

A COMPREHENSIVE INVESTIGATION OF PUBLIC HEALTH PROBLEMS AND PREVENTIVE STRATEGIES FOR INDOOR AIR POLLUTION

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ABSTRACT

The quality of indoor air (IAQ) is one of the primary factors influencing people's health and wellbeing. The measurement, identification, and potential health impacts of IAQ are currently not well understood by the general public. Microbial spores, pollen, allergens, sulfur dioxide (SO₂), carbon monoxide (CO), nitrous oxide (NO), volatile organic compounds (VOCs), particulate matter (PM), microbial spores, pollen, and other airborne pollutants are the main causes of IAQ degradation. The origins of the main indoor air pollutants, their molecular toxicity mechanisms, and their impacts on neurological, cardiovascular, ophthalmic, and fetal health are all covered in this study. Modern approaches and environmentally friendly techniques for controlling and lowering pollution levels are also highlighted, and ongoing projects to improve and manage IAQ are examined, along with their special benefits and possibilities. Children and women are more vulnerable to poor indoor air quality because of their unique physical features and longer exposure durations. A variety of health problems can be brought on by indoor air pollution because it sets off several damage pathways, such as oxidative stress, DNA methylation, epigenetic changes, and gene activation. Exposure increases the risk of early mortality, SBS, acute

lower respiratory tract infections, and low birth weight in exposed populations. However, lung cancer, chronic obstructive pulmonary disease, and cardiovascular problems are the primary causes of disability and early mortality.

Key words: *Indoor Air Pollution, Public Health, Preventive Measures*

Introduction: Due to modern lifestyles and increasing urbanization, people are spending more time indoors—whether at workplaces, theaters, restaurants, retail stores, or homes where they are exposed to indoor air pollutants. Air pollution is one of the biggest environmental hazards to human health, according to the WHO, because of the connection between air quality and health. Up until now, a lot of focus has been on lowering personal exposure to indoor air pollutants, which necessitates examining interior sources and the potential for lowering emissions from them. Consequently, indoor air quality (IAQ) has become a critical concern, significantly impacting human health and well-being in both living and working environments (Cincinelli, A., & Martellini, T., 2017). Numerous scientific studies have established a clear connection between improved air quality and positive health outcomes. Indoor air pollution can have both immediate and long-term effects on health, with severe cases potentially leading to life-threatening conditions. In addition to interior activities and materials, outside influences can affect the concentration of contaminants in indoor air. The interior environment is an extension of the exterior atmosphere, meaning that the quality of the air outside has a direct impact on the quality of the air within, regardless of the level of insulation, even in areas that are mechanically conditioned and ventilated or naturally ventilated. Carbon monoxide (CO) and other non-reactive pollutants can enter an interior space and be exacerbated by unvented gas burners, flawed cooking and heating appliances, fireplaces, tobacco smoke, and automobile emissions from adjoining garages (Vardoulakis, Set al. 2020). However, reactive pollutants that normally originate outside, including ozone (O₃) and sulfur dioxide (SO₂) rapidly diminish once they reach an interior environment. The presence of people indoors and

their metabolism are linked to carbon dioxide, which is regarded as an indication of air quality in non-industrial indoor contexts including homes, workplaces, and schools. Indicators of the presence of additional contaminants are also found in it. Despite having little to no toxicological effects on humans at low doses, CO₂ directly affects human health at greater quantities. CO₂ produces respiratory acidosis and hypercapnia at concentrations above 5%, and it can induce convulsions, coma, and even death at values over 10% (Wolkoff, P., 2018).

The majority of human exposure to indoor air pollutants comes from a variety of sources, including emissions from heating appliances, cooking activities, furniture, flooring, wall coverings, paints, glues, waxes, polishes, cleaning supplies, personal care items, and tobacco smoking. House age and size, air exchange rates, door and window openings, building improvements, and external pollutant levels can all have an impact on interior air pollutant concentrations. The volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) included in cleaning solutions and personal care items are often partly oxidized and condensed, resulting in the formation of small particles.

1. The indoor air quality problems

Indoor surroundings may be at least twice as contaminated as outside ones, according to the most recent research on human exposure to indoor pollution (European Commission, 2003). In fact, compared to the air in a living room, the air on an urban street with typical traffic may be cleaner. Particularly in highly industrialized or heavily populated places, interior air pollution has historically gotten far less attention than outside air pollution (Moreno-Rangel, A et al 2020). The European Environment Agency (2013) notes that as buildings are increasingly walled off from the outside world to save energy costs for heating and cooling, the dangers of prolonged exposure to indoor air pollution have been more obvious in recent years. In many buildings, interior pollutants build up because mechanical ventilation is the only method used to circulate internal air with a significantly lower amount of external air dilution. A recent commission study estimates that nearly three billion people worldwide are exposed to poor indoor air quality (IAQ) daily due to the use of

solid fuels for heating, cooking, and lighting. According to the Royal College of Physicians (2016), household air pollution has a profound impact on the respiratory and cardiovascular systems, significantly contributing to global morbidity and mortality rates (Cincinelli, A., & Martellini, T., 2017). The research also emphasized the substantial role that low IAQ has in the overall number of premature deaths.

The first explicit IAQ recommendations were released by the WHO in 2010 (World Health Organization and WHO Regional Office for Europe, 2010), and other organizations in a number of nations have since embraced them. Although these recommendations were the first attempt to create a broad indoor air quality standard (World Health Organization, 2010) they only addressed a small number of priority indoor air contaminants that were known to have harmful health impacts (Baeza Romero, M. T. et al, 2022). The intrinsic complexity of indoor air pollution and the paucity of data about the long-term health impacts of each pollutant make it difficult to implement a comprehensive quantitative regulation that covers all physical, chemical, biological, and particle exposures. Particulate particles, biological pollutants (allergens, bacteria, mold, fungus, spores, etc.), physical agents (temperature, electromagnetic fields) as well as more than 400 distinct chemical constituents, primarily inorganic and volatile organic chemicals (VOCs and VOCs, respectively). Organic emergent compounds released by plastics, medications, or personal hygiene items have been found in interior settings more recently. Apart from the diverse range of indoor pollutants, their prevalence and concentration are influenced by several elements, including outside air quality, the nation's socioeconomic progress, activity types, occupancy, environmental variables, time of year, etc. Furthermore, pollution sources and emission rates are subject to rapid change over time (Luengas et al., 2015). While outdoor pollutants are largely influenced by human activities such as road traffic and industry, indoor pollutants originate from both permanent and occasional sources. Permanent sources include building materials, adhesives, paints, and varnishes, while occasional sources encompass furniture, cleaning and disinfection products, cooking, personal care items, and even human metabolism. Furthermore, indoor gas-phase interactions from other indoor airborne chemicals may result in secondary pollutants (Weschler, C. J, 2006).

IAQ and human health have been shown to be negatively impacted by a number of indoor air contaminants. Toxic metals, microbes, PM, radon, SO₂, O₃, CO, NO_x, and volatile and semi-volatile organic compounds (VOCs) are the primary indoor air pollutants.

1. The primary pollutants found in indoor air

IAQ and human health have been shown to be negatively impacted by a number of indoor air contaminants (Vardoulakis, Set al. 2020). Toxic metals, microbes, PM, radon, SO₂, O₃, CO, NO_x, and volatile and semi-volatile organic compounds (VOCs) are the primary indoor air pollutants (Cincinelli, A., & Martellini, T., 2017).

2.1 Particulate matters: Particulate matter (PM) consists of carbonaceous particles combined with reactive metals and adsorbed organic compounds. Its primary components include sulfates, nitrates, endotoxins, polycyclic aromatic hydrocarbons, and heavy metals such as iron, nickel, copper, zinc, and vanadium. PM is typically classified into three categories based on particle size: (i) coarse particles (PM₁₀) with a diameter of less than 10 µm, (ii) fine particles (PM_{2.5}) with a diameter of less than 2.5 µm, and (iii) ultrafine particles (PM_{0.1}) with a diameter of less than 0.1 µm. PM is particularly concerning because it can be inhaled, posing serious health risks to the heart and lungs. Studies have shown that indoor PM levels often exceed outdoor levels. Indoor PM sources include both particles that infiltrate from the outdoor environment and those generated by indoor activities. PM is mostly released into houses as a result of cooking, burning fossil fuels, smoking, using machinery, and domestic hobbies. Due to its capacity to enter both the alveoli and the tiny airways, PM_{0.1} produced by burning fossil fuels poses a larger health risk than PM₁₀ and PM_{2.5}. Research on the concentration of main indoor pollutants has shown that the biggest contributors of indoor air pollution are cooking and smoking cigarettes, whereas cleaning activities typically contribute less to indoor PM. Smoking is a recognized cause of indoor PM_{2.5}, with concentrations in winter being higher than in summer and estimates of increases in households

with smokers ranging from 25 to 45 $\mu\text{g}/\text{m}^3$ (Cincinelli, A., & Martellini, T., 2017).

2.2 VOCs: Volatile organic compounds (VOCs) are gases emitted from liquids or solids and encompass a wide range of substances. One of the most common VOCs is formaldehyde, a colourless gas with a strong odour, which is released from particleboard, plywood, glues, and other building materials. Indoor VOC concentrations are at least ten times higher than outdoor levels, regardless of a building's location. There are four primary sources of indoor VOCs; firstly, human activities such as cooking, smoking, and the use of cleaning and personal care products; secondly, indoor chemical reactions; thirdly outdoor air infiltration through ventilation systems, and fourthly emissions from building materials. Several factors influence VOC concentrations, including building modifications, the frequency of door and window openings, outdoor VOC levels, air exchange rates, and the age and size of the structure. Research has identified approximately 50 different VOCs released during a 90-minute cooking period. Due to their low boiling points and ease of volatilization even at room temperature, the World Health Organization (WHO) has categorized VOCs into four groups. 1st, VVOCs (very volatile organic compounds) with T_b between 50 and 100 °C; VOCs (volatile organic compounds) with T_b between 100 and 240 °C; SVOCs (semi-volatile inorganic compounds) with T_b between 240 and 380 °C; and POM (particulate organic matter) with T_b more than 380 °C. There are typically three major ways to be exposed to volatile organic compounds (VOCs) emitted from consumer products: ingestion, inhalation, or skin contact. Short-term exposure to low concentrations of VOCs causes no significant harm to most individuals, but long-term exposure to certain VOCs is thought to pose a major danger to human health and may even cause cancer. Regarding SVOCs, direct transdermal absorption from the air contributes more than inhaled consumption (Wolkoff, P., 2018).

2.3 Nox: The primary nitrogen oxides, nitrogen dioxide (NO_2) and nitric oxide (NO), are closely associated with combustion sources such as heaters and cooking stoves. Ambient NO and NO_2 concentrations are significantly influenced by local

sources and sinks. Indoor concentrations of these pollutants often exceed outdoor levels when gas stoves and heaters are in use, whereas in buildings without combustion activities, indoor NO_2 levels are typically about half of those found outdoors. NO_2 is considered a major pollutant because NO readily oxidizes to form NO_2 under ambient conditions. When NO_2 reacts with water, it produces nitrous acid (HONO), a strong oxidant and a common indoor pollutant (Soulou, I., 2021) Both indoor and outdoor sources contribute to indoor NO_2 levels, meaning high outdoor NO_2 concentrations from combustion processes or traffic emissions can impact indoor air quality. Studies indicate that proximity to roads significantly affects indoor NO_2 levels, and the extent of air exchange between indoor and outdoor environments also plays a crucial role. Key indoor sources of NO_2 include smoking and the use of combustion-based appliances such as stoves, ovens, water heaters, fireplaces, and equipment that burn wood, gas, oil, coal, or kerosene.

2.4 Ozone the atmospheric photochemical interactions of O_2 , NO_x , and VOCs mostly create ozone, a potent oxidizing agent. However, because it reacts slowly with the majority of airborne contaminants, it cannot be employed to remove other chemical pollutants from interior environments. Ozone allows for a quick response with a number of indoor contaminants; however, the byproducts of the reaction can harm materials and annoy people. The external environment and electrical device functioning are the primary causes of indoor ozone. Devices that often release indoor ozone gas include photocopiers, air purifiers, disinfection equipment, and other office supplies. These devices' ozone emission processes may be separated into two groups: photochemical and corona discharge. Multiple variables have been found to influence indoor ozone levels: (i) outdoor ozone levels; (ii) indoor emission rates; (iii) air-exchange rates; (iv) surface-removal rates; and (v) interactions between airborne ozone and other chemicals. Depending on the air exchange rate, indoor ozone levels typically range from 20% to 80% of outside ozone levels. Although skin exposure is a known vector, breathing is the main way that humans are exposed to ozone.

2.5 SO₂: The most prevalent gas in the category of sulfur oxides (SO_x) found in the atmosphere is sulfur dioxide (SO₂). The main source of SO₂ is the burning of fossil fuels, which it mixes with PMs and aerosols to create a complicated mixture of different air pollutants. Tobacco smoke, kerosene heaters, coal or wood stoves, oil furnaces, and vented gas appliances are indoor sources of SO₂ emissions. Furthermore, outside air is thought to be a major source of SO₂ indoors. Compared to outside levels, indoor SO₂ levels are frequently lower. Because SO₂ is easily absorbed by interior surfaces and reactivated, indoor emissions are typically low. The hourly SO₂ concentration in buildings is reported to frequently be less than 20 parts per billion. Only inhalation exposes humans to SO₂, which might affect respiratory function (Wolkoff, P., 2018).

2.6 Biological pollutants: Indoor biological pollutants include house dust, cockroaches, mites, pollen, and allergens such as animal fur and cat saliva, as well as microorganisms like bacteria, fungi, and viruses. These biological allergens, also known as antigens, can be produced by various insects, animals, mites, plants, and fungi. When they interact with specific immunoglobulin E (IgE) antibodies, they can trigger allergic reactions. Both indoor and outdoor environments contribute to allergen exposure. Indoor sources include molds, plants, insects, rodents, furred pets (such as dog and cat dander), and house dust mites, while outdoor allergens originate from sources like plants and airborne molds. Bacteria and viruses are often introduced or carried by humans and animals. Exposure to biological allergens has been linked to sensitization, respiratory infections, allergic respiratory disorders, and wheezing. Additionally, indoor exposure to bacteria and viruses can lead to a range of infectious and non-infectious health issues (Wolkoff, P., 2018).

3. Indoor Air Pollution's Impact on Human Health

3.1 Building-Associated Illness: Over the past decades, declining indoor air quality (IAQ) in buildings and homes has been associated with various symptoms and illnesses. Exposure to inorganic, organic, physical, and biological contaminants indoors—though often at low levels—is

widespread, continuous, and unavoidable. As a result, the impact of indoor air pollution (IAP) on human health has been a significant concern. According to the World Health Organization (WHO), building-associated illness refers to any health condition caused by indoor environmental factors. These illnesses are typically categorized into two main groups: Sick Building Syndrome (SBS) and Building-Related Illness (BRI).3.1.1 Sick Building Syndrome (SBS) (Tiotiu, A.,2020)

A collection of symptoms that are connected to the physical surroundings of particular buildings are frequently referred to as SBS. It is challenging to pinpoint the exact reasons of SBS's acute health and comfort consequences, which manifest when patients spend a specific period of time in a building. In a structure, these impacts might be pervasive or restricted to certain locations. Symptoms have been shown to get worse with the amount of time spent in buildings and to go away with more time spent outside of them. The WHO has classified SBS symptoms brought on by IAP into four groups: (i) irritation of mucous membranes, such as the eyes, throat, and nose; (ii) neurotoxic effects, such as headaches, irritability, and exhaustion; (iii) asthma and symptoms similar to asthma, such as tightness in the chest and wheezing; and (iv) dryness and irritation of the skin, gastrointestinal issues (such as diarrhea), and other issues. Infants, the elderly, those with chronic illnesses, and the majority of urban inhabitants of any age have increased health risks connected with IAP-related SBS symptoms, according to research by the International Labour Organization (ILO). High room temperatures, humid buildings, and insufficient ventilation rates all appear to raise the risk of SBS prevalence. Furthermore, the prevalence of SBS symptoms is significantly influenced by other risk variables, including gender, atopy, and psychosocial factors. (Lin, C. C., at al,2022)

3.2 Acute Respiratory Infection: Because pollutants generally enter the human body by breathing, the respiratory system is often the primary focus of IAP effects. Acute respiratory infections are divided into acute lower respiratory infections (ALRIs) and upper respiratory infections (URIs) based on the region of the respiratory tract that is impacted. URIs are upper

respiratory diseases that are frequently moderate in nature and are brought on by biological pollutants (viruses, bacteria, fungus, fungal spores, and mites). Common symptoms include cough, sinusitis, and otitis media. In contrast, ALRI, an acute lung infection, is brought on by bacteria or viruses and causes inflammation of the lung. A million children under the age of five die each year from childhood ALRI, which has been proven to be 78% more likely to occur in children with IAP. The comparatively greater lung surface area of youngsters may be the reason of this. The risk of having ALRI is two to three times higher for children who live in buildings that use solid fuels than for those that use clean fuels, according to research. IAP negatively impacts the respiratory tract's host defenses against infections, both specific and nonspecific. Additionally, cooking moms have a higher prevalence of chronic bronchitis and respiratory infections that are more severe due to IAP. (Murphy, J., et al, 2023)

Cardiovascular Diseases (CVDs): Solid fuel consumption in households releases various contaminants, including particulate matter (PM), polycyclic aromatic hydrocarbons (PAHs), carbon monoxide (CO), heavy metals, and other organic pollutants, all of which have been linked to cardiovascular diseases (CVDs). Exposure to PM_{2.5} is particularly associated with acute cardiovascular conditions such as atrial fibrillation, myocardial infarction, cardiac arrhythmia, heart failure, and ischemic stroke. PM contributes to CVDs by inducing oxidative stress, systemic inflammation, increased blood coagulability, and autonomic and vascular imbalance. It also plays a key role in the release of endothelins (potent vasoconstrictors), fibrinogen, platelet activation, and increased plasma viscosity, all of which can negatively impact cardiovascular health. Additionally, carbon monoxide (CO) in indoor air influences the production of carboxyhemoglobin, which significantly affects cardiovascular function by reducing oxygen delivery to tissues. Exposure to PAHs and lead (Pb) from cooking fuel has been shown to increase oxidative damage, activate the renin-angiotensin system, and reduce nitric oxide levels, ultimately leading to increased vascular tone and peripheral vascular resistance—both of which contribute to cardiovascular strain. (Radbil, J., et al. 2024)

3 Present-Day Techniques for IAQ Monitoring and Control:

Two-dimensional (2D) nanostructured materials have attracted significant attention over the past decade due to their unique physical and chemical properties, making them highly suitable for gas-sensing applications. These materials exhibit exceptional characteristics, including high surface sensitivity, a large surface-to-volume ratio, and superior semiconducting capabilities. A promising approach for developing high-performance indoor air quality (IAQ) monitoring sensors is the integration of 2D nanostructured materials with materials of different dimensions. This strategy has led to four distinct IAQ monitoring designs by combining 2D nanostructures with 3D bulk materials, other 2D nanostructures, 1D nanostructures (such as nanotubes, nanowires, nanofibers, and nanorods), and 0D nanomaterials (such as quantum dots, nanoparticles, nanocrystals, and nanoclusters). These materials offer advantages in photonic, electrical, and chemical sensing applications due to their high surface-to-volume ratio, unique morphology, and rapid electron-transport capabilities. In recent developments, Van der Waals heterostructures, formed by stacking multiple 2D materials, have been explored for IAQ monitoring (Tran, V. et al, 2020) . Examples include graphene/MoSe₂, graphene/black phosphorus/MoSe₂, and graphene/WS₂/graphene. Additionally, layered 2D-nanostructured semiconductors can be integrated with conventional 3D bulk semiconductor substrates, either by direct growth or transplantation, to create innovative gas-sensing devices. These heterostructure-based devices leverage the superior properties of their components, making them highly effective for IAQ detection. A key trend in IAQ monitoring is the development of low-cost sensor networks and systems, with metal oxide (MOx) sensors emerging as one of the most effective technologies. These sensors are valued for their affordability, high sensitivity, ease of use, and compatibility with modern electronics, making them ideal for portable and remote IAQ monitoring. Metal oxide semiconductor gas sensors have shown promising results in detecting volatile organic compounds (VOCs) and carbon monoxide (CO) in indoor environments. Various

metal oxides, including SnO₂, ZnO, TiO₂, In₂O₃, Fe₂O₃, MoO₃, Co₃O₄, CuO, NiO, and CdO, have been successfully utilized in IAQ-sensing applications (Dai, X., et al,2023).

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