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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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The present document aims to summarize findings from key studies that underscore the health effects of air pollution. It is structured to present the evidence regarding the association between exposure to air contaminants and health outcomes.

1. INTRODUCTION

The impact of air pollution on human health has been extensively studied, revealing significant correlations with increased mortality and a wide range of diseases. Air pollution, particularly from fine particulate matter (PM) and ozone (O_3), has been identified among the major risk factors contributing to the global burden of disease. However, those are not the only air pollutants, nitrogen oxides, sulfur dioxide, and carbon monoxide among others are also of concern (Chen et al., 2022; Ku et al., 2017; Nguyen et al., 2022; Shcheklein & Dubinin, 2020). The sources of PM are diverse, ranging from vehicle emissions and industrial processes to power plants and natural events like wildfires and dust storms. Particulate matter is composed of microscopic particles, a mixture of chemicals and biological elements small enough to be deposited when inhaled. PM having a diameter of <10 µm is deposited mainly in the large conducting airways, but PM of <2.5 µm can cross the alveolar-capillary barrier and travel to other organs within the body (Garcia et al., 2023; Lelieveld et al., 2015). Ozone's toxicity stems from its ability to generate oxidative stress and trigger inflammatory responses in the body. Exposure to ambient air pollution is a leading contributor to global disease burden, significantly affecting morbidity and mortality rates. According to the Global Burden of Disease Study 2015, ambient $PM_{2.5}$ was the fifth-ranking mortality risk factor globally in 2015, causing approximately 4.2 million deaths and 103.1 million disability-adjusted life years (DALYs) (Cohen et al., 2017). Exposure to ozone was associated with 254,000 deaths globally and a loss of 4.1 million DALYs in 2015, predominantly affecting those with chronic obstructive pulmonary disease (COPD) (Cohen et al., 2017). The analysis of global, regional, and country-level data from 1990 to 2015 shows a disturbing trend of increasing deaths attributable to air pollution, particularly in low-income and middle-income countries. The highest burdens were observed in East and South Asia, accounting for 59% of the total deaths related to ambient

$PM_{2.5}$ exposure in 2015 (Cohen et al., 2017; Lelieveld et al., 2015). Despite reductions in air pollution levels in some high-income countries, global mortality rates associated with $PM_{2.5}$ have continued to rise due to increasing pollution in densely populated and rapidly industrializing regions. Models estimating premature deaths assuming the same present scenario indicate that the contribution of air pollution may double by 2050 (Lelieveld et al., 2015).

2. BACKGROUND

2.1 Evidence associating air contaminants with health outcomes.

The detrimental effects of air pollution extend beyond mortality to significantly impact overall health, it may shorten life expectancy or reduce years of healthy life. Overall health status and other factors may modify the effect of air pollution in health. Many other non-communicable diseases (Campbell-Lendrum & Prüss-Ustün, 2019) have been also related to air pollution such as immune system diseases (Glencross et al., 2020), cardiovascular damage (Al-Kindi et al., 2020), inflammation (Arias-Pérez et al., 2020), neurological and cognitive decline (Schraufnagel et al., 2019), bone health decline (Prada et al., 2020), pulmonary diseases (Ko Ui Won, 2022) and autoimmune diseases (Zhao et al., 2019).

Particulate Matter

Particulate matter is a mixture of tiny solid particles and liquid droplets in the air, categorized by size. $PM_{2.5}$ is particularly harmful as it can penetrate deeply into the lungs and bloodstream, causing significant cardiovascular, respiratory, and systemic health issues (Garcia et al., 2023), with notable variations in relative risk based on age (Cohen et al., 2017). In low-income countries, indoor air pollution due to the burning of solid fuels is the major source of $PM_{2.5}$ and it is a major health concern. In more industrial countries the most important emissions are generated by traffic and industries, whereas other regions of the world have agricultural emissions as the major source of particles (Lelieveld et al., 2015).

The inhalation of PM can have profound health effects, impacting various bodily systems. Respiratory infections are one of the primary concerns, as PM can irritate the airways, making them more susceptible to infections and exacerbating existing conditions such as asthma and COPD (Gavett & Koren, 2012; Xu et al., 2020; Zieliński et al., 2018). COPD is a lung disease characterized by breathing difficulties, and exposure to PM can significantly worsen its symptoms by irritating the airways and lungs (Zieliński et al., 2018). Prenatal and postnatal exposure to PM are of particular concert as they can negatively affect lung function and contribute to airway hyperresponsiveness (Xu et al., 2020). The toxicity of particles is considered concentration-dependent, but not source-dependent, as there is no evidence

supporting source-specific risks for burden estimation, but this issue needs to be deeply investigated. Increasing levels of fine particulate air pollution are associated with a significant rise in cardiopulmonary mortality. Specifically, each 10 μg/m³ elevation in long-term average $PM_{2.5}$ concentrations corresponds to an approximate 6% increased risk of cardiopulmonary mortality, 8% of lung cancer and 4% of risk of all causes (Pope III et al., 2002).

Heart disease is another major health issue linked to PM exposure. The fine particles can cause inflammation and increase blood pressure, thereby damaging the heart and blood vessels. This can lead to an increased risk of heart attacks, strokes, and other cardiovascular problems (Brook et al., 2010; Fang et al., 2010; Liang et al., 2020; Nelin et al., 2012; Thompson, 2018). Exposure to PM is an established cardiovascular risk factor and reducing exposure would lower the risks (Brook et al., 2010). Additionally, long-term exposure to PM is a significant risk factor for lung cancer (Ciabattini et al., 2021; Cui et al., 2014; Lippi & Mattiuzzi, 2020; Thompson, 2018). The particles can damage the cells lining the lungs, leading to mutations that may result in cancer.

Beyond respiratory and cardiovascular problems, PM exposure has been associated with a range of other health issues. These include diabetes (Lao et al., 2019; Liu et al., 2016; Thompson, 2018; Zhou et al., 2022), cognitive decline (Aretz et al., 2021; Ranft et al., 2009; Shehab & Pope, 2019), and even premature death (Burnett et al., 2018; Li, et al., 2018).

Nitrogen Oxides

Nitrogen oxides (NO_x), including nitrogen dioxide (NO_2) and nitric oxide (NO), are produced primarily through high-temperature combustion processes in vehicle engines and power plants. NO_x are reddish-brown gases that significantly contribute to the formation of ground-level ozone and fine PM, both of which have detrimental health effects. Exposure to NO_x can irritate the respiratory system, leading to various health issues (Shcheklein & Dubinin, 2020).

One of the most immediate effects of NO_2 exposure is respiratory irritation (Chen et al., 2022; Jiang et al., 2019a). The gas irritates the tissues lining the nose, throat, and lungs, causing symptoms like coughing, wheezing, shortness of breath, and chest tightness. This irritation can exacerbate pre-existing respiratory conditions, making them more severe and harder to manage. For individuals with asthma, NO_2 is particularly problematic as it can trigger asthma attacks and worsen overall symptoms, leading to increased difficulty in controlling the condition (Ghosh et al., 2012; Kjaer & Rasmussen, 1996).

Moreover, exposure to NO_2 can weaken the body's defense mechanisms against respiratory infections, increasing susceptibility to illnesses such as bronchitis and pneumonia (Ghosh et al., 2012; Lee et al., 2013; Pershagen et al., 1995). The compromised immune response makes it easier for pathogens to infect the respiratory tract, leading to more frequent and severe infections. A longitudinal study reported an association between NO_2 exposure and

respiratory illness, finding it more robust for bronchitis than for upper airway inflammation, with increased risk between birth and 2 years (Ghosh et al., 2012).

Long-term exposure to NO_2 can also result in significant lung function impairment (Gaffin et al., 2018; Jiang et al., 2019b; Rao et al., 1992). Continuous inhalation of this gas can damage lung tissues, reducing overall lung function and making breathing more difficult. This reduction in lung capacity not only affects daily activities but also decreases the ability to exercise, impacting overall health and quality of life (Eckhardt & Wu, 2021).

Sulfur Dioxide

Sulfur dioxide (SO_2) is a colourless gas with a pungent odour, primarily produced by volcanic eruptions and industrial processes such as burning sulphur-containing fossil fuels like coal and oil. Despite significant regulatory efforts to reduce SO_2 levels, exposure to this gas continues to pose health risks, particularly respiratory irritation. SO_2 in the atmosphere can react to form fine sulfate particles, which contribute to $PM_{2.5}$ pollution and exacerbate respiratory problems (Ku et al., 2017)

Exposure to SO_2 can irritate the tissues lining the nose, throat, and lungs, leading to symptoms such as coughing, wheezing, shortness of breath, chest tightness, and a burning sensation in the upper airways. These symptoms can be particularly severe for individuals with pre-existing respiratory conditions, such as asthma. In such cases, SO_2 can worsen asthma symptoms, triggering asthma attacks and making it more difficult to manage the condition effectively (Chen et al., 2012; Chen et al., 2022; Linn et al., 1987), even at short peak exposures (Johns et al., 2011).

In addition to immediate respiratory irritation, SO_2 exposure can increase susceptibility to respiratory infections. It weakens the body's defence mechanisms, making individuals more prone to illnesses like bronchitis and pneumonia. This increased vulnerability to infections highlights the broader impact of SO_2 on public health, extending beyond just those with existing respiratory issues (Tomić-Spirić et al., 2021).

Ozone

Ozone is a gas molecule composed of three oxygen atoms and is a major component of ground-level smog. Ground-level O_3 is formed through chemical reactions between sunlight and pollutants such as NO_x and volatile organic compounds (VOCs) emitted from vehicles and power plants (Nguyen et al., 2022). While O_3 in the stratosphere plays a crucial role in protecting the Earth from harmful ultraviolet radiation, ground-level O_3 poses significant health risks. Exposure to ground-level O_3 can irritate the respiratory system, leading to a variety of health problems (Chen et al., 2022). Ozone exposure irritates the tissues lining the lungs, akin to a sunburn on the skin. This irritation can cause symptoms such as coughing,

wheezing, chest tightness, and shortness of breath. These effects are particularly pronounced in individuals with asthma, as O_3 can significantly worsen asthma symptoms, trigger asthma attacks, increase the need for medication, and result in more frequent hospital visits (Lin et al., 2008). Male and older asthma patients may be more vulnerable to O_3 air pollution, especially in the warm season (Fang et al., 2022). Furthermore, exposure to O_3 can reduce lung function, making it more difficult to breathe deeply and exercise. This reduction in lung function can be temporary, but with long-term exposure, it may become permanent, impacting overall respiratory health. In addition to these direct respiratory effects, O_3 weakens the body's defence system against respiratory infections, increasing susceptibility to illnesses like bronchitis and pneumonia (Backus et al., 2010; Dimakopoulou et al., 2020).

Carbon Monoxide

Carbon monoxide (CO) is a colourless, odourless gas produced by the incomplete combustion of fuels such as gasoline, wood, and coal. Its undetectable nature makes it particularly dangerous because it cannot be detected by human senses. CO interferes with the oxygen-carrying capacity of red blood cells, leading to a range of health effects that can escalate rapidly. Initially, exposure to CO often causes mild headaches, which can easily be mistaken for common headaches, delaying the recognition of CO poisoning (Chen et al., 2022).

As CO levels increase in the blood, symptoms such as dizziness, nausea, and vomiting become more pronounced. These symptoms can be particularly hazardous as they may lead to falls or impair the ability to escape from the source of the CO. Additionally, CO poisoning can cause extreme fatigue and weakness, further impairing judgment, and coordination, which makes it difficult for individuals to leave a contaminated environment (Roderique et al., 2015).

At higher concentrations, CO exposure can lead to confusion, disorientation, and even hallucinations. This mental impairment can be life-threatening as it prevents individuals from seeking help or understanding the need to evacuate. In severe cases, the effects of CO poisoning escalate to loss of consciousness and even death due to the deprivation of oxygen in vital organs such as the brain and heart (Abdel salam et al., 2021).

The health risks associated with CO underscore the importance of preventing CO exposure through proper ventilation and the use of CO detectors. Awareness and early detection are crucial in preventing the harmful and potentially fatal effects of this silent and invisible gas.

2.2 Actions toward clean air for all.

These findings underscore the critical need for comprehensive air quality management and policy interventions aimed at reducing emissions from major sources such as coal combustion and vehicular traffic. Effective policy measures could lead to significant health benefits and reductions in the disease burden attributable to air pollution. The substantial public health

benefits observed in countries with great aggressive air quality management programs, such as the United States, illustrate the potential gains from such interventions (Cohen et al., 2017). International authorities and organizations are promoting actions toward clean air for everyone. European Green Deal Policies aim to promote the implementation of actions that can significantly impact air quality. The European Commission does play a significant role in ensuring that EU Member States adopt actions aligned with the European Green Deal. This enforcement is primarily achieved through the European Climate Law, which legally binds Member States to achieve climate neutrality by 2050 and sets a greenhouse gas emissions reduction target of at least 55% by 2030 compared to 1990 levels ('Climate action Green Deal', 2019; 'Delivering European Green Deal', 2019). The European Climate Law was established to provide a framework for achieving the Green Deal's objectives. It mandates regular assessments and adjustments to national policies and measures to ensure they are on track to meet these targets. Moreover, the law includes mechanisms for monitoring and reporting progress, enabling the European Commission to take corrective action if necessary ('Delivering European Green Deal', 2019).

The World Health Organization (WHO) does not have the authority to enforce its guidelines on air quality or compel governments to implement specific actions. Instead, the WHO provides scientifically based recommendations and guidelines intended to help countries improve air quality and protect public health. The WHO encourages governments to adopt these guidelines to mitigate the health risks associated with poor air quality, but the implementation of these measures is ultimately at the discretion of each country's government. WHO published in 2021 the last version of its WHO global air quality guidelines (WHO, 2021) recommending several key measures to enhance air quality and protect public health from pollution's harmful effects. These measures are informed by scientific evidence and involve various sectors:

1. **Regulatory Actions**: Governments should enforce national air quality standards that align with WHO guidelines, covering pollutants such as $PM_{2.5}$, PM_{10}, nitrogen dioxide, sulfur dioxide, and ozone. Regular updates are needed to reflect new scientific findings.

2. **Emission Reductions**: Efforts should focus on minimizing or eliminating polluting activities: a. Transportation: Promote cleaner fuels and vehicles, improve fuel quality, and support public transportation and electric vehicles. b. Industry: Implement stricter emission controls and adopt cleaner technologies. c. Agriculture: Reduce emissions from practices like open burning of agricultural waste. d. Residential Heating: Shift to cleaner fuels and technologies for home heating.

3. **Urban Planning**: Incorporate air quality considerations into urban planning to reduce exposure: by optimizing traffic flow, increasing green spaces, and appropriate location

of industrial areas. Encourage shorter travel distances and use of public transportation (reduce private) and promote walking and cycling in cities.

4. **Public Awareness**: Conduct campaigns to inform the public about the health risks of air pollution and encourage behaviors that reduce emissions and personal exposure, such as energy-efficient practices and reducing the use of high-emission appliances. Public awareness is expected to be of major relevance to effectively engage all actors in implementing the needed measures to reduce air pollution.
5. **Monitoring and Data**: Establish extensive air quality monitoring networks and ensure the data is publicly accessible to inform policy decisions. Use high-resolution models and citizen science initiatives to supplement governmental monitoring.
6. **Health Risk Assessments**: Perform assessments to estimate the health impact of air pollution and understand the benefits of air quality improvements, guiding policy decisions.
7. **International Collaboration**: Engage in global initiatives to share knowledge, build capacity, and coordinate actions to address transboundary air pollution.
8. **Research and Development**: Support research into the health effects of air pollution, new monitoring technologies, and innovative mitigation strategies. Evaluate the effectiveness of interventions and explore new methods to reduce emissions and exposure. By implementing these strategies, countries can significantly improve air quality and protect public health (WHO, 2021).

2.2.1 Tables

Table 1. contains the field of action, actions planned and their potential impact in air quality that such actions may have according to the European Green Deal

Field of action	Action	Impact on Clean Air
Emissions Reduction	Achieve a minimum 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels.	Reducing greenhouse gas emissions also decreases the release of harmful pollutants like particulate matter ($PM_{2.5}$, PM_{10}), NO_x, and SO_2 from industrial activities and transportation. This leads to improved air quality and reduced health risks associated with air pollution.
Renewable Energy Use	Increase the share of renewable energy to at least 32% by 2030, with a target to reach 45%.	Transitioning to renewable energy sources like wind, solar, and hydropower reduces reliance on fossil fuels, which are major sources of air pollution. This helps in lowering emissions of pollutants such as NO_x, SO_2, and VOCs that contribute to poor air quality.

Enhanced Energy Efficiency	Improve energy efficiency by at least 32.5% by 2030.	Enhancing energy efficiency in buildings, transport, and industry reduces overall energy consumption, which instead decreases the amount of fuel burned. This results in lower emissions of air pollutants from energy production and consumption.
Carbon Pricing	Increase carbon pricing to road transport and maritime sectors and extend the share of sustainable aviation fuels.	Carbon pricing creates a financial incentive to reduce emissions. By putting a price on carbon emissions, industries and transport sectors are encouraged to adopt cleaner technologies and fuels, thereby reducing the emission of harmful pollutants.
Circular Economy	Implement a new circular economy action plan to reduce waste and ensure sustainable product design.	Promoting the reuse, recycling, and reduction of waste helps decrease the need for raw material extraction and processing, which are significant sources of air pollution. Sustainable product design also minimizes emissions throughout the product lifecycle.
Clean Mobility	Promote zero-emission vehicles and clean public transport and support the development of necessary infrastructure.	Shifting to electric vehicles and enhancing public transport reduces the number of fossil-fuel-powered vehicles on the road. This leads to lower emissions of NO_x, PM, and other pollutants from the transport sector.
Biodiversity and Ecosystems	Launch initiatives to halt biodiversity loss and protect ecosystems.	Healthy ecosystems, including forests and wetlands, act as natural air filters by absorbing pollutants and producing clean oxygen. Protecting and restoring these ecosystems contributes to better air quality.
Industrial Transition	Support green industrial transformation through the Green Deal Industrial Plan.	By fostering innovation and the adoption of clean technologies in industry, this action reduces emissions of pollutants from industrial processes. Cleaner production methods and technologies help improve air quality.
Building Renovation	Double renovation rates of buildings to enhance energy efficiency and reduce greenhouse gas emissions.	Energy-efficient buildings require less heating and cooling, reducing the demand for energy and thus the emissions from power plants. Renovations often include improved ventilation and the use of non-toxic materials, directly improving indoor air quality as well.

Source: adapted from the document European Green Deal Policy Guide KPMG ('European Green Deal Policy Guide - KPMG global', 2021)

3. CONCLUSION

The findings from the present report highlight the severe health impacts of air pollution, particularly from fine PM and ozone O_3, which contribute significantly to the global burden of disease. Air pollutants such as nitrogen oxides, sulpur dioxide, and carbon monoxide are also of concern due to their detrimental effects on respiratory, cardiovascular, and overall health. Exposure to $PM_{2.5}$ is linked to increased mortality rates, cardiovascular and respiratory diseases, and other serious health conditions, especially in low-income and middle-income countries. Similarly, nitrogen oxides and sulpur dioxide contribute to respiratory irritation and exacerbate conditions like asthma, while ozone exposure reduces lung function and increases

susceptibility to respiratory infections. Carbon monoxide poses a silent threat, causing severe health effects due to its undetectable nature. Effective air quality management and policy interventions are crucial to mitigating these health risks. Actions such as reducing emissions from major sources, promoting renewable energy, improving energy efficiency, and encouraging clean transportation can lead to significant health benefits. International initiatives, such as the European Green Deal and WHO guidelines, provide frameworks for improving air quality and protecting public health. Addressing air pollution through comprehensive strategies and international collaboration is essential to reduce its health burden and improve quality of life globally. Implementing scientifically informed policies and increasing public awareness are critical steps toward achieving clean air for all.

REFERENCES

Abdel salam, M. E., Elawady, E. H., Khater, A. S., Eweda, S. A. & Abd el moneam, M. H. (2021). Neuropsychiatric sequelae of acute carbon monoxide poisoning: The predictive role of neuron specific enolase and glial fibrillary acidic protein. *NeuroToxicology*, 85, 115–120. https://doi.org/https://doi.org/10.1016/j.neuro.2021.05.003

Al-Kindi, S. G., Brook, R. D., Biswal, S. & Rajagopalan, S. (2020). Environmental determinants of cardiovascular disease: Lessons learned from air pollution. *Nature Reviews Cardiology*, 17(10), 656–672. https://doi.org/10.1038/s41569-020-0371-2

Aretz, B., Janssen, F., Vonk, J. M., Heneka, M. T., Boezen, H. M. & Doblhammer, G. (2021). Long-term exposure to fine particulate matter, lung function and cognitive performance: A prospective dutch cohort study on the underlying routes. *Environmental Research*, 201, 111533. https://doi.org/10.1016/j.envres.2021.111533

Arias-Pérez, R. D., Taborda, N. A., Gómez, D. M., Narvaez, J. F., Porras, J. & Hernandez, J. C. (2020). Inflammatory effects of particulate matter air pollution. *Environmental Science and Pollution Research*, 27(34), 42390–42404. https://doi.org/10.1007/s11356-020-10574-w

Backus, G. S., Howden, R., Fostel, J., Bauer, A. K., Cho, H.-Y., Marzec, J., Peden, D. B. & Kleeberger, S. R. (2010). Protective role of interleukin-10 in ozone-induced pulmonary inflammation. *Environ Health Perspect*, 118(12), 1721–1727. https://doi.org/10.1289/ehp.1002182

Brook, R. D., Rajagopalan, S., Pope, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V., Holguin, F., Hong , Y., Luepker, R.V., Mittleman, M.A., Peters, A., Siscovick, D., Smith, S.C., Whitsel, L. & Kaufman, J. D. (2010). Particulate matter air pollution and cardiovascular disease. *Circulation*, 121(21), 2331–2378. https://doi.org/10.1161/CIR.0b013e3181dbece1

Burnett, R., Chen, H., Szyszkowicz, M., Fann, N., Hubbell, B., Pope, C. A., … Spadaro, J. V. (2018). Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *Proceedings of the National Academy of Sciences*, 115(38), 9592–9597. https://doi.org/10.1073/pnas.1803222115

Campbell-Lendrum, D. & Prüss-Ustün, A. (2019). Climate change, air pollution and noncommunicable diseases. *Bull World Health Organ*, 97(2), 160–161. https://doi.org/10.2471/BLT.18.224295

Chen, R., Huang, W., Wong, C.-M., Wang, Z., Quoc Thach, T., Chen, B. & Kan, H. (2012). Short-term exposure to sulfur dioxide and daily mortality in 17 chinese cities: The china air pollution and health effects study (CAPES). *Environmental Research*, 118, 101–106. https://doi.org/10.1016/j.envres.2012.07.003

Chen, Z., Liu, N., Tang, H., Gao, X., Zhang, Y., Kan, H., … Zhao, Z. (2022). Health effects of exposure to sulfur dioxide, nitrogen dioxide, ozone, and carbon monoxide between 1980 and 2019: A systematic review and meta-analysis. *Indoor Air*, 32(11), e13170. https://doi.org/10.1111/ina.13170

Ciabattini, M., Rizzello, E., Lucaroni, F., Palombi, L. & Boffetta, P. (2021). Systematic review and meta-analysis of recent high-quality studies on exposure to particulate matter and risk of lung cancer. *Environmental Research*, 196, 110440. https://doi.org/10.1016/j.envres.2020.110440

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., … Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the global burden of diseases study 2015. *The Lancet*, 389(10082), 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6

Cui, P., Huang, Y., Han, J., Song, F. & Chen, K. (2014). Ambient particulate matter and lung cancer incidence and mortality: A meta-analysis of prospective studies. *European Journal of Public Health*, 25(2), 324–329. https://doi.org/10.1093/eurpub/cku145

Dimakopoulou, K., Douros, J., Samoli, E., Karakatsani, A., Rodopoulou, S., Papakosta, D., … Katsouyanni, K. (2020). Long-term exposure to ozone and children's respiratory health: Results from the RESPOZE study. *Environmental Research*, 182, 109002. https://doi.org/10.1016/j.envres.2019.109002

Eckhardt, C. M. & Wu, H. (2021). Environmental exposures and lung aging: Molecular mechanisms and implications for improving respiratory health. *Current Environmental Health Reports*, 8(4), 281–293. https://doi.org/10.1007/s40572-021-00328-2

European Commission. (2024, August 12). *Climate Action and the Green Deal.* https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/climate-action-and-green-deal_en

European Commission. (2024, July 26). *Delivering the European Green Deal.* https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

Fang, S. C., Cassidy, A. & Christiani, D. C. (2010). A systematic review of occupational exposure to particulate matter and cardiovascular disease. *International Journal of Environmental Research and Public Health*, 7(4), 1773–1806. https://doi.org/10.3390/ijerph7041773

Fang, X., Huang, S., Zhu, Y., Lei, J., Xu, Y., Niu, Y. & Chen, R. (2022). Short-term exposure to ozone and asthma exacerbation in adults: A longitudinal study in china. *Front Public Health*, 10, 1070231. https://doi.org/10.3389/fpubh.2022.1070231

Gaffin, J. M., Hauptman, M., Petty, C. R., Sheehan, W. J., Lai, P. S., Wolfson, J. M., … Phipatanakul, W. (2018). Nitrogen dioxide exposure in school classrooms of inner-city children with asthma. *Journal of Allergy and Clinical Immunology*, 141(6), 2249–2255. https://doi.org/10.1016/j.jaci.2017.08.028

Garcia, A., Santa-Helena, E., De Falco, A., Paula Ribeiro, J. de, Gioda, A. & Gioda, C. R. (2023). Toxicological effects of fine particulate matter (PM2.5): Health risks and associated systemic injuries—systematic review. *Water, Air, & Soil Pollution*, 234(6), 346. https://doi.org/10.1007/s11270-023-06278-9

Gavett, S. H. & Koren, H. S. (2012). The role of particulate matter in exacerbation of atopic asthma. *International Archives of Allergy and Immunology*, 124(1-3), 109–112. https://doi.org/10.1159/000053685

Ghosh, R., Joad, J., Benes, I., Dostal, M., Sram, R. J. & Hertz-Picciotto, I. (2012). Ambient nitrogen oxides exposure and early childhood respiratory illnesses. *Environment International*, 39(1), 96–102. https://doi.org/10.1016/j.envint.2011.10.001

Glencross, D. A., Ho, T.-R., Camiña, N., Hawrylowicz, C. M. & Pfeffer, P. E. (2020). Air pollution and its effects on the immune system. *Free Radical Biology and Medicine*, 151, 56–68. https://doi.org/10.1016/j.freeradbiomed.2020.01.179

Jiang, Y., Niu, Y., Xia, Y., Liu, C., Lin, Z., Wang, W., … Kan, H. (2019b). Effects of personal nitrogen dioxide exposure on airway inflammation and lung function. *Environmental Research*, 177, 108620. https://doi.org/10.1016/j.envres.2019.108620

Jiang, Y., Niu, Y., Xia, Y., Liu, C., Lin, Z., Wang, W., … Kan, H. (2019a). Effects of personal nitrogen dioxide exposure on airway inflammation and lung function. *Environmental Research*, 177, 108620. https://doi.org/10.1016/j.envres.2019.108620

Johns, D. O., Pinto, J. P., Kim, J. Y. & Owens, E. O. (2011). Respiratory effects of short term peak exposures to sulfur dioxide. In J. O. Nriagu (Ed.), *Encyclopedia of environmental health* (pp. 852–859). Burlington: Elsevier. https://doi.org/10.1016/B978-0-444-52272-6.00726-1

Kjaer, Sk & Rasmussen, Tr. (1996). Clinical studies of effects of nitrogen oxides in healthy and asthmatic subjects. *Central European Journal of Public Health*, 4, 23. https://api.semanticscholar.org/CorpusID:77193154

Ko Ui Won, Kyung Sun Young. (2022). Adverse effects of air pollution on pulmonary diseases. *Tuberculosis and Respiratory Diseases*, 85(4), 313–319. https://doi.org/10.4046/trd.2022.0116

KPMG. (2024, August 9). *Our insights*. https://kpmg.com/xx/en/home/insights/2021/11/european-green-deal-policy-guide.html

Ku, T., Chen, M., Li, B., Yun, Y., Li, G. & Sang, N. (2017). Synergistic effects of particulate matter (PM(2.5)) and sulfur dioxide (SO(2)) on neurodegeneration via the microRNA-mediated regulation of tau phosphorylation. *Toxicology Research (Camb)*, 6(1), 7–16. https://doi.org/10.1039/c6tx00314a

Lao, X. Q., Guo, C., Chang, L., Bo, Y., Zhang, Z., Chuang, Y. C., … Chan, T.-C. (2019). Long-term exposure to ambient fine particulate matter (PM2.5) and incident type 2 diabetes: A longitudinal cohort study. *Diabetologia*, 62(5), 759–769. https://doi.org/10.1007/s00125-019-4825-1

Lee, L. T., Ho, C. H. B. & Putti, T. C. (2013). Bronchiolitis obliterans organizing pneumonia following nitric acid fume exposure. *Occupational Medicine*, 64(2), 136–138. https://doi.org/10.1093/occmed/kqt147

Lelieveld, J., Evans, J. S., Fnais, M., Giannadaki, D. & Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature*, 525(7569), 367–371. https://doi.org/10.1038/nature15371

Li, T., Yan, M., Sun, Q., & Anderson, G. B. (2018). Mortality risks from a spectrum of causes associated with wide-ranging exposure to fine particulate matter: A case-crossover study in Beijing, China. *Environment International*, 111, 52–59. https://doi.org/10.1016/j.envint.2017.10.023

Liang, F., Liu, F., Huang, K., Yang, X., Li, J., Xiao, Q., … Gu, D. (2020). Long-term exposure to fine particulate matter and cardiovascular disease in china. *Journal of the American College of Cardiology*, 75(7), 707–717. https://doi.org/10.1016/j.jacc.2019.12.031

Lin, S., Liu, X., Le, L. H. & Hwang, S. A. (2008). Chronic exposure to ambient ozone and asthma hospital admissions among children. *Environmental Health Perspectives*, 116(12), 1725–1730. https://doi.org/10.1289/ehp.11184

Linn, W. S., Avol, E. L., Peng, R. C., Shamoo, D. A. & Hackney, J. D. (1987). Replicated dose-response study of sulfur dioxide effects in normal, atopic, and asthmatic volunteers. *American Review of Respiratory Disease*, 136(5), 1127–1134. https://doi.org/10.1164/ajrccm/136.5.1127

Lippi, G. & Mattiuzzi, C. (2020). Particulate matter pollution and lung cancer: A worldwide perspective. *The Clinical Respiratory Journal*, 14(2), 179–180. https://doi.org/10.1111/crj.13115

Liu, C., Yang, C., Zhao, Y., Ma, Z., Bi, J., Liu, Y., … Chen, R. (2016). Associations between long-term exposure to ambient particulate air pollution and type 2 diabetes prevalence, blood glucose and glycosylated hemoglobin levels in china. *Environment International*, 92-93, 416–421. https://doi.org/10.1016/j.envint.2016.03.028

Nelin, T. D., Joseph, A. M., Gorr, M. W. & Wold, L. E. (2012). Direct and indirect effects of particulate matter on the cardiovascular system. *Toxicology Letters*, 208(3), 293–299. https://doi.org/10.1016/j.toxlet.2011.11.008

Nguyen, D.-H., Lin, C., Vu, C.-T., Cheruiyot, N. K., Nguyen, M. K., Le, T. H., … Bui, X.-T. (2022). Tropospheric ozone and NOx: A review of worldwide variation and meteorological influences. *Environmental Technology & Innovation*, 28, 102809. https://doi.org/10.1016/j.eti.2022.102809

Pershagen, G., Rylander, E., Norberg, S., Eriksson, M. & Nordvall, S. L. (1995). Air Pollution Involving Nitrogen Dioxide Exposure and Wheezing Bronchitis in Children. *International Journal of Epidemiology*, 24(6), 1147–1153. https://doi.org/10.1093/ije/24.6.1147

Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K. & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA*, 287(9), 1132–1141. https://doi.org/10.1001/jama.287.9.1132

Prada, D., López, G., Solleiro-Villavicencio, H., Garcia-Cuellar, C. & Baccarelli, A. A. (2020). Molecular and cellular mechanisms linking air pollution and bone damage. *Environmental Research*, 185, 109465. https://doi.org/10.1016/j.envres.2020.109465

Ranft, U., Schikowski, T., Sugiri, D., Krutmann, J. & Krämer, U. (2009). Long-term exposure to traffic-related particulate matter impairs cognitive function in the elderly. *Environmental Research*, 109(8), 1004–1011. https://doi.org/10.1016/j.envres.2009.08.003

Rao, M. N., Patel, T. S., Agarwal, A. L., Kulkarni, P. K., Kashyap, S. K. & Chatterjee, S. K. (1992). Effect of exposure to oxides of nitrogen on pulmonary function. *Indian Journal of Community Medicine*. https://api.semanticscholar.org/CorpusID:74377379

Roderique, J. D., Josef, C. S., Feldman, M. J. & Spiess, B. D. (2015). A modern literature review of carbon monoxide poisoning theories, therapies, and potential targets for therapy advancement. *Toxicology*, 334, 45–58. https://doi.org/10.1016/j.tox.2015.05.004

Schraufnagel, D. E., Balmes, J. R., Cowl, C. T., De Matteis, S., Jung, S.-H., Mortimer, K., … Wuebbles, D. J. (2019). Air pollution and noncommunicable diseases: A review by the forum of international respiratory societies’ environmental committee, part 2: Air pollution and organ systems. *CHEST*, 155(2), 417–426. https://doi.org/10.1016/j.chest.2018.10.041

Shcheklein, S. E. & Dubinin, A. M. (2020). Analysis of nitrogen oxide emissions from modern vehicles using hydrogen or other natural and synthetic fuels in combustion chamber. *International Journal of Hydrogen Energy*, 45(1), 1151–1157. https://doi.org/10.1016/j.ijhydene.2019.10.206

Shehab, M. A. & Pope, F. D. (2019). Effects of short-term exposure to particulate matter air pollution on cognitive performance. *Scientific Reports*, 9(1), 8237. https://doi.org/10.1038/s41598-019-44561-0

Thompson, J. E. (2018). Airborne particulate matter: Human exposure and health effects. *Journal of Occupational and Environmental Medicine*, 60(5). https://journals.lww.com/joem/fulltext/2018/05000/airborne_particulate_matter__human_exposure_and.2.aspx

Tomić-Spirić, V., Kovačević, G., Marinković, J., Janković, J., Ćirković, A., Đerić, A. M., … Janković, S. (2021). Sulfur dioxide and exacerbation of allergic respiratory diseases: A time-stratified case-crossover study. *Journal of Research in Medical Sciences*, 26, 109. https://doi.org/10.4103/jrms.JRMS_6_20

WHO. (2021). *WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide* (pp. xxi, 273 p.). Geneva: World Health Organization Publications.

Xu, X., Zhang, J., Yang, X., Zhang, Y. & Chen, Z. (2020). The role and potential pathogenic mechanism of particulate matter in childhood asthma: A review and perspective. *Journal of Immunology Research*, 2020(1), 8254909. https://doi.org/10.1155/2020/8254909

Zhao, C.-N., Xu, Z., Wu, G.-C., Mao, Y.-M., Liu, L.-N., Qian-Wu, … Pan, H.-F. (2019). Emerging role of air pollution in autoimmune diseases. *Autoimmunity Reviews*, 18(6), 607–614. https://doi.org/10.1016/j.autrev.2018.12.010

Zhou, X., Li, C., Cheng, H., Xie, J., Li, F., Wang, L. & Ding, R. (2022). Association between ambient air pollution exposure during pregnancy and gestational diabetes mellitus: A meta-analysis of cohort studies. *Environmental Science and Pollution Research*, 29(45), 68615–68635. https://doi.org/10.1007/s11356-022-20594-3

Zieliński, M., Gąsior, M., Jastrzębski, D., Desperak, A. & Ziora, D. (2018). Influence of particulate matter air pollution on exacerbation of chronic obstructive pulmonary disease depending on aerodynamic diameter and the time of exposure in the selected population with coexistent cardiovascular diseases. *Advances in Respiratory Medicine*, 86(5), 227–233. https://doi.org/10.5603/ARM.2018.0036