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Authors: Maji, Sanjoy, Ahmed, Sirajuddin, Kaur-Sidhu, Maninder, Mor, Suman, and Ravindra, Khaiwal

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Health Risks of Major Air Pollutants, their Drivers and Mitigation Strategies: A Review

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Sanjoy Maji[1], Sirajuddin Ahmed[1], Maninder Kaur-Sidhu[2], Suman Mor[3] and Khaiwal Ravindra[2]

[1]Jamia Millia Islamia (Central University), New Delhi, India. [2]Postgraduate Institute of Medical Education and Research (PGIMER), Chandigarh, India. [3]Panjab University, Chandigarh, India

ABSTRACT: The impact of increasing air pollution on human health and the environment is a major concern worldwide. Exposure to air pollution is one of the leading risk factors and substantially contributes to morbidity and premature mortality. This review paper aims to examine the exposure of major air pollutants (i.e., particulate matter, sulfur dioxide, oxides of nitrogen, carbon monoxide) and its association with respiratory, cardiovascular, reproductive, and genotoxic adverse health outcomes that can cause DNA damage leading to genetic mutations. The study emphasized how a better understanding of source-receptor relationships and exposure assessment methodologies can support effective air quality management planning. Hence, there is a need to augment various exposure indicators (spatial modeling, personal/area monitoring, emphasizing central/rural site measurements, etc.) to generate reliable surrogates for informed decision-making. The critical drivers of anthropogenic interference for air pollution remain urbanization, growing vehicle use, and industrialization. This requires innovative approaches, such as energy-efficient and technologically sustainable solutions to gradually replace conventional fossil fuel from primary energy mix with renewable energy. It holds the key to meet future energy challenges and minimizing air pollution emissions. Further, there is an urgent need to frame effective public policy with graded mitigation actions to reduce the adverse impact of air pollution on human health and the environment.

KEYWORDS: Air pollution, exposure assessment, particulate matter, health effects, sustainability

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CORRESPONDING AUTHOR: Ravindra Khaiwal, Department of Community Medicine & School of Public Health, Post Graduate Institute of Medical Education & Research (PGIMER), Chandigarh 160012, India. Emails: khaiwal@yahoo.com; khaiwal.ravindra@pgimer.edu.in

Introduction

The atmosphere is one of the building blocks of the biosphere for the life-supporting environment on this planet. The availability of clean air is vital for the well-being of human health and the proper functioning of the environment. The atmosphere serves as a medium through which emitted air pollutants are dispersed and transported (Vallero, 2014). These pollutants further undergo a chemical transformation and contribute to atmospheric pollution. The growing concerns about air pollution and its associated impacts on health and the environment have taken a central position in the priority research areas. Air pollution has far-reaching effects on local, regional, and global levels based on the residence time of pollutants in the atmosphere and their physicochemical dynamics. Emission sources, secondary pollutant formation, dispersion of pollutants, and meteorological factors are the prime aspects of ambient air pollutant concentrations (Biswal et al., 2023).

According to recent findings, air pollution resulting from industries, vehicles, agricultural and mining activities is increasing rapidly in Low-Middle income countries (LMICs). About 4.2 million deaths, as per the Global Burden of Disease (GBD) study, could be attributed to ambient air pollution (Landrigan et al., 2018). Global estimates of deaths from air pollution exceed the number of deaths altogether caused by risk factors associated with water pollution, occupational, and soil pollution (Landrigan et al., 2018). The GBD Comparative Risk Assessments study designates indoor air pollution as the second and ambient air pollution being the third-largest global environmental health risk factors (Kaur-Sidhu et al., 2020; Ravindra, et al., 2019; World Health Organization, 2014). Accounting for the health significance of ambient air pollution, the International Agency for Research on Cancer (IARC) listed outdoor air pollution and particulate matter in outdoor air pollution as "known carcinogens to humans" (Loomis et al., 2014).

Epidemiological evidence from the past few decades suggests that air pollution leads to morbidity and mortality. Various studies have reported associations between emerging health impacts such as respiratory and cardiovascular mortality resulting from acute-chronic exposure to particulate matter in the air (Chen et al., 2012; World Health Organization, 2003). Several studies assess the linkage between exposure level and adverse health impact indicators such as increased hospital admissions for respiratory and cardiovascular ailments (American Thoracic Society [ATS], 2000; Kaur-Sidhu et al., 2019; Mostofsky et al., 2012; World Health Organization, 2000). Air pollution significantly contributes to GBD and the long time exposure to fine particulate matter ($PM_{2.5}$) is attributable to more than 4.2 million deaths and above 100 million disability-adjusted life years (DALYs), constituting 7.6% of overall global mortality and 4.2% of global DALYs (Cohen et al., 2017; World Health Organization, 2016a).

Some health effects are due to either short-term exposure to high concentrations of air pollutants or prolonged exposure to low levels. Short-term exposure leads to the onset of acute effects such as irritation in the upper respiratory tract and increased asthma symptoms. In contrast, long-term exposure has been observed to be responsible for chronic health effects such as cardiovascular diseases (Dockery, 2001), reproductive dysfunction (J. Zhang et al., 2018) and genotoxic effects (Klumpp et al., 2006). Besides, several other studies also linked air pollution with adverse pregnancy outcomes (Liu et al., 2003; Lu et al., 2020; Perera, 2003; Zhan et al., 2020), tuberculosis (Lin, 2007; Mishra, 1999), asthma exacerbation (Guarnieri, 2014; Jerrett, 2008; Schraufnagelet al., 2019), cancers (Martoni, 2018; Pope et al., 2002), and cognitive impairments (Brabhukumr et al., 2020; Chen, 2009; Krishnamoorthy et al., 2018; Sunyer, 2015).

Human health risk assessment studies are spread worldwide across different populations in different exposure settings with diverse climatological conditions to understand the various attributes of air pollution. Evidence from various multicity studies have been able to establish the magnitude of health impacts due to ambient air pollution on different baseline population health status (HEI International Scientific Oversight Committee, 2010; Katsouyanni et al., 2009; Samoli et al., 2003, Wong et al., 2008). APHENA study from Europe and NMMAPS survey from the United States have reported an increase in the risk of mortality by 0.6% and 0.21 %, respectively (Katsouyanni et al., 2001; Samet et al., 2000), whereas in India, mortality risk is reported to aggravate by 0.4% and 0.15% in Chennai (Balakrishnan et al., 2011) and Delhi (Maji et al., 2017; Rajarathnam et al., 2011) respectively with an increase of 10 μg/m^3 levels in PM_{10} concentration. A collective study of four big metropolitan cities in China reported a 0.6% (95% CI [0.3%, 0.9%]) increase in mortality from all causes daily with PM_{10} levels of 51.6–141.8 μg/m^3 (Wong et al., 2008). Different systematic meta-analysis of exposure assessment studies extrapolated the findings to capture the estimate of health burden at a diverse range of air pollutant concentrations at national and regional levels.

There are many geographic confounding factors of health effect estimates of air pollution. Lower-and middle-income countries face many challenges, such as inadequate health facilities, poor nutritional status, lack of awareness, and a large share of the geriatric population, which make their population more vulnerable to air pollution-related health impacts. However, due to the limited number of air-pollution-related health impact studies in lower-and middle-income countries, health risk estimates heavily rely on extrapolation of the results from studies conducted in Europe and North America. This could make it unrealistic for the general public to comprehend the magnitude of the health burden due to air pollution.

With the growing urbanization, industrialization and growth in motorized transport, the adverse impact of air pollution on public health is expected to become more crucial. Exposure to the cocktail of pollutants is a complex task. Further, the lack of data on spatial and temporal levels of air pollution may obstruct identifying the exposure variability in the study population. Hence, the present review aims to improve the understanding of air pollution exposure and associated health risk, including drivers of air pollution. The paper examines the exposure risk assessment of major air pollutants (i.e., particulate matter, sulfur dioxide, oxides of nitrogen, carbon monoxide) and their associated impact on respiratory, cardiovascular, reproductive, and genotoxic leading to adverse health outcomes. The review has also focused on the key driving factors contributing to air pollution and discusses major challenges and mitigation strategies for improving air quality.

Air Pollution and Exposure Risk Assessment

The mere occurrence of any pollutants in the environment may not inevitably pose a threat to human health. According to US National Research Council (US NRC), exposure can be defined as a contact over time and space between an agent and a target (Lioy, 1991). Exposure to pollutants has three dimensions, namely, (i) the intensity of exposure, (ii) space, and (iii) time. Precisely, exposure assessment is the process where the magnitude of exposure is linked to a pollutant along with the information on the characteristics of the exposed population. Conceptually, exposure assessment is comprised of five distinct components: (a) sources of pollutants, (b) transport of these pollutants from source to the target organism, (c) exposure of a target organism, (d) dose received by the organism, and (e) health effects resulting from these exposures. A source is the point or area of origin, whereas an exposure pathway is a physical path from a source to a target. Exposure matrices depend on the characteristics of the pollutant in question along with factors of exposure variation such as activity patterns, lifestyle characteristics, microenvironment parameters and intensity of the contact.

Therefore, human-exposure assessment forms the critical link between ambient pollutant concentration and potential human health effects. Approaches for exposure assessment vary based on numerous factors, including the study's objective, time, possible pathways, and available resources. Accordingly, the design of an exposure assessment also varies from simply using the available monitoring data for approximating the exposure to air pollution to a sophisticated exposure assessment approach, which requires the disclosure of the study participants in different micro-settings for the estimation of individual exposure profiles.

Various exposure assessment models serve as an essential tool in air pollution epidemiology studies for analyzing the population exposure and associated health impacts of air pollution (Özkaynak et al., 2013). The exposure prediction models rely on historical data to simulate the concentration of pollutants to predict future concentrations. Further, the valuable information yielded from these models can serve as decision-making tools. However, these modeling frameworks remain to be evaluated for prediction errors and misclassification of exposure pollutants as the exposure varies spatiotemporally due to a person's activity in different locations. The exposure-outcome relationship mainly depends on the pollutant in question, the spatial distribution of the pollutant concentration at different micro-habitat, as well as local determinants of pollutant dispersions.

Other heterogeneity factors also come from individual population sensitivities like age and health status of the target. Young children and the elderly are among the most vulnerable to air pollution effects (Villeneuve et al., 2007). Individuals with pre-existing cardiovascular and respiratory ailments are more prone to risk (Xing et al., 2016). Socioeconomic status also determines susceptibility to air pollutants. Literature advocates that economically deprived population groups may experience higher health burdens due to insufficient nutritional status and limited access to health care (Laurent et al., 2007). Thus, enhancing exposure indicators (spatial modeling, personal monitoring, emphasizing urban/rural site measurements, etc.) is needed to generate reliable surrogates to accurately estimate human exposure.

Outdoor Versus Indoor Air Pollution Exposure Profile

Characterization of exposure is a central issue for health impact studies, as it provides a general understanding of the intensity and diversity of exposure occurring within a population as well as the potential human health effects of air pollutants. It is to highlight that there is a difference between "exposure" and "concentration." The target is exposed because it comes into contact with the pollutant. High pollutant concentrations in the ambient atmosphere may not mean high exposure. Air pollution exposure is estimated according to the time spent at a location by the individual and the level of the air pollutant in the atmosphere. There may be a considerable difference in air pollutant concentration in the outdoor and indoor air environments. There are different factors of differences in outdoor and indoor air pollutant concentration like pollutant concentration, meteorology, chemical reactivity of the pollutant, as well as ventilation coefficient of the house.

An average person spends about 90% of their time indoor environment, though it varies for tropical and subtropical countries (Leech et al., 2002). Apart from indoor pollution sources, infiltration of ambient air influence the air quality indoors. There may be a considerable difference in the exposure profile of an individual in the outdoor and indoor micro-environment depending on household characteristics, ventilation coefficients, and meteorological factors, which all influence the penetration of air pollutants from the outdoor to indoor atmosphere. Besides, there may be indoor sources of air pollutants, which may be more critical for households that use solid biomass cooking fuel. These include particulate matter, carbon monoxide, sulfur and nitrogen oxides. Burning crop residue and solid biomass fuels also produce a cocktail of toxic pollutants, including arsenic, benzene, fluorine, formaldehyde, and poly-aromatic hydrocarbons (Ravindra, et al., 2023; J. Zhang & Smith, 2003).

The concentration of $PM_{2.5}$ in an indoor micro-environment using solid biomass cooking fuel could be two to five folds higher than that of households using LPG (Balakrishnan et al., 2013; Sidhu et al., 2017). Exposure to volatile organic compounds (VOCs) in the indoor atmosphere (from air fresheners, cleaning products, paints, and building materials) sometimes outweighs VOC exposure in the ambient atmosphere (Wallace, 2001). Exposure to asbestos, radon, and lead from construction materials as well as exposure to free radicals and reactive compounds due to indoor air pollution reactions, is a classic example of indoor air pollution exposure. Differences in indoor-outdoor pollutant levels also depend on the pollutant in question. Air pollutants such as PM_{10} and $PM_{2.5}$, sulfur dioxide (SO_2), and oxides of nitrogen (NO_x) certainly infiltrate from outdoors to indoors. Whereas, in the case of ozone, there is substantial spatial variation in indoor-outdoor settings.

Human exposure profile varies from subject to subject depending on individual activity patterns and other micro-environmental parameters. However, widely held epidemiologic studies on the health effects of urban air pollution consider ambient air pollutant concentrations as the primary exposure metric. An exposure route by inhalation via the respiratory tract is considered the quickest pathway of exposure to air pollution apart from ocular and dermal absorption. The monitored or modeled ambient pollutant concentration act as a proxy indicator for estimating air pollution exposure. Based on these considerations, the setting up of routine air quality networks takes place. However, the proposed interventions, such as improved cookstoves, have failed to bring any health outcomes or pollution reduction.

However, several countries are focusing on establishing real-time ambient air quality monitoring facilities, but they focus exclusively on urban locations and the exposure profile of rural populations is often neglected. On the contrary, rural households face the most significant threat due to household air pollution. The rural areas that are deprived of clean cooking fuel are typically found to be more polluted than urban areas. There is a need to emphasize more on rural monitoring networks to produce air quality exposure profiles for individuals residing in far-flung rural areas. In the absence of a realistic exposure profile of the rural population, it is hard to compare the cross-sectional variability of relative risk due to variations in air pollution exposure profiles in urban and rural locations.

Major Air Pollutants and Their Associated Health Impacts

An individual inhales about 20,000 L of air daily and inhaling polluted air increases the risk of associated diseases. There are more than 100 industrial chemical species that increase the risk of exposure through their mixing in ambient air. Exposure to air pollutants may come from both gaseous or particulate pollutants. The toxic effect of particulate matter depends on its composition, mainly containing heavy metals, organic compounds

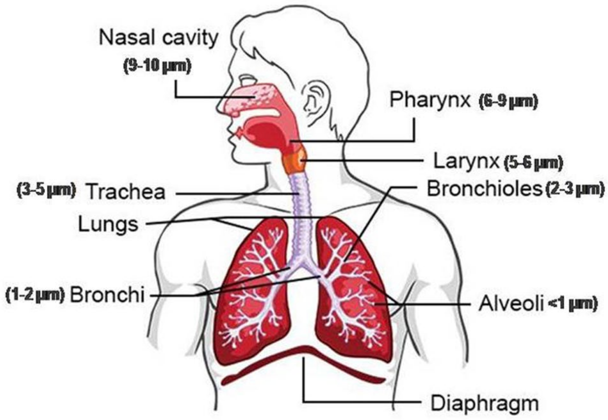

Figure 1. Deposition of inhaled particles in the human respiratory tract.

such as polycyclic aromatic hydrocarbons, polychlorinated benzenes and dioxin and furans, depending on the location of the source.

During 1960 to 1990, there was a wave of health impact studies from different North American urban centers (Anderson, 1965, 1967; Ayres, 1970; Dockery, 1989; Hodgson, 1970; Pope et al., 1992; Schimmel, 1978; Schwartz, 1991; Schwartz & Dockery, 1992) and European cities (Doll, 1978; Holland & Reid, 1965; Melia, 1977; Schwartz & Marcus, 1990; Speizer, 1968; Wichmann, 1989) linking increasing contaminant concentration with harmful health outcomes ranging from irritation to death. Acute health impacts lead to respiratory and cardiovascular hospital admissions (Guttikunda et al., 2013; Maji et al., 2018), emergency department visits, days of constrained events and respiratory symptoms such as cough, wheezing and respiratory infections (Agarwal et al., 2006; Chen et al., 2012; Mostofsky et al., 2012; Sharma et al., 2019), whereas exposure to a higher degree of pollution load for a prolonged period leads to increased incidence of chronic respiratory and cardiovascular diseases which may even lead to mortality effects and even genotoxic effects.

Effect of particulate matter on the respiratory system

The health effects of particulate matter primarily depend on the deposition of the respiratory tract and their toxicity and reactivity. Particle size influences the deposition of particles in the respiratory tract. The particles size in the atmosphere is defined through the aerodynamic diameter, categorized into three major fractions; namely, inhalable particles (enter with air into the nose or mouth), thoracic particulates (penetrate and pass beyond the larynx), and respirable particulates (penetrate beyond the terminal bronchioles) as shown in Figure 1. Particles of larger size, PM_{10}, consists commonly of carbon-containing earth crust materials, whereas the fine particles, $PM_{2.5}$, contain a consistently greater quantity of nitrate, sulfate, and trace metals. Numerous studies have highlighted the toxicological effects of $PM_{2.5}$ and the deposition efficiency of particulate matter on the respiratory tract, as shown in Figure 2. The deposition rate in individuals with developing respiratory ailments may be more due to lung susceptibility.

The airways are the direct entry point for contaminants; respiratory diseases are the first organ of health effects. Air particles are deposited into three respiratory sections: the extrathoracic (mostly coarse particles-PM_{10}), tracheobronchial (PM_{5-10}) and alveolar regions (fine particles $PM_{2.5}$). The particulate deposition fraction (3–5 mm) is reported to be higher in women than in men. The health effects are more associated with fine particles that reach the tracheobronchial and alveolar regions. Risk estimates on the human respiratory system for particulate exposure are described in Table 1.

Effect of Gaseous Pollutants on the Respiratory System

Gaseous pollutants depending on their solubility, are absorbed differently by various segments of the respiratory tract. Sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) are standard criteria air pollutants, but their mechanism of toxicity is different. SO_2 is water-soluble, capable of getting absorbed in the upper respiratory tract, and causes irritating effects in the upper respiratory system. Exposure to increased SO_2 levels aggravates existing respiratory and cardiovascular diseases (Newell et al., 2018). In comparison, NO_2 is a poorly water-soluble gas that penetrates more deeply in the respiratory tract compared to SO_2 and causes irritating effects in the lower respiratory system. Exposure to NO_2 is reported to impair lung development and cause influenza and other asthmatic problems in young children (Katsouyanni et al., 2001; J. Zhang et al., 2018). Ozone is a secondary pollutant that irritates airways in the lungs and interferes with host defense mechanisms in the body. Acute effects of ozone exposure include pulmonary system effects, whereas chronic exposure develops reduced lung function and the development of asthma (Bell et al., 2005).

Effects on cardiovascular system

Air pollutants, upon inhalation, get into the bloodstream and are transported to the heart. The harmful substances can directly lead to structural damage to the cardiovascular system, including inflammation and degenerative changes, as highlighted by Pope et al.(2004). Air pollution-related acute cardiovascular diseases include the burden of stroke, arrhythmias, coronary heart disease, and sudden cardiac arrest. Table 2 shows the short-term effects collated from numerous epidemiological studies triggered by air pollution on cardiovascular mortality. Cardiovascular disease accounts for about 60% to 80% of premature air pollution-related deaths worldwide (World Health Organization, 2014). Roth et al. (2015) examined that between 1990 and 2013, the deaths attributable to cardiovascular diseases have amplified by 41%. Significant associations are reported to exist between elevated $PM_{2.5}$ levels and increased risk of ischemic heart diseases, myocardial infarction and cerebrovascular diseases (Nawrot et al., 2011).

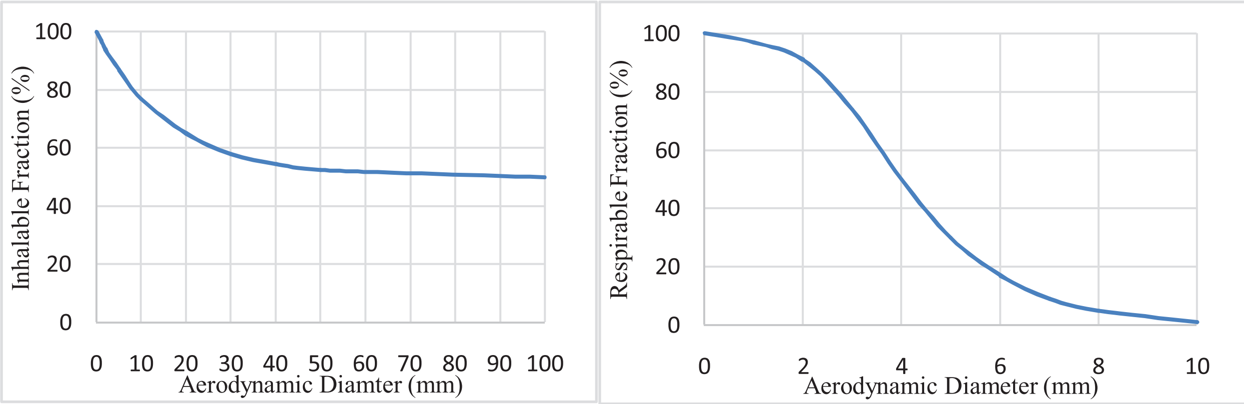

Figure 2. Particulate matter deposition (a) inhalable and (b) respirable particulate matter in the respiratory system.

Table 1. Particulate Matter Exposure Effects Estimate on the Human Respiratory System.

OUTCOME	COUNTRIES	OR [95% CI]	REFERENCE
Daily mortality (Respiratory) with 10 μg/m³ air pollution increment	Global	1.3 [0.5, 2.09]	World Health Organization (2004)
	Yazd, Iran	10.21 [4.19, 14.89]	Miri et al. (2017)
	USA, 112 Cities	1.68 [1.04, 2.33]	Zanobetti et al. (2009)
	US 27 cities	1.8 [0.2, 3.4]	Franklin et al. (2007)
	California	2.2 [0.6, 3.9]	Ostro et al. (2006)
	Asia 4 Cities	0.62 [0.16, 1.04]	Wong et al. (2008)
Daily mortality (Respiratory) with 20 μg/m³ air pollution increment	European Cities	1.3 (0.4, 1.9)	Katsouyanni et al. (2003)
	Japan 13 Cities, Age > 65 year	1.4 [0.9, 2.1]	Omori et al. (2003)
All-cause mortality with 10 μg/m³ air pollution increment	USA	0.21 [0.09,0.33]	Health Effects Institute (2003)
		4.0 [1, 8]	Pope et al. (2002)
Cardiopulmonary mortality with 10 μg/m³ air pollution increment		6 [2, 10]	

Table 2. Particulate Matter Exposure Effects Estimate on the Human Cardiovascular System.

OUTCOME	COUNTRIES	OR [95% CI]	REFERENCE
Daily mortality (Cardio-respiratory) with 10 μg/m³ air pollution increment	Lima, Peru	1.029 [1.01, 1.05]	Tapia et al. (2020)
	Yazd, Iran	7.3 [4.19, 10.21]	Miri et al. (2017)
	USA	0.31 [0.13, 0.49]	Health Effects Institute (2003)
	US, 112 Cities	0.85 [0.46, 1.24]	Zanobetti et al. (2009)
	US cities	1.3 [0.3, 2.4]	Klemm and Mason (2003)
	California, 9 cities	0.6 [0.0, 1.1]	Ostro et al. (2006)
	Asia 4 Cities	0.59 [0.22, 0.93]	Wong et al. (2008)
Daily mortality (Cardio-respiratory) with 20 μg/m³ air pollution increment	European Cities	1.5 [0.9, 2.1]	Katsouyanni et al. (2003)
	Japan 13 Cities, Age > 65 years	1.1 [0.7, 1.5]	Omori et al. (2003)

Reproductive toxicity

Air pollution has been considered as a possible deteriorating factor of reproductive health, influencing infertility and adverse pregnancy outcomes, including low birth weight (LBW), preterm, stillbirth, and risk of new-borns death. Ravindra, Chanana, Mor, et al. (2021) have also established the relationship between air pollution exposure and the risk of congenital malformations. Studies using animals have shown the toxic effects of heavy metals and polyaromatic hydrocarbons (PAHs) bound to particulate matter on semen quality. Carbon monoxide (CO) is a colorless and odorless gas produced primarily by the incomplete burning of fossil fuels in household fuel use, industrial uses and the transport sector. Symptoms of CO exposure include fatigue, headaches and dizziness. Moderate concentrations result in impaired vision and disturbed coordination.

At higher concentrations, CO exposure can be fatal (World Health Organization, 1999). Adverse birth outcomes due to CO exposure during the first trimester have also been reported (Salam et al., 2005). Evidence suggests that pregnant women residing in regions of high air pollution have a 20% increased risk of LBW and preterm birth (Liu et al., 2019). Brabhukumr et al. (2020) reported that exposure to solid biomass fuel smoke significantly affects cognitive performance and intelligence quotient among children. Polycyclic aromatic hydrocarbons such as benzopyrene have also been proven to be a developmental, reproductive, carcinogenic and mutagenic toxicants (Bolden et al., 2017). The mothers who were exposed to PAHs during pregnancy have higher odds of small gestational age, born with LBW and smaller head circumference (Schraufnagel et al., 2019).

Neurotoxicity

Numerous studies have reported that air pollution has been associated with diseases of the central nervous system. Current research shows that exposure to fine particles causes various neurological and neurodegenerative diseases, developmental impairment, etc. In the developing brains of infants, children are particularly at higher risk due to toxic air pollutants. Exposure to household air pollutants is associated with a lower intelligence quotient (IQ) and poor mental development (Brabhukumr et al., 2020). Indoor smoke, flame retardants, vehicular emissions, and VOCs are also reported to be associated with decreased cognitive functions, lack of concentration, inability to recall and respond, and sleep disorders are usual neurotoxic effects of air pollution (D'Angiulli 2018; Kilburn et al., 2010).

Genotoxic effects of air pollution

Epidemiological evidence shows that air pollution-related genotoxic damage is responsible for increased mortality (Levorato et al., 2015). Prolonged exposure to fine particles, irritant gases, heavy metals, PAH, benzene and soot from diesel engines has been linked to causing DNA damage resulting in genetic mutations. Schraufnagel et al. (2019) highlighted that other malignancies, such as bladder cancer and childhood leukemia, are also associated with exposure to high air pollution. Vulnerable populations and children are found to be at increased risk as genetic damage increases the risk of developing chronic diseases, including cancer.

Drivers of Air Pollution

Air pollution is recognized as a major sustainability concern and has been included in the goals and targets of SDGs. There is an urgent need to reduce air pollution exposure to the population. In most low-and middle-income countries, air pollution concentrations exceed the prescribed health-based criteria established by several national and international agencies (World Health Organization, 2016b). It is not practical to anticipate ambient pollutant concentrations to fall rapidly to the levels of the listed guidelines. The main driving forces that have a negative impact on air quality are related to urbanization, industrialization, transport, demand in the agriculture sector, etc. The trend of urbanization, together with industrialization and economic growth, are significant factors affecting ambient air quality.

The simultaneous increase in vehicular number and road network, increase in per capita energy consumption, and rapid construction of associated social infrastructure are some of the major characteristics of any urban development, which in turn lead to high emissions resulting in the deterioration of primary air quality. These driving forces have a reinforcing effect on other factors that further aggravate the problem of air pollution. Air pollution-related mortality, morbidity and the risk associated with human health depend upon the source of the pollutant. The elicit information about the sources of air pollution serves as an important tool for exposure estimation of health effects. Identifying the source of origin of pollutants causing such health effects can further be targeted to achieve maximum health benefits (Hopke, 2008; Thunis et al., 2019).

Thus the advanced monitoring and estimation of major sources of pollution indicating a sectoral contribution can support in designing effective air quality management plans and rectifying emission inventories. The most commonly used source apportionment methods are emission reduction (a method used at a regional level to support short-term and long-term air quality plans), mass transfers (source and receptor models are used for short and long-term planning) and incremental methods (used in urban settings for estimating the impact of local pollutants on the region). For effective air quality management, an integrated approach is required in which the information derived from source apportionment studies, exposure assessment studies, and emission inventory can be co-related/fed into modeled data to further formulate a region-wise airshed-based approach. Such methodologies in the air quality management planning process are required so that data and decision-making at different levels can be correlated to functions and measures at various levels. However, the choice of method to apportion the air pollutant to their emission sources for air quality planning must be considered carefully to reduce systematic biases. Further, research is required in order to find ways to eliminate exposure thresholds that would be sufficient to achieve target health goals and SDGs.

Urbanization

The growing trend of urbanization is a crucial and critical driver of increasing air pollution. Due to improved social infrastructure and better quality of life, urban centers are always the primary choice of living for the majority of the world's population. The global urban population increased from 0.75 billion in 1950 to 4.22 billion in 2018 (Kundu & Pandey, 2020). World Health Organization and UN-Habitat (2010) estimated a doubling of the urban population (3.4 to 6.4 billion) by 2050. Globally many countries are continuously making efforts to monitor and mitigate air pollution. The air quality scenario amongst high-income countries is improved compared to mid-low-income countries that are still progressing toward urbanization and economic development (X. Zhang et al., 2022).

Among the lower-and middle-income counties, India is the second-most populous country in the world. It is projected that about 50% of the population is expected to be residing in urban regions by 2050. Also, cities with a population between 1 and 10 million are expected to reach 85 by 2051 against 32 in 2001 (Planning Commission, Government of India, 2011). The urbanization drift will lead to increased energy and fuel demand as well as increased transportation needs, which will ultimately contribute to higher air pollution levels. Primary energy demand in India, which stood at 441 Mtoe in 2000, is expected to reach 1,237 Mtoe in 2030 and 1,573 Mtoe in 2040. As per the statistics, all over the world, more than 63% of primary energy comes from coal and oil. In India, over 80% energy needs are met by three fuels: coal, oil, and solid biomass. Coal is considered as dirtiest of the fossil fuels. However, due to the predominance of coal, coal is the most important and abundant fossil fuel in India and accounts for 44% of India's energy needs (International Energy Agency, 2021). Coal is the fastest-growing carbon-emitting energy source in the energy mix of China and India and together contribute 25% of total CO_2 emissions worldwide.

Growing Vehicle Use

Extensive urbanization and rapid economic growth have led to higher motorization demand (Barnett, 2011). Increased motorization eventually leads to more pollution and increased usage of energy. Despite technological and diesel fuel quality improvements, diesel vehicles are a major source of airborne particulate matter pollution. The transport sector has seen a surge in demand for diesel models of passenger vehicles due to the lower price of diesel and the widening price gap with petrol.

Global demand for mobility is growing rapidly; as per the projections, the number of vehicles is projected to triple by 2050 by the International Energy Agency (IEA, 2016). India's road density is about thrice (1.42 km/sq.km of road length) in comparison to the USA (0.67 km/sq.km) and China (0.40 km/sq.km) (MoRTH, 2012). The national highway network has grown twice in the last decade (MORTH, 2012). In India, the density of motor vehicles has risen 450 times, from less than 0.5 million to approximately 140 million in the last six decades (MoRTH, 2012). Vehicular emissions are of major concern as these are ground-level sources. Vehicles in major metropolitan cities are estimated to account for 70% of carbon monoxide (CO), 50% of hydrocarbon (HC), 30% to 40% of oxides of nitrogen (NOx), and 30% of particulate matter (PM) of the total pollution load (Central Pollution Control Board [CPCB], 2010).

According to the statistics of OICA (OICA, 2010), vehicles alone contribute to 16% of the CO_2 emissions globally. Globally, the percentage share of oil demand by the road transport sector is projected to increase from 57% in 2010 to 60% in 2035. In the Asia Pacific, gasoline demand is projected to rise by more than 3 million barrels per day (mb/d) between 2012 and 2035 (Organization of the Petroleum Exporting Countries, 2013). Among developing countries, the need of the hour is to address vehicular pollution by expanding a cleaner transport fleet (CNG and e-vehicles) with strict exhaust emission norms (e.g., BS-VI in India), scrapping old vehicles and promoting public transport.

Industrialization

Emissions from industrial facilities, including thermal power plants, manufacturing factories, mines, oil refineries, and agricultural operations, release a variety of pollutants into the atmosphere. The majority of industries contributing to air pollution include metals, chemicals, petroleum, pesticides, cleaners, plastics, solvents, paints, etc. The emission of air pollutants from industry is either due to the release of air pollutants from a process or due to emissions from the consumption of fuels. Some of the major air pollutants from industry include particulate matter, SOx, NOx, hydrogen sulfide, hydrogen fluoride, CO, O_3, lead, mercury, organic solvents, chlorine, and ammonia.

The energy consumption by the industrial sector has increased from 28% to 36% between 1990 and 2019. The estimates put the industry's share in total final consumption, which is expected to increase up to 41% by 2040. Emission inventory studies from India reported that industries contribute about 51%, 35%, and 18% to PM_{10}, SO_2 and NOx emission loads, respectively (TERI, 2019). According to a World Bank report, since 1990, total emissions from fossil-fuel consumption and cement production have grown more than two times in India (World Bank, 2009). Commission for Air Quality Management in National Capital Region and adjoining areas (CAQM) has framed a policy to curb air pollution in NCR to bring transformation in the industrial and transport sector by completely switching to affordable cleaner fuels in a phased manner. Thus, there is a need for framing holistic, long-term region-based multi-sectoral strategies to curb air pollution.

Challenges and Mitigation Strategies for Clean Air

The rapidly growing trend of urbanization coupled with industrialization and ever-increasing traffic are the main causal factors for deteriorating air quality (Biswal et al., 2023). The extent of contribution from different emission sources is the product of emission rates and activity levels. Mitigation strategies for clean air depend on a sustainable solution for the future energy demand (Ravindra, Kaur-Sidhu, Mor, et al., 2021). Technological advancement, energy efficiency initiatives and structural changes to gradually replace conventional fossil fuel from primary energy mix with renewable energy hold the key to meeting future energy challenges (Ravindra et al., 2016; X. Zhang et al., 2022). Efficient energy demand and supply management is equally crucial in abatement strategies. Understanding the various challenges of managing energy demand and supply by different sectors is thus necessary to deal with future emission control for mitigation strategies for clean air.

Fossil fuel consumption over the past century has risen, making it a primary source of energy in various countries globally. Two-thirds of the world's electricity is produced by fossil fuels. One of the striking trends of a shift in the primary energy mix is that over the year's relative percentage of liquid fuel consumption has decreased. In contrast, coal which is considered the most polluting fossil fuel has increased noticeably. Coal is cheap and indigenously available; between 2000 and 2014, global coal consumption has grown about 64% (World Energy Council, 2016). Coal has become the fastest-growing energy source in the energy mix of low- and middle-income countries. In India, coal is the most important and abundant fossil fuel.

There is growing environmental concern about the emissions from coal-fired power generation causing air pollution, mainly due to the poor quality of Indian coal, which has an average ash content of 40% or more (Jayanti et al., 2007). There is also broad agreement that improved fuel efficiency and advanced technologies (viz. fluidized bed combustion, integrated gasification combined cycle, coal gasification combined technologies, etc.) for emission standards will be able to make a decisive impact on air quality. Using a better grade of coal in thermal power plants and other industrial applications, such as Continuous Emission Monitoring System (CEMS) expansion, is a viable techno-economic solution for regulating air pollution from the industrial sector.

Followed by power, the transportation sector uses the most amount of energy. Rapid urbanization coupled with growing economic prosperity and lack of public transport infrastructure has led to higher motorization. But motorization also brings more pollution. The transport sector accounts for 27% of global final energy demand (https://www.worldbank.org/en/topic/transport/overview). Emissions from the transport sector vary widely on account of vehicle technology (e.g., Euro I, Euro II, Euro III, and Euro IV), fuel (type and quality) and operating characteristics. Vehicles in urban areas account for 70% of carbon monoxide (CO), 50% of hydrocarbon (HC), 30% to 40% of oxides of nitrogen (NOx), 30% of particulate matter (PM) towards the total pollution load (CPCB, 2010). In terms of pollution load, CNG has significantly reduced particulate matter. However, it is widely postulated that at the present rate of vehicle growth, improved fuel efficiency and technologies for emission standards alone will not be able to control the pace of air pollution from the sector.

Gradual replacement of oil with much cleaner fuels such as hydrogen, biofuels, CNG, or LPG offers an excellent opportunity for alternative fuels for the transportation sector. Natural gas is currently being utilized successfully as a transport fuel in some of the metropolitan cities (cities having a population of more than 1 million) in India. The use of natural gas relies upon the proven engine and fuel distribution, storage and dispenser technologies. Thus, successful extensive penetration of alternative fuels in the transport sector requires an effective implementation strategy (refueling stations, fuel storage and distribution). Technical and economic viability and market acceptance will be decisive factors for the success of alternative fuels and vehicle technologies to reduce traffic-related air pollution.

Discussion

Poor air quality has been related to many harmful health effects on human health. Short-term health effects may range from irritation in the upper respiratory system to long-term exposure results in cardio-pulmonary dysfunction, especially among vulnerable populations. The population with pre-existing cardiopulmonary diseases is particularly susceptible to the episodic increase of air pollutant concentration. The effect estimates of various criteria air pollutants have been established through several multicity studies and meta-analyses of different independent air-pollution health impact studies. However, the independent, additive, or synergistic effects of a cocktail of gaseous co-pollutants are not fully recognized yet and need to be investigated further.

In lower-and middle-income counties, the high population density, high exposure gradient, poor nutritional status, inadequate health facilities, a large number of old-age population and public ignorance are major contributing factors to increased air pollution-related health burden. In the past decades, there has been an increasing awareness of the harmful effects of air pollution in metropolitan cities. Health impact studies in rural areas are still neglected mainly due to the unavailability of reliable exposure data (Ravindra et al., 2022). It is also important to develop new study designs and exposure assessment methods that are apt for rural indoor air pollution settings. Further, there is potential to make use of artificial intelligence and machine learning to predict the impact of air pollution and plan health sector preparedness (Ravindra, et al., 2023; Ravindra, et al., 2019).

One of the major challenges for creating public awareness about the risks of health effects of air pollution is the availability of very limited geographical evidence on health impact studies correlating vital statistics records with air pollution data (Mor et al., 2022). Another major challenge of air quality health research is the availability of good quality air pollution data and centralized mortality and morbidity data records. The central registry system of vital statistics is not adequately framed to record morbidity and mortality counts due to air pollution. The morbidity count data with respiratory and/or cardiovascular ailments is a more sensitive estimator of air quality data. Though morbidity count data is available from the medical records of an individual hospital but there is no central registry to record city-level morbidity count data.

Moreover, the medical record system of individual hospitals does not have a consistent format to record the cause of disease as per the International Classification of Diseases. Another important estimator of the harmful effects of air pollution is a daily count of mortality data which is recorded for institutional death only. Parting deaths other than institutional remain undocumented. Another drawback of the available mortality count data is the unavailability of medically certified coding of the cause of death.

Improved methods of exposure assessment are evidently needed in epidemiology. Precise evaluation of human exposure depends on microenvironmental air pollutants concentration levels weighted by population-time-activity diaries. However, our exposure data mostly rely on air pollution data from a limited number of manual air quality monitoring stations. Available 24-hourly average air pollution data from manual monitoring stations is neither an accurate measure of population-level exposure, nor it can be used to study the daily fluctuation level of air pollution. Though recently, continuous monitoring stations have been installed across the cities, the availability of air pollution data from rural areas still remains a challenge.

Conclusion

A primary focus of regulatory authorities is to develop programs focused on protecting the environment and public health from deteriorating air quality. Thus, it is crucial to understand all the factors of air pollution that pose health risks for the general public and implement pollution control strategies accordingly. Changes in population growth, rapid industrialization and urbanization, along with the growth of vehicular numbers, are expected to continue for the coming decades. The majority of metropolitan cities exceed air quality standards. Despite several mitigation measures, the air pollution level and the number of non-attainment cities have increased in the past decades. It is well understood that if air pollution levels are abridged, the incidence of diseases related to the cardiovascular and respiratory systems would be considerably reduced. Identifying the pollution source with the advanced monitoring and source apportionment techniques that cause such adverse health effects can be targeted to achieve maximum health benefits. Nevertheless, the considerable exposure impacts of air pollution should be considered in developing public health policy and supporting air quality management planning for the region. This will help to develop effective mitigation strategies to alleviate the adverse effect of air pollution on human health and the environment.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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