It is known that $PM_{2.5}$ exerting a great influence on the cardiovascular and respiratory system in all population groups, and contributes to the morbidity, hospital admissions and premature deaths (Wong et al., 2002; Gent et al., 2009; WHO, 2013; Xing et al., 2016; Matković et al., 2020). As Hayes et al (2020) stated, each increase of 10 $\mu g/m^3$ $PM_{2.5}$ is associated with a 16% increase in mortality from ischemic heart disease and a 14% increase in mortality from stroke. Dominici et al (2006) reported that long-term exposure to elevated concentrations of $PM_{2.5}$ has been related to the significant incidence of COPD and asthma. Air pollution-related carcinogenesis, which mostly occurred in the elderly, has also been studied as of particular interest to the public health, but remains to be elucidated. Still, extensive evidence from numerous of studies provide arguments of positive correlation between

elevated concentrations of airborne $PM_{2.5}$ and incidence and mortality of lung, tracheal or bronchus cancer (Pope et al., 2002; Ding et al., 2014; Cao et al., 2018; Turner et al., 2020).

Calculating the health costs has been the subject of a number of studies over the last 30 years. Intrinsic value of life and health, and the monetary equivalent of the public health expenditures are quite sufficient arguments to reduce the impacts of the $PM_{2.5}$ air pollution. By reducing $PM_{2.5}$ emissions, countries can reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma. At the same time, public health policy tends to invest funds in medical treatments that certainly have an impact on the national economy, and vice versa.

Research published by Lelieveld et al. (2019) demonstrates that air pollution, particularly PM2.5, contributes to approximately 800,000 premature deaths annually across Europe, underlining the severe public health burden of pollution. Long-term exposure to fine particulate matter is associated with increased incidences of heart attacks, strokes, COPD, and lung cancer (Raaschou-Nielsen et al., 2013; Beelen et al., 2014).

The health impacts are not uniformly distributed, as studies indicate substantial geographical and socio-economic disparities. For example, research by Forouzanfar et al. (2016) demonstrates that Eastern Europe suffers from higher mortality rates due to air pollution compared to Western European countries, largely due to the slower implementation of stringent pollution control measures. Moreover, children and the elderly are disproportionately affected, with children exposed to air pollution exhibiting increased risks of asthma, bronchitis, and developmental issues (Brunekreef & Holgate, 2002; Gehring et al., 2013). The WHO (2024) further confirms that air pollution exacerbates pre-existing health conditions, particularly among vulnerable populations, amplifying public health disparities across Europe.

From an economic perspective, the costs associated with air pollution are staggering. Holland et al. (2015) estimate that the health-related costs alone, driven by premature deaths, hospital admissions, and lost workdays, amount to between €330 billion and €940 billion per year in the EU. These estimates are supported by research from the OECD (2014), which emphasizes the economic strain imposed by pollution-induced healthcare expenditures and productivity losses. The European Commission (2013) notes that implementing cleaner air policies, such as the EU's Clean Air Package, could prevent 58,000 premature deaths annually, leading to healthcare savings of up to €40 billion. Despite these potential savings, the initial costs of transitioning to cleaner technologies, particularly in the energy and transport sectors, remain a barrier for many European countries (Amann et al., 2013).

The transboundary nature of air pollution complicates mitigation efforts, as pollutants such as PM and O3, can travel long distances, affecting regions far from their original source (Li et al., 2017). This has prompted coordinated efforts through the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP), which has facilitated significant reductions in sulfur and nitrogen emissions across Europe (Höglund-Isaksson et al., 2017). Additionally, urban air

pollution has intensified due to traffic emissions, with NOx and black carbon concentrations frequently exceeding EU air quality standards in major cities (Kiesewetter et al., 2015).

The interaction between climate change and air pollution exacerbates these consequences. Research by Fiore et al. (2015) underscores that climate-induced changes in temperature, humidity, and wind patterns can influence the concentration and distribution of air pollutants, worsening public health outcomes. Similarly, Bind et al. (2016) point out that higher temperatures can increase ozone formation, further complicating the mitigation of pollution-related health risks. Therefore, integrated approaches that address both climate change and air quality are necessary to minimize the future impacts of air pollution in Europe (von Schneidemesser et al., 2015).

In addition to its impacts on human health, air pollution poses a significant threat to the environment. Pollutants such as sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds (VOCs) can cause damage to ecosystems through acidification, eutrophication, and ozone formation. Acid deposition, primarily driven by sulfur and nitrogen compounds, has been linked to soil degradation and water acidification, particularly in sensitive ecosystems like the Scandinavian boreal forests (De Vries et al., 2015). Studies by Skjelkvåle et al. (2001) and Fenn et al. (2003) have documented the long-term effects of acid rain on European ecosystems, where terrestrial and aquatic biodiversity has been significantly affected. The loss of fish populations in acidified lakes and rivers in Sweden and Norway is a direct consequence of these pollutants, as reported by Henriksen et al. (1992). Moreover, ozone pollution contributes to the reduction of crop yields and forest productivity, with Mills et al. (2011) estimating that O3-induced yield losses for staple crops like wheat, barley, and potatoes could reduce agricultural productivity by up to 10% in parts of Europe.

Acid rain, resulting from the deposition of sulfur and nitrogen compounds, has been a major environmental concern in Europe for decades. Acidification of soils and water bodies can lead to the loss of biodiversity, as many plant and aquatic species are sensitive to changes in pH levels. Although emissions of SO2 have decreased significantly in Europe since the 1980s, acidification remains a problem in certain regions, particularly in areas with low buffering capacity, such as the Scandinavian countries and parts of Eastern Europe (Sutton et al., 2011).

Eutrophication, the process by which excessive nutrients, particularly nitrogen compounds, accumulate in water bodies, leading to algal blooms and oxygen depletion, is another critical consequence of air pollution. Nitrogen oxides and ammonia emitted from agriculture, transport, and industry contribute to the nitrogen load in aquatic ecosystems, causing harmful effects on biodiversity and water quality.

Research by Dise et al. (2011) showed that nitrogen deposition has led to the decline of plant species adapted to low-nutrient environments, resulting in the loss of biodiversity in grasslands and heathlands across Europe. The study also emphasized the role of nitrogen pollution in disrupting the balance of nutrient cycles, leading to long-term degradation of sensitive ecosystems such as peatlands and wetlands.

Ground-level ozone, a secondary pollutant formed by the reaction of VOCs and NOx in the presence of sunlight, is harmful to vegetation and crops. Ozone exposure reduces photosynthesis, damages leaf structure, and impairs plant growth, leading to reduced agricultural yields and forest productivity. In Europe, ozone pollution is a significant concern for both food security and ecosystem health.

A study conducted by Mills et al. (2018) estimated that ozone pollution causes crop yield losses worth billions of euros each year in Europe. The most affected crops include wheat, maize, and soybeans, which are highly sensitive to ozone damage. Additionally, forest ecosystems are at risk, with ozone exposure reducing tree growth and increasing vulnerability to pests and diseases.

The economic consequences of air pollution in Europe are substantial, with costs arising from healthcare expenses, loss of productivity, and damage to ecosystems and infrastructure. Air pollution-related illnesses lead to increased healthcare expenditures and lost workdays, while damage to agriculture, forests, and water bodies has long-term economic implications.

The health impacts of air pollution place a significant burden on healthcare systems across Europe. According to the European Commission (2017), air pollution costs the European economy an estimated €330-940 billion annually in healthcare expenditures and lost productivity due to illness and premature deaths. These costs are borne disproportionately by countries with higher pollution levels and weaker healthcare infrastructure, such as those in Eastern and Southern Europe.

A report by the OECD (2016) highlighted that the economic costs of air pollution-related health impacts, including hospital admissions, medication, and outpatient care, represent a significant portion of national healthcare budgets. Additionally, lost workdays due to pollution-induced illnesses contribute to reduced economic productivity, particularly in urban and industrial areas where pollution levels are highest.

Air pollution, particularly ozone and nitrogen deposition, has negative consequences for agriculture in Europe. As previously mentioned, ozone exposure reduces crop yields, leading to economic losses for farmers and higher food prices for consumers. The European Commission (2017) estimated that ozone pollution causes crop losses worth approximately €3 billion annually, with the most affected countries being those with intensive agriculture, such as Spain, Italy, and France.

Nitrogen deposition from air pollution also affects agricultural productivity by altering soil nutrient levels and promoting the growth of invasive species. A study by Bobbink et al. (2010) found that nitrogen deposition can lead to the degradation of semi-natural grasslands, which are important for livestock grazing and biodiversity conservation. The loss of these ecosystems has economic implications for farmers who rely on them for grazing and hay production.

Air pollution, particularly from sulfur dioxide and nitrogen oxides, can cause damage to buildings and infrastructure through the process of acid deposition. Acid rain accelerates the

corrosion of metals, stone, and concrete, leading to higher maintenance and repair costs for historic buildings, monuments, and infrastructure. In Europe, the economic costs of acid rain-related damage to buildings are estimated to be in the billions of euros annually (European Commission, 2017).

A study by Tidblad et al. (2010) found that the rate of corrosion of building materials, such as limestone and steel, is strongly correlated with the concentration of SO2 in the atmosphere. Although SO2 emissions have decreased significantly in Europe, many historic buildings and cultural heritage sites remain vulnerable to pollution-induced deterioration, particularly in urban areas with high traffic emissions.

It is evident that the economic development and pollution rate are closely related, although there is no clear consensus on the nature of that relationship. In mathematical terms, this relationship (usually referred to as Environmental Kuznets Curve) can be divided into following categories:

- An inverted U-shaped relationship, – that was introduced in the context of environmental degradation with three different stages: scale effect where the environment is increasingly polluted due to increased exploitation of natural resources, composition effect that emphasizes cleaner activities in production where consequently pollution rate stagnates in spite of economic growth, and techniques effect where, due to increased economic development, obsolete technologies are replaced by cleaner ones and consequently pollution rate decreases (Ekins, 1997; Kiliç & Balan, 2018).
- A monotonically increasing relationship where there is a clear positive feedback between GDP per capita and environmental impact. In other words, there is “an increasing rate of environmental degradation per unit of income as countries become richer” (Bagliani et al., 2006).
- N-shaped relationship that basically represents prolonged inverted U-shaped relationship where beyond certain income level negative pressure on the environment increases again (Allard et al., 2018).

As Grossman and Krueger (1994) stated, GDP growth is associated with deteriorating of environmental quality. However, after reaching critical level of income, economic growth tends to alleviate environmental issues (Grossman & Krueger 1991). In last few decades, there is lot of evidences that further economic development and transformation based on knowledge, innovations, new technologies and environmental governance could be driving forces for improvement of the environmental standards and quality (Holtz-Eakin & Selden 1992; Shao et al., 2016; Kogan et al., 2017; Feng et al., 2019; Huang et al., 2019; Li et al., 2020).

Recently available data of European Environment Agency suggest that over the last 50 years the environmental policies of EU-27 countries have been able to curb air pollution (EEA 2020). According to the same source, the EU-27 has failed to reduce $PM_{2.5}$ air pollution to the extent that it does not significantly affect human health. Individually oriented environmental policies

implemented to reduce $PM_{2.5}$ emissions from road transport, domestic heating, industry and agriculture have proved insufficient. On the other hand, the COVID crisis highlighted the need for a common European response to public health and economic challenges. As a result of lock-down measures, the concentrations of $PM_{2.5}$ emissions have decreased significantly (EEA 2020), pointing out that radical changes have yet to be made in the EU-27 economy in terms of reducing air pollution. Recently, EU-27 responded with paradigm of sustainability transition based on decoupling of harmful environmental pollution from economic growth. This ambition has been immersed in a new policies and initiatives, such as European Green Deal, with the key message that the economy does not have to be in conflict with the environment.

The research done during and after COVID-19, in the period from 2020 to 2024, has seen a significant reevaluation of the consequences of air pollution in Europe, particularly as new scientific data has emerged in light of the COVID-19 pandemic, advancements in monitoring technology, and evolving policy frameworks. Recent studies have continued to highlight the far-reaching impacts of air pollution on human health, environmental integrity, and economic sustainability. According to the European Environment Agency's (EEA) 2023 report, air pollution remains the leading environmental risk factor for premature mortality in Europe, with fine particulate matter (PM2.5), nitrogen dioxide (NO2), and ground-level ozone (O3) contributing to more than 380,000 premature deaths annually within the European Union (EEA, 2023). This period has also brought attention to the exacerbating effects of air pollution on respiratory diseases, particularly in the context of the COVID-19 pandemic. Research by Travaglio et al. (2021) identified a positive correlation between long-term exposure to PM2.5 and higher mortality rates from COVID-19, underscoring the interaction between pollution and vulnerability to viral infections.

In terms of health impacts, recent meta-analyses have strengthened the link between air pollution and cardiovascular and respiratory diseases. A 2022 study by Schraufnagel et al. emphasized that prolonged exposure to air pollution exacerbates chronic conditions such as asthma, COPD, and ischemic heart disease, particularly in urban populations. Furthermore, a study by Vicedo-Cabrera et al. (2023) found that short-term spikes in ozone levels during heatwaves significantly increase hospital admissions for respiratory diseases, highlighting the compounded risks posed by climate change and air pollution. In children, prenatal and early-life exposure to air pollution has been linked to developmental issues, including cognitive impairment and lower lung function (Vrijheid et al., 2021). These findings align with the WHO's (2022) revised air quality guidelines, which lower the recommended exposure thresholds for PM2.5 and NO2 to further reduce public health risks.

Environmentally, the consequences of air pollution continue to affect biodiversity and ecosystem services. Amann et al. (2020) demonstrate that nitrogen deposition remains a significant threat to biodiversity in Europe, with sensitive habitats such as heathlands and alpine ecosystems particularly vulnerable. Nitrogen oxides and ammonia emissions from agriculture and transport contribute to eutrophication, which disrupts plant diversity and alters species composition in terrestrial and aquatic ecosystems (Sutton et al., 2020).

Acidification, though reduced since the 1990s, remains a concern in certain regions, particularly in northern Europe. According to an assessment by De Vries et al. (2022), although sulfur deposition has declined substantially due to regulatory efforts, nitrogen-driven acidification continues to degrade soil quality and water bodies, adversely affecting forest growth and freshwater biodiversity.

The agricultural sector has also been impacted by air pollution, with ozone exposure reducing crop yields across Europe. According to a study by Wilkinson et al. (2021), ground-level ozone caused yield losses of up to 5-10% for key European crops such as wheat, barley, and potatoes between 2020 and 2022. These losses are projected to increase as climate change exacerbates ozone formation, threatening food security and economic stability. The European Commission's 2021 Farm to Fork Strategy has emphasized the need to address agricultural emissions, particularly ammonia, to reduce air pollution and its associated impacts on crop productivity and biodiversity.

Economically, the costs of air pollution remain substantial. The Health and Environment Alliance (HEAL, 2021) estimates that air pollution-related healthcare costs, absenteeism, and reduced labor productivity result in economic losses of approximately €600 billion annually for the European Union. These costs are disproportionately borne by lower-income populations, who are more likely to live in areas with higher levels of pollution and have limited access to healthcare (Pisoni et al., 2021). Furthermore, studies by the OECD (2019) highlight the economic co-benefits of implementing stricter air quality standards. For instance, the adoption of cleaner technologies in the transport and energy sectors could save the EU economy an estimated €60 billion per year by 2030 through reduced healthcare costs and increased productivity.

Urban air pollution continues to be a critical issue, with cities such as Paris, Milan, and Warsaw frequently exceeding the WHO's recommended limits for PM2.5 and NO2 (EEA, 2022). A study by Quéré et al. (2021) found that lockdowns during the COVID-19 pandemic provided temporary relief from traffic-related pollution, but levels quickly rebounded as restrictions were lifted, highlighting the resilience of underlying pollution sources. Urban green spaces have been shown to mitigate air pollution's impacts by absorbing particulate matter and providing health benefits to city residents (Lai et al., 2021), but their effectiveness is limited by the scale of emissions and urban sprawl.

Policy responses during this period have been mixed. The EU's Green Deal and Zero Pollution Action Plan aim to achieve a 55% reduction in greenhouse gas emissions and a 25% reduction in premature deaths due to air pollution by 2030 (European Commission, 2021). However, critics argue that the current pace of implementation is insufficient to meet these goals. For example, a report by Kiesewetter et al. (2022) suggests that while PM2.5 levels have generally decreased, reductions in NO2 and ammonia emissions are lagging, particularly in the transport and agricultural sectors. Recent legislative developments, such as the tightening of the National Emissions Ceiling Directive (NECD) and the proposed revision of the Ambient Air

Quality Directive (AAQD) in 2022, are steps towards addressing these challenges, but enforcement and compliance remain critical issues (Schucht et al., 2022).

Another significant development has been the focus on the intersection of air pollution and climate change. Research by Liu et al. (2023) shows that climate change is likely to exacerbate the frequency and severity of air pollution events, particularly through increased heatwave-induced ozone formation and changes in atmospheric circulation patterns. This period has seen growing calls for integrated air quality and climate policies to address these interconnected issues. Von Schneidemesser et al. (2021) argue that aligning air pollution control with climate mitigation efforts, particularly in sectors like energy and transport, is essential for achieving long-term reductions in pollution levels.

3. CONCLUSION

Air pollution remains a major concern in Europe, with widespread consequences for human health, ecosystems, and the economy. While regulatory measures and awareness campaigns have been implemented to mitigate these effects, ongoing research and international collaboration are essential to develop sustainable solutions. Tackling the root causes of air pollution, such as emissions from industrial activities and transportation, is key to safeguarding Europe's environment and public health.

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