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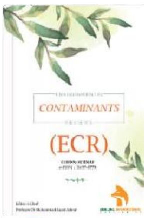

REVIEW ARTICLE

INDOOR AIR POLLUTION: SOURCES AND OCCURRENCE, HEALTH EFFECTS, AND MITIGATION STRATEGIES

Aniefiok E. Ite [a,b]*, Idaresit A. Ite[a]

[a] *Department of Chemistry, Akwa Ibom State University, P.M.B. 1167, Uyo, Akwa Ibom State, Nigeria.*
[b] *Research and Development Unit, Akwa Ibom State University, P.M.B. 1167, Uyo, Akwa Ibom State, Nigeria.*
**Corresponding author email: aniefiokite@yahoo.co.uk*

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ABSTRACT

Advances in industrialisation, urbanisation, and increased energy demand and consumption across the world lead to severe air pollution, which poses significant impacts on indoor air quality in our homes, schools, businesses, and other indoor spaces. Over the years, vulnerable populations have experienced poor indoor air quality and the associated economic cost of illnesses in several developed and developing countries. Air quality degradation challenges our efforts for sustainable, clean air and hinders progress towards the United Nations Sustainable Development Goals (SDGs) in various developing countries around the world. In recent years, the scientific community has faced the task of understanding the fate and occurrence of various indoor air pollutants as well as their ecotoxicological implications. Understanding the sources and occurrence of adverse impacts on the environment, human health, and economic burden of poor indoor air quality is crucial for developing effective preventative controls and mitigation strategies. The detection and characterisation of some of these indoor air pollutants at trace levels will enable researchers to understand the environmental fate and behaviour of various indoor air pollutants. The detection and characterisation of indoor air pollutants will begin with the development of sensitive and cost-effective, robust methods and long-term monitoring for sustainable environmental management and cost-effective risk mitigation strategies. Therefore, the goal of this review paper is to explain indoor air pollutants' sources and occurrences, as well as their adverse human health effects. Sustainable environments necessitate reducing indoor emissions, adopting air pollution prevention and control policies, and developing effective risk mitigation strategies. Governments worldwide must promote clean air policies, strategies, and plans to improve indoor air quality and reduce emissions, thereby promoting sustainable environments.

KEYWORDS

Indoor Air pollution; Air pollutants, Human exposure, Health effects, Mitigation strategies

1. INTRODUCTION

The most significant location for exposure to pollutants is indoor environments, which are basically the technosphere for modern man and largely powered by fossil fuel combustion. In the modern world, most people spend 90% of their time in different indoor environments (e.g., homes, schools, workplaces, restaurants, and other public spaces) (Schweizer et al., 2007; Mannan and Al-Ghamdi, 2021), and as such, the overall daily exposure will be considerably influenced by indoor air quality (IAQ) and impact human health as well as productivity. Determination of personal exposure to environmental pollutants is mainly influenced by time-microenvironment-activity patterns as people move through various spaces or microenvironments (Schweizer et al., 2007). Air pollutants associated with both natural disasters, such as bush burning, forest fires, volcanic eruptions, dust storms, etc., and anthropogenic activities have had various negative impacts on the indoor environments and human health.

Over the last sixty years, advances in industrialisation and urbanisation have resulted in large volumes of emissions from industrial plants, petroleum exploration and production, energy generation, chemical production, vehicular traffic, and waste incineration, causing severe air pollution around the world (Ite and Ibok, 2013; Ite et al., 2013; Ite et al., 2016; Lala et al., 2023). Apart from flares and associated carbon particles (soot) from artisanal crude oil refining operations in Nigeria's Niger Delta area, gas flaring and venting release substantial climatic forcing and harmful air pollutants, including black carbon, methane, and volatile organic compounds (Ite and Ibok, 2013; Ite and Ite, 2024; Ite et al., 2024). In addition, in the last century, the burning of fossil fuels has resulted in increased energy consumption, which has led to both air pollution and a gradual shift in the composition of the atmosphere (Kampa and Castanas, 2008).

Sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3), volatile and semi-volatile organic compounds (VOCs and SVOCs), heavy metals, and respirable particulate matter ($PM_{2.5}$ and PM_{10}) are among the most common air pollutants. It is known that the toxic effects of these pollutants are influenced by various factors such as their physical and chemical properties, reaction characteristics, disintegration time, and atmospheric dispersion conditions (Kampa and Castanas, 2008; Kelly et al., 2012; Manisalidis et al., 2020). Ineffective and incomplete combustion processes used for cooking and heating, the introduction of pollutants from the outside world, human activity (such as smoking, the presence of biological agents, and the use of chemicals), consumer goods, emissions from building materials or furniture, and inadequate ventilation or air conditioning system maintenance can all lead to indoor pollution (Perez-Padilla et al., 2010; Schwela, 2014; Tran et al., 2020; Samet et al., 2021; Newell et al., 2022; González-Caballero et al., 2024; Karri et al.,

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Indoor air can be just as polluted as outdoor air because of higher concentrations of VOCs and other indoor pollutants, with indoor sources contributing to the burden of poor indoor air quality (Jones, 1999; Cincinelli and Martellini, 2017; González-Caballero et al., 2024). Indoor air pollution is a challenging issue due to the lack of global standardisation in building codes, which may not be enforced or exist in certain situations. People in underdeveloped countries mostly rely on in situ energy generation for their everyday needs. Domestic electricity generation and cooking, primarily using firewood and kerosene, are major sources of pollutant emissions in Nigeria's Niger Delta region. When fuels such as coal and wood are burned in indoor environments, particulate matter (PM) and VOCs are released into the air along with smoke.

Untreated biomass and coal account for 90% of home energy in developing countries, causing poor indoor air quality (IAQ) due to high concentrations of pollutants from combustion (Bruce et al., 2000). According to a study, authors estimates from the regional air quality in the Niger Delta region indicate that household emissions emit 70 kt/year of CO, 50 kt/year of NO_x, 3 kt/year of PM_{10}, 2.4 kt/year of SO_2, 60 t/year of VOC, 5.7 mt/year of CO_2, and 2 kt/year of CH_4 (Fagbeja et al., 2013). In the developed countries, glues, paints, sealants, carpets, wallpapers, and furniture are just a few examples of the materials used in buildings that release VOCs and SVOCs into the indoor air. Exposure to indoor air pollution is particularly harmful in places where there may be a combination of inadequate ventilation, lax construction codes and regulations, and indoor pollution sources such as cooking, cleaning, smoking, and heating fires (Schwela, 2014; Tham, 2016; Rivas et al., 2019; Manisalidis et al., 2020; Hasager et al., 2021; Dida et al., 2022; González-Caballero et al., 2024; Nassikas et al., 2024). In 2012, ambient air pollution caused 3.7 million deaths, while household air pollution from indoor use of solid fuels for cooking and heating caused 4.3 million deaths (WHO, 2014).

Particulate matter is a diverse mixture of inorganic and organic components, consisting of minuscule solid particles and liquid droplets of primary and secondary origin (Arita and Costa, 2011; Lippmann, 2011; Ite et al., 2017; Hamanaka and Mutlu, 2018). Particulate matter is mostly composed of inorganic compounds including silica, iron, and alkali and alkaline earth metals, as well as residual solid carbon; its minor elements include lead, zinc, arsenic, and selenium (Courson and Gallucci, 2019). An organic phase and an aqueous phase with dissolved salts can both be found in liquid droplets of ambient particulate matter. Ambient particulate matter is a diverse mixture of sizes, origins, formation processes, and physiochemical characteristics, with trimodal distributions consisting of fine fraction (PM_1), intermodal fraction ($PM_{1-2.5}$), and coarse fraction ($PM_{2.5-10}$) (Cohen et al., 2004; Khan et al., 2021). The composition of particulate matter (PM) is highly variable and influenced by its origin and atmospheric processes, including pollutants like soot, PAHs, CO, and formaldehyde (CH2O) from combustion.

In urban areas, PM is a prevalent substance in the ambient environment, comprises a blend of black soot, fuel residues, and gaseous water droplets, and is the most harmful component of the traffic-related air pollution cocktail. Indoor pollutants, including non-combustion sources like building materials, paints, plastics, cleaning agents, batteries, and pipes, include formaldehyde, radon, asbestos, lead, VOCs and SVOCs, dampness, and mould, among others (Hasager et al., 2021). PM, primarily deposited in the head's airways, enters the lungs and introduces foreign chemicals into the bloodstream, leading to increased morbidity and mortality rates from cardiorespiratory diseases and lung cancer risk (Arita and Costa, 2011). Over the years, numerous epidemiologic studies worldwide have consistently documented the significant adverse effects of ambient air pollution on the environment, human health, and well-being.

Poor air quality in educational environments significantly impacts students' learning, health, academic performance, and wellbeing, especially in urban schools with high levels of pollution and poor ventilation. Air pollution is one of the leading causes of health complications among students' and staff, and in the past decades, numerous research studies have been published on IAQ in schools worldwide (Moschandreas and Vuilleumier, 1999; Lee and Chang, 2000; Synnefa et al., 2003; Fromme et al., 2007; Godwin and Batterman, 2007; Santamouris et al., 2008; Yang et al., 2009; Almeida et al., 2011; Yousaf and Khan, 2013; Jovanović et al., 2014; Schwela, 2014; Madureira et al., 2016; Verriele et al., 2016; Vilčeková et al., 2017; Korsavi et al., 2020; Manisalidis et al., 2020; Dida et al., 2022; González-Caballero et al., 2024; Nassikas et al., 2024). Some of the human health implications associated with PM pollutants in schools include higher susceptibility of children to environmental pollutants, higher inhalation rates per body mass, and extended time spent in the education environment (Nkwocha et al., 2008; Cartieaux et al., 2011; Abdel-Salam, 2017; de Gennaro et al., 2014; de Gennaro et al., 2014; Abdel-Salam, 2017).

Occupants actively contribute to their built environment by influencing its performance, environmental conditions, and indoor environmental quality (IEQ), which subsequently affect occupant health and well-being. In a study, a group researchers evaluated IAQ as a function of occupant-related parameters such as adaptive behaviours, occupancy patterns, occupant CO_2 generation rates, and occupancy densities (Korsavi et al., 2020). The study reveals that 17% of CO_2 variations are attributed to open area, 14% to occupants' generation rates, and 11% to occupancy density, with occupants' adaptive behaviours being the most significant factor (Korsavi et al., 2020). Several studies found that various pollutant factors lead to IAQ concerns in some schools around the world. For examples, high PM_{10} and CO_2 levels were obtained in Porto, Portugal, Hong Kong, Munich, Germany, Kosice, Slovakia, and Qatari (Vilčeková et al., 2017; Fromme et al., 2007; Madureira et al., 2016; Lee and Chang, 2000; Abdel-Salam, 2017).

High mean concentrations of both PM_{10} and $PM_{2.5}$ levels were obtained in Lahore, Pakistan (Yousaf and Khan, 2013). A mean indoor CO_2 content that is greater than the ASHRAE Guidelines-62 of 1000 ppm was obtained in Athens, Greece, and Serbia, or the CO_2 level established by Portuguese legislation (Moschandreas and Vuilleumier, 1999; Synnefa et al., 2003; Santamouris et al., 2008; Jovanović et al., 2014; Almeida et al., 2011). The high concentration of CH_2O measured in indoor environments in South Korea was attributed to furniture or construction materials and France (Yang et al., 2009; Verriele et al., 2016). In addition, high average SO_2 concentrations were obtained in French schools (Meininghaus et al., 2003). Indoor air quality policies vary across states and countries, often lacking enforcement. Many educational buildings lack such policies. Without a single regulatory framework, policymakers can reduce exposures and improve IAQ through research and advocacy, thereby protecting human health.

The high exposure risk of indoor and outdoor environmental air pollutants, even at relatively low concentrations, poses significant health impacts (Kim et al., 2015; Manisalidis et al., 2020). The adverse effects of airborne pollutants and poor indoor air quality (IAQ) on human health can lead to health complications, school absences, and acute health symptoms that decrease students' performance (Almeida et al., 2011). Over the years, numerous epidemiological studies have emerged showing adverse health effects associated with short-term and long-term exposure to particulate matter pollution (Brunekreef and Holgate, 2002; Davidson et al., 2005; Pope and Dockery, 2006; Halonen et al., 2009; Brook et al., 2010; Calkovska and Herting, 2010; Linares and Diaz, 2010; Celo and Dabek-Zlotorzynska, 2011; Guaita et al., 2011; Iavicoli et al., 2011; Jahn et al., 2011; Janssen et al., 2013; Strak et al., 2013; Kim et al., 2015; Du et al., 2016; Manisalidis et al., 2020).

Indoor air pollution associated with particulate matter, primarily caused by the use of biomass fuel for cooking and heating, significantly contributes to the burden of disease in low- and middle-income countries, particularly sub-Saharan Africa and South Asia (Bennitt et al., 2021). The major source of indoor air pollution in high-income countries is the continuous emissions of chemicals associated with building products, innovative fixtures, electronic appliances, and construction materials, furnishings, and materials used in business spaces as well as private indoor spaces (Tran et al., 2020; Bennitt et al., 2021; Mannan and Al-Ghamdi, 2021). Building materials, insulation, and electrical appliances are typically assembled using adhesives such as urea- and phenol-formaldehyde-based resins, which emit formaldehyde and other VOCs into indoor environments, posing a health risk to humans (He et al., 2012; Lucattini et al., 2018; Goldstein et al., 2021; Sonne et al., 2022).

Indoor pollution sources that release gases into the air are the primary cause of indoor air quality problems and the second most significant environmental risk factor contributing to the disease burden after ambient particulate matter pollution. The impact of PM-related air pollution on cardiorespiratory health is unclear, with the specific particle size fractions and sources of particles being the focus (Halonen et al., 2009; Brook et al., 2010; Strak et al., 2013). Good indoor air quality is a crucial component of a healthy indoor learning environment and significantly promotes students learning ability, boosts teacher and staff productivity, and impacts human health and well-being (Heudorf et al., 2009; Sadrizadeh et al., 2022). Indoor environment is influenced by several factors such as air exchange rate, humidity, temperature, ventilation, air movement, biological, particle, and gaseous pollutants (Graudenz et al., 2005; Faulkner et al., 2015; Tran et al., 2020).

IAQ, which can affect everybody's comfort and productivity, is important for the health and wellbeing of building occupants. Ambient PM pollution poses a significant public health risk, causing health-related symptoms and reduced productivity. Poor indoor air quality can lead to increased mortality and lower physical and mental health, with social, political, and economic consequences (Jones and Molina, 2024). There is paucity of information on indoor air quality in rural areas in Nigeria, while research efforts to investigate the prospective health implications of high concentrations of gaseous pollutants on rural populations are restricted to estimates (Oguntoke et al., 2010). This review paper examines indoor air pollutants sources and occurrences, adverse human health risks, preventative controls, and mitigation strategies for future directions. It is known that our environment is being exposed to a growing number of indoor air pollutants from various sources, which may threaten indoor air quality and pose human health risks.

2. SOURCES AND OCCURRENCE OF INDOOR AIR POLLUTANTS

The sources of pollutants vary significantly across various environments, making it challenging to identify and assess the contributions of the different kinds, sources, and concentrations of indoor air pollutants in different indoor environments. Outdoor air greatly increases indoor levels of classical air pollutants, including nitrogen oxides and ultrafine particles, because the same pollutants are present in both indoor and outdoor air but in different proportions (Mendes and Teixeira, 2014; Hänninen and Goodman, 2019; Rosário Filho et al., 2021). Major sources of outdoor air pollution are fossil fuel burning in industries and automobile emissions. In urban areas, traffic emissions are the main source of air pollution, which usually contains carbon monoxide, nitrogen dioxide, ozone, and particulates, the most harmful component of the air pollution cocktail.

Outdoor air is primarily contaminated with sulphur dioxide, a primary pollutant from fossil fuel combustion, and ozone, a secondary pollutant from the photochemical reaction of NO_x and VOCs (Chen and Guo, 2019). Indoor air can contain both outdoor and indoor air pollutants since indoor air contaminants are not entirely derived from outdoor sources (Nassikas et al., 2024). In Nigeria's Niger Delta region, the origin of indoor air pollutants is partly attributed to anthropogenic activities like gas flaring and venting associated with unsustainable petroleum exploration and production, as well as artisanal refining practices (Ite and Ibok, 2013; Ite and Ite, 2024). Apart from health risks attributed to indoor air pollution, indoor air pollutants may become outdoor in densely populated areas where biomass is used, a phenomenon known as the "neighbourhood" pollution effect (Rosário Filho et al., 2021).

Indoor air pollutants that affect indoor air quality can originate from many sources, including some that are external to the indoor environment and some that originate within the environment. Ambient air pollution can also have an adverse effect on indoor air quality and impact human health because of the burning of solid fuel, smoke, vapours, mould, and chemicals used in certain paints, furnishings, and various cleaning products within the indoor environment (Schwela, 2014; Rivas et al., 2019; Manisalidis et al., 2020; Dida et al., 2022; Mamuya and Bachwenkizi, 2024; Nassikas et al., 2024). Indoor air quality is influenced by various factors, including ventilation, building tightness, filtration, pollutant mixes, interior emission sources, and occupant activities. It has been observed that increased airtight measures for energy conservation reduce air exchange between the indoor and outdoor environments, and as such, pollution levels can also vary from house to house.

Indoor air pollutants can be categorised into groups based on their type and source. Classification based on types of pollutants has been documented by some researchers, and the major categories are: (a) biological pollutants, (b) chemical pollutants, (c) combustion by-products, and (d) particulate matter (Cooke, 1991; Karri et al., 2024). Several studies have examined the harmful effects of chemical and biological pollutants in various indoor environments, categorizing indoor air pollution into biological and chemical sources (Ghanizadeh and Godini, 2018; Tran et al., 2020; Gonzalez-Martin et al., 2021; Ahmed et al., 2019). The issue of health, comfort, activity levels, and work efficiency has become a growing concern in various settings, such as homes, offices, schools, and hospitals.

There are several global studies that have established a significant relationship between indoor air quality and health risks, implying that it significantly impacts human health and well-being (Smith et al., 2000; Okello et al., 2018; Saini et al., 2020; Tran et al., 2020; Vardoulakis et al., 2020; Pillarisetti et al., 2022; Saini et al., 2022; Lewis et al., 2023; Mamuya and Bachwenkizi, 2024). Studies indicate an increase in indoor air pollutants due to various factors including chemicals in home products, building materials, combustion processes, cigarette smoke, HVAC (heating, ventilation, and air conditioning) systems, inadequate ventilation, hotter temperatures, and higher humidity, all contributing to indoor air pollution (Schweizer et al., 2007; Schwela, 2014; Hänninen and Goodman, 2019; Rivas et al., 2019; Manisalidis et al., 2020; Dida et al., 2022; Nassikas et al., 2024). IAQ is a multifaceted issue influenced by various pollutants from both indoor and outdoor sources, affecting chemical, biological, and physical contaminants that eventually contribute to the overall indoor environment (Figure 1) (Tham, 2016; Gonzalez-Martin et al., 2021; Pillarisetti et al., 2022; Kumar et al., 2023b; González-Caballero et al., 2024).

As illustrated in Figure 1, urban and rural environments share similar sources of indoor air pollution, but the amounts of emissions vary; for example, cooking emissions in urban environments are often significantly lower than those in rural areas, where biomass burning is the primary source of emissions (Pillarisetti et al., 2022). The impact of traffic on exposure is also present in both contexts, albeit the degree of exposure varies depending on the proximity and how frequently individuals come in contact with traffic and traffic-related air pollution (Raju et al., 2020; Gonzalez-Martin et al., 2021). In some indoor settings in both developed and developing countries, office equipment, such as printers, photocopiers, electronics, and gas cooktops, as well as other indoor sources (such as furniture, paints, varnishes, solvents, and cleaning supplies), can release particulate matter (PM) and other pollutants into indoor air (Figure 2) (Maisey et al., 2013). Indoor air pollutants are a major environmental health concern that have been identified as harmful to indoor air quality and human health, particularly in developing countries, where the situation is made worse by high exposure levels and little resources (Tran et al., 2020; Mamuya and Bachwenkizi, 2024).

Indoor air quality is a multifaceted issue influenced by outdoor air quality, indoor human activities such as cooking, cleaning, or smoking, and the building materials, furniture, and indoor equipment (Fadeyi et al., 2013; Weschler, 2016; Peng et al., 2017; Marć et al., 2018; Rivas et al., 2019; Tran et al., 2020; Pillarisetti et al., 2022; González-Caballero et al., 2024). Particulate matter (PM), which includes fibres and asbestos, volatile inorganic compounds (CO, CO_2, NO_x, O_3), volatile organic compounds (VOCs; benzene, toluene, ethylbenzene, xylenes, naphthalene, formaldehyde, trichloroethylene, a-pinene, and limonene), and biological pollutants (allergens, fungi, bacteria, and viruses) are significant and often studied indoor air pollutants (Pillarisetti et al., 2022). Sick building syndrome (SBS) is a non-specific group of symptoms caused by exposure to indoor air pollutants such as NOx, VOCs, SVOCs, SO_2, O_3, CO, PM, radon, toxic metals, and microorganisms, resulting from exposure to building variables like lighting, noise, and psychological effects (Mendes and Teixeira, 2014; Jansz, 2024).

Indoor environmental factors (e.g., chemical contaminants, bioaerosols, air ventilation, temperature, relative air humidity, building dampness, and lighting, etc.) and individual risk factors (e.g., gender, work stress, and job dissatisfaction, etc.) have inconsistently been linked to SBS cases, making it difficult to generalise (Joshi, 2008; Laumbach, 2008; Jansz, 2024). Sick building syndrome, building-related diseases, and building-associated symptoms are the three categories of building health issues found in many buildings, including residential, office, commercial, and educational buildings (Joshi, 2008). Overall, the consequences of poor indoor air quality and chemical contaminants share a strong relationship with sick building syndrome that can be caused by short-term or long-term exposure to various indoor air pollutants. The major sources of indoor air pollutants are being discussed below.

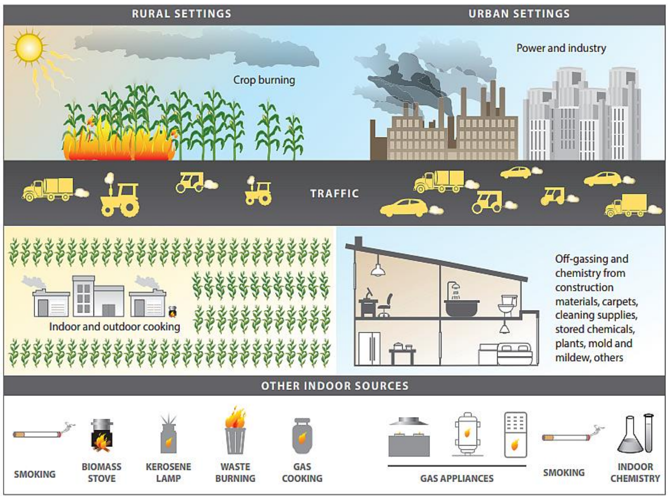

Figure 1: Major sources of indoor air pollutants in rural (left) and urban (right) settings [Source: (Pillarisetti et al., 2022)].

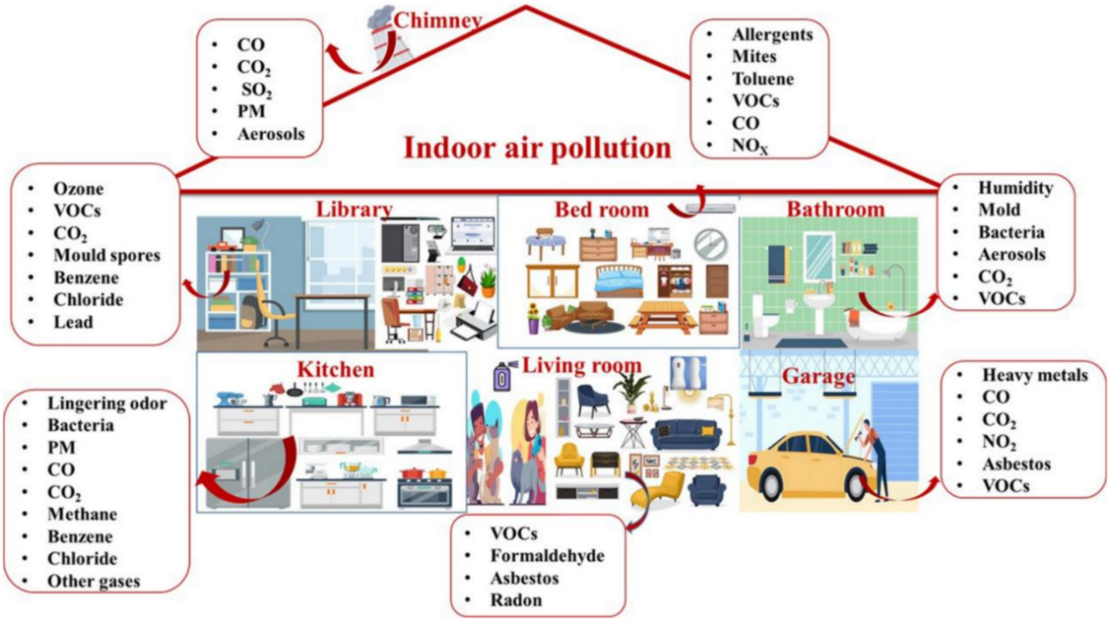

Figure 2: Graphical representation of various sources of indoor air pollutants [Source:(Kumar et al., 2023b)].

2.1 Combustion By-Products

Combustion by-products are gases and respirable particles produced by incomplete combustion of fossil fuels like oil, gas, kerosene, firewood, coal, and propane. They include particulate matter, volatile products like carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, formaldehyde, water vapour, and sulphur dioxide (Lomnicki et al., 2014; Balakrishnan et al., 2018; González-Caballero et al., 2024). Indoor combustion products are produced from appliances like gas, sand fireplaces, coal-burning stoves, furnaces, tobacco smoking, and biomass or fossil fuel combustion in gas ranges, wood-burning stoves, fireplaces, and gas and kerosene space heaters, contributing to indoor air pollutants. The combustion of biomass or fossil fuels produces various pollutants, including respirable particulate matter and gaseous pollutants, which can significantly affect human health and climate by affecting air quality, visibility, and atmospheric chemistry (Manisalidis et al., 2020).

Particulate matter, composed of fine and ultrafine particulates, carbon soot, fuel mineral components, and organic compounds, releases gases like carbon monoxide, carbon dioxide, nitrogen dioxide, nitric oxide, and sulphur dioxide, depending on the fuel type (Lomnicki et al., 2014; Schwela, 2014; Pillarisetti et al., 2022; González-Caballero et al., 2024). According to a study, the type of fuel and combustion appliance influence the production of combustion by-products, with specific contaminants emitted depending on the fuel type, combustion process, and appliance type (Lomnicki et al., 2014). Gas heaters and stoves that function efficiently release minimal particulates and a variety of other possible pollutants that do not remain in the indoor environment, while wood-burning stoves emit significantly more contaminants that become indoor pollutants (Lomnicki et al., 2014; Schwela, 2014).

It is known that the by-products that an appliance produces are influenced by how well it is designed, constructed, installed, and maintained. However, short-term exposure to indoor pollutants levels can be rather high for unvented or inadequately vented systems and indoor environments due to the episodic nature of combustion processes (Schwela, 2014). In rural regions of South and Southeast Asia, South America, West Africa, Sub-Saharan Africa, and impoverished Chinese provinces, firewood, charcoal, and other biomass energy are widely used (Schwela, 2014; Hanif, 2018; Newell et al., 2022; González-Caballero et al., 2024).

In industrialised countries, indoor air pollution is a common problem due to the fact that improved energy efficiency can occasionally make indoor environments relatively airtight, reducing the quantity of outside air exchange and the flow of indoor air pollutants outside. The unvented combustion method of cooking with natural gas, which is used in the majority of households in the United States and developing countries, greatly raises indoor nitrogen dioxide and carbon monoxide levels, especially in kitchens (Nicole, 2014; Schwela, 2014; Pillarisetti et al., 2022; Lewis et al., 2023; González-Caballero et al., 2024). Kerosene heaters are unvented equipment; therefore, if there is not enough ventilation in the room while the heater is in use, combustion products might accumulate (Hanoune and Carteret, 2015). Unvented combustion sources like gas and kerosene space heaters are prevalent in households in developed countries, contributing to poor indoor air quality when used without efficient ventilation, with kerosene appliances emitting emissions comparable to gas-powered equipment (Hanoune and Carteret, 2015; Tran et al., 2020).

Kerosene heaters emit carbon particles, which may contain organic compounds with carcinogenic activity, and wood stoves, commonly used for heating, can be contaminated by these organic-coated carbon particles due to improper venting or inadequate seals (Schwela, 2014). It is known that unvented combustion appliances release combustion products into the room where heaters are operated, and the degree of venting and usage pattern significantly impacts contamination exposure (Schwela, 2014; Hanoune and Carteret, 2015). However, indoor concentrations of carbon monoxide and nitrogen dioxide are often higher than outside levels when major sources are present, especially during the winter when internal ventilation is typically restricted (Nicole, 2014; Schwela, 2014; Tran et al., 2020; González-Caballero et al., 2024).

Indoor air pollution caused by inadequate access to clean cooking technologies and fuels and the use of open stoves for cooking and heating is raising concerns in impoverished communities and developing countries around the world. Indoor air pollution is a major contributor to indoor air pollution in low- and middle-income countries, primarily due to the use of solid fuels for residential energy, active and passive smoking, cooking oil mists and fumes, and mosquito coil smoke (Bruce et al., 2000; Marais et al., 2014; Ofori et al., 2018). The use of biomass energy for domestic cooking and heating without adequate ventilation is associated with high levels of indoor air pollution, which is the biggest environmental health risk and is linked to cardiovascular diseases (Ofori et al., 2018).

Nigeria, a major exporter of crude oil and natural gas, faces a paradox in energy consumption, with a significant portion of its population in the most communities relying primarily on solid fuel for domestic energy needs due in part to inadequate access to clean energy (e.g., electricity and natural gas) (Ite et al., 2013; Ite et al., 2024). Nigeria's fuel choices are influenced by cost and socioeconomic status, with inadequate power supply leading to reliance on backup generators and kerosene, and fuelwood and waste burning accounting for over 80% of energy consumption (Marais et al., 2014). The country's high reliance on solid fuels for domestic energy is a major factor contributing to its ranking among the top sub-Saharan African nations with high air pollution levels (Hanif, 2018; González-Caballero et al., 2024). The use of solid fuels on open stoves significantly contributes to indoor air pollution in developing countries, but household air pollution is not adequately monitored, and various domestic energy sources also contribute.

The air quality in kitchens is often poor in developing countries, and there is a dearth of information on how African cooking practices impact indoor air pollution in urban homes. Households contribute to indoor air pollution levels by using kerosene stoves or wood-burning stoves, which can increase toxic smoke and particle matter build-up within households, potentially leading to deadly consequences. Cooking releases harmful pollutants into the kitchen from food materials and combusted fuels, and cooking fume has a significant impact on indoor air quality, which in turn has a significant impact on people's health (Giwa et al., 2019; Song et al., 2022). A group researcher investigated the concentrations of pollutants in 75 domestic kitchens in an urban area of Southwestern Nigeria, using kerosene and liquefied petroleum gas stoves, and measured them at breathing zone level from the ground (Giwa et al., 2019). The LPG-stove kitchens emitted CO, CO_2, and $PM_{2.5}$ at concentrations of 29 ppm, 895 ppm, and 328 µg/m^3, respectively, while the kerosene-stove kitchens released these at concentrations of 31 ppm, 897 ppm, and 345 µg/m^3 (Giwa et al., 2019).

The study found that frying, stewing, and boiling are the cooking methods with the highest concentrations of pollutants in kitchens, exceeding the WHO's indoor air quality limit (Giwa et al., 2019). Findings from the study highlight the need for improved cooking practices to reduce pollution levels. Factors such as food supplies, ingredients, fuel and stove types, ventilation conditions, cooking styles, time, and temperature contribute to the emission of these pollutants, which are harmful to the environment and human health (Giwa et al., 2019; Abdul Raheem et al., 2022; Song et al., 2022). In a related study, a group researcher investigated household indoor concentration levels of some selected pollutants, and the results obtained revealed that concentrations of NO_2, SO_2, and O_3 in kitchens range from 15 to 722 µg/m^3 for NO_2, 3 to 101 µg/m^3 for SO_2, and 2 to 46 µg/m^3 for ozone in kitchens (Agbo et al., 2021). In urban households, kitchens had significantly higher median concentrations of NO_2 (94 µg/m^3) than other rooms, despite similar median levels of SO_2 (3 - 4 µg/m^3) and O_3 (14 - 20 µg/m^3) in all rooms (Agbo et al., 2021). Findings from the study revealed that rural kitchen NO_2 and SO_2 are ≥4 times higher compared to urban kitchens in the dry season, and ambient NO_2 and O_3 in the dry season are a factor 6 higher compared to in the wet season (Agbo et al., 2021). The study found that households using solid fuels like firewood (101 – 722 µg/m^3) and charcoal (134 – 356 µg/m^3) have higher NO_2 concentrations compared to those using LPG (19-174 µg/m^3) and other fuels (Agbo et al., 2021).

Air pollution significantly contributes to premature deaths globally, and evidence from few studies indicates that dirty fuel use, cooking stoves, and domestic kitchen styles negatively impact indoor air quality (Abdullahi et al., 2013; Wang et al., 2017; Giwa et al., 2019). Cooking releases gaseous and particulate pollutants into the kitchen from food materials (esters, ketones, heterocyclic compounds, PAH, alcohols, ketones, alkenes, alkanes, etc.) and combusted fuels (CO, NOx, SO_x, PM, CO_2, PAH, etc.), and cooking fume has a significant impact on indoor air quality and impact on human health (Abdullahi et al., 2013; Wang et al., 2017; Giwa et al., 2019; Song et al., 2022). The emission of pollutants, which are harmful to the environment and human health, can be influenced by various factors such as food materials, fuel types, ventilation conditions, cooking styles, time, and temperature (Giwa et al., 2019; Song et al., 2022).

Evidence from some studies has shown that combustion by-products have been linked to harmful health consequences such as cancer, DNA damage, respiratory disorders, cardiorespiratory and neurological disorders, physical harm, sick building syndrome, inadvertent weight loss, reduced body mass index (BMI), elevated blood pressure, and carbon monoxide death (Lomnicki et al., 2014; Bede-Ojimadu and Orisakwe, 2020; Tran et al., 2020; Amadu et al., 2023; Idowu et al., 2023; Rasel et al., 2024). There are serious health hazards associated with solid fuel consumption in rural Bangladeshi homes, including problems with the eyes, heart, cardiovascular, and metabolism issues (Rasel et al., 2024). Research has consistently demonstrated that combustion by-products adversely impact both indoor air quality (IAQ) and human health. Indoor air pollution, primarily caused by solid fuels on open stoves, leads to around 2 million premature deaths annually in Sub-Saharan Africa and Asia (Balakrishnan et al., 2018; González-Caballero et al., 2024). In recent times, studies have shown that inefficient combustion of cooking fuels leads to air pollution, causing health risks like respiratory diseases and heart issues, resulting in significant mortality in sub-Saharan Africa. (Bede-Ojimadu and Orisakwe, 2020; Amadu et al., 2023; González-Caballero et al., 2024).

2.2 Indoor Particulate Matter

Indoor particulate matter (PM), for which outdoor particles are a partial source, is a mixture of highly different solid and liquid particles suspended in the atmosphere, which can vary in chemical composition, form, shape, and size, and many of the toxic chemical components are harmful to human health. Primary particles, such as nitrogen oxides (NO_X), sulphur dioxide (SO_2), and certain organic chemicals, can directly release primary particles into the atmosphere, or chemical interactions can create secondary particles in the atmosphere. Both interior-sourced and outdoor-originating particles can be considered part of the indoor particulate matter. Depending on where the particulate matter originated, indoor particulate pollution can be classified into primary and secondary particles (Fromme, 2019; Zhang et al., 2021a).

Primary indoor pollutants are generated from domestic activities such as burning processes (tobacco smoking, unvented space heaters, use of candles, and burning of incense/mosquito coils), cooking activities (including cooking method, cooking oil, energy source (stove), cooking pan, food, additives, and oil temperature, etc.), cleaning activities (washing, dusting, and vacuum cleaning), and secondary organic aerosols from the use of consumer products (e.g., sprays and cleaning products) (Fromme, 2012; Fromme, 2019; Zhang et al., 2021a). Electronic devices in office settings, including computers, printers, and photocopiers, are known to emit various air pollutants like nanosized particles and ozone, which can trigger reactions causing secondary pollutants (Khatri et al., 2013; Rivas et al., 2019).

Pollutants that have seeped into the interior environment and particles produced by chemical interactions between indoor precursors and external sources are referred to as secondary particulate matter (Hassanvand et al., 2014). These particles are produced by photochemical, catalytic, or other chemical reactions between polluting gas components like sulphur dioxide, nitrogen oxides, and hydrocarbons, or between these gas components and oxygen (Li et al., 2019; Manisalidis et al., 2020). Particulate matter, influenced by its origin and source, can exhibit unique characteristics like a small aerodynamic diameter, a high surface/volume ratio, complex chemical composition, and a high toxicity index (Zhang et al., 2021a). Air pollution's PM components consist of carbonaceous particles, organic chemicals, and reactive metals, including sulphates, nitrates, endotoxin, polycyclic aromatic hydrocarbons, and heavy metals like iron, nickel, copper, zinc, and vanadium (Figure 3) (Ferro et al., 2004b; Schwela, 2014; Adams et al., 2015; Mohankumar and Senthilkumar, 2017; Hamanaka and Mutlu, 2018; González-Caballero et al., 2024).

Penetration of particles from the ambient aerosol (outdoor environment) into the indoor environment and particles produced within by activities are the two types of indoor PM sources (Fromme, 2019; Tran et al., 2020; Zhang et al., 2021a). Particulate matter (PM) may be classified based on its aerodynamic diameter (a function of particle mass and shape), with PM_{10} and $PM_{2.5}$ being the most common, with diameters < 10 µm and < 2.5 µm, respectively (Newell et al., 2022). Based on the particle size, the classification of PM can be divided into four groups: coarse particles (PM_{10} ≤ 10 µm), fine particles ($PM_{2.5}$ ≤ 2.5 µm), ultrafine particles ($PM_{0.1}$ ≤ 0.1 µm), and quasi-ultrafine particles ($PM_{0.3}$ ≤ 0.3 µm) (Schraufnagel, 2020; Newell et al., 2022; Kang et al., 2009; Badran et al., 2020; Okam et al., 2024).

The morphological characterisation and chemical speciation of particulate matter provide information on their characteristics and possible sources, while the ratio of $PM_{2.5}$ to PM_{10} ($PM_{2.5}/PM_{10}$) can indicate whether the sources are natural or anthropogenic (Kang et al., 2009; Okam et al., 2024; Li et al., 2019). Identification of these particles can help determine the source and origin of indoor PM concentrations, which are impacted by both internal and external sources and materials as well as activities. Accurately identifying the sources of air pollution is crucial to reduce exposure to pollutants and associated health risks, even though PM can be present in both indoor and outdoor environments (Tran et al., 2020; Chojer et al., 2024). Coarse particles from natural and industrial sources typically don't penetrate the upper bronchus, while fine and ultrafine particles from fossil fuel combustion pose a greater health risk in small airways and alveoli (Brook et al., 2004; Miller et al., 2012; Schwela, 2014; Chin, 2015; Hamanaka and Mutlu, 2018; Li et al., 2019).

Although mucus and cilia remove the majority of PM in the human body, the $PM_{2.5}$ fraction that makes up 96% of the particles in the pulmonary parenchyma remains mostly in the lung (Li et al., 2019). Apart from penetrating the gas-exchange area of the lung, $PM_{2.5}$ may also cross the respiratory barrier, enter the circulatory system, and then travel throughout the entire body (Wang et al., 2015; Li et al., 2019). Particulate matter is the most harmful component of the air pollution cocktail, as it is a combination of substances rather than a single gas, and its varying sizes cause different deposition patterns in human airways. Particulate matter, which travels long distances in the atmosphere, significantly impacts human health, air quality, and climate change due to its long-range atmospheric transportation. It has been documented that the spatial and temporal distribution of PM is variable and is strongly influenced by both climatic and meteorological conditions (Pöschl, 2005; Wiseman and Zereini, 2011; Ite et al., 2017). In general, the particulate matter's physicochemical composition, shape, size, and elemental composition, as well as the presence of additional contaminants and climatic conditions, all affect its concentration and toxicity.

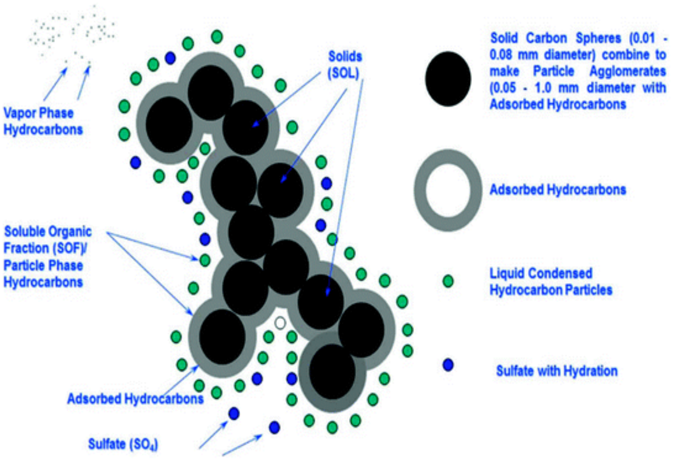

Figure 1: Schematic representation of PM [Source: Mohankumar and Senthilkumar, 2017)]

PM concentrations in indoor environments are influenced by factors like occupants, buildings (structural design and materials), ventilation, air purifiers, temperature and humidity, and other sources of pollutants, both indoor and outdoor (Son, 2023). Although these factors influence the overall health and safety of indoor and outdoor spaces, various outdoor PM sources contributing to indoor PM pollution include transport, oil combustion, vehicle exhaust, emissions from power plants, road dust, secondary inorganic aerosols, crustal dust, mineral dust, waste incineration, fossil fuel oil combustion, and various other anthropogenic sources (Adams et al., 2015; Karagulian et al., 2015; Liu et al., 2017; Sulaymon et al., 2020). Indoor fine particulate matter, often exceeding outdoor levels, poses a significant health risk, particularly in respiratory conditions, causing severe health effects on the lungs and heart (Brook et al., 2004; Miller et al., 2012; Chin, 2015).

Fossil fuel combustion produces $PM_{0.1}$, which poses a greater health threat due to its penetration into small airways and alveoli compared to PM_{10} and $PM_{2.5}$ (Brook et al., 2004; Miller et al., 2012; Chin, 2015). Cooking and cigarette smoking are the main contributors to indoor air PM, while cleaning activities typically contribute less to indoor PM, according to studies on the concentration of key indoor pollutants (Ferro et al., 2004a; Rivas et al., 2019; Vardoulakis et al., 2020). Indoor $PM_{2.5}$ is mostly caused by smoking, with estimates of increases in houses including smokers ranging from 25 to 45 $\mu g/m^3$ and a higher concentration in the winter than in the summer (Wallace, 1996). Cooking activities emit millions of ultra-fine particles through the burning of fossil fuel, firewood, and food, which can spread indoors, causing adverse health issues for occupants in the indoor environment (Dennekamp et al., 2001; Yu et al., 2015a; Kim et al., 2018). It has been reported that other normal human activities like walking and sitting on furniture contribute to 25% of indoor PM concentrations due to the resuspension of house dust, and human activities' source strengths for $PM_{2.5}$ and PM_{10} ranged from 0.03 to 0.5 $mg.min^{-1}$ and from 0.1 to 1.4 $mg.min^{-1}$, respectively (Wallace, 1996; Ferro et al., 2004b).

Evidence from several studies has shown that PM exposure is associated with an increase in morbidity and mortality in both developed and developing countries, although the underlying mechanisms remain incompletely established (Brook et al., 2004; Miller et al., 2012; Chin, 2015; Li et al., 2019; Schraufnagel, 2020; Okam et al., 2024). According to a study, several plausible mechanisms have been described, including increased coagulation, arrhythmias, acute arterial vasoconstriction, systemic inflammatory responses, and chronic atherosclerosis promotion, with short-term exposures revealing a 0.4 – 0.6% increase in daily mortality with each 10 $\mu g\ m^{-3}$ increase (Brook et al., 2004). Epidemiological studies have demonstrated a consistent increased risk for cardiovascular events due to both short- and long-term exposure to ambient PM concentrations, with larger associations observed for cardiovascular mortality and respiratory mortality (Brook et al., 2004).

Few studies have reported that PM_{10} exposure is linked to increased hospitalisations and health care visits for respiratory and cardiovascular diseases, as well as lower respiratory symptoms, exacerbation of asthma, coughing, and small declines in lung function, as reported in American and European time series studies (Schwela, 2014; Feng et al., 2019; Slama et al., 2019). A study found a strong association between PM10 pollution and mortality, particularly in emergency department admissions (EDAs) for cardiopulmonary diseases, with seasonal temperatures determining the effects on chronic obstructive pulmonary disease (COPD) and heart failure EDAs (Feng et al., 2019).

Indoor particulate matter, particularly in schools, is linked to health issues and respiratory diseases, particularly among children who spend most of their time indoors. Over the years, there has been an increase in indoor air quality-related health issues, with documented increases in particles in school buildings in both developed and developing countries worldwide (Fromme et al., 2007; de Gennaro et al., 2014; Trompetter et al., 2018; Ite et al., 2019; Cooper et al., 2020; Sadrizadeh et al., 2022; Thoua et al., 2022; Matilla et al., 2023; Son, 2023). In a study, found that 64 schools in Munich and a nearby district experienced high exposure to particulate matter, with winter PM concentrations and high CO_2 levels indicating inadequate ventilation is a major factor contributing to poor indoor air quality (Fromme et al., 2007). The study in Palmerston North, New Zealand, carried out by examined the air quality in two primary school classrooms for children aged 7-9 during the southern hemisphere winter season (Trompetter et al., 2018).

Evidence from the study showed that ventilation significantly impacts indoor air quality and student wellbeing (Trompetter et al., 2018). Therefore, understanding factors affecting PM pollution, such as occupant activities, ventilation, and outdoor environment infiltration, is crucial for health protection, and assessing children's exposure to indoor $PM_{2.5}$ is essential to improving exposure mitigation strategies. Research shows that children spend over one-third of their day in learning microenvironments, but weak evidence suggests a significant and consistent association between environmental factors and indoor $PM_{2.5}$ concentrations, indicating the need for further robust analyses (Cooper et al., 2020). Childhood exposure to air pollution can lead to persistent lung function issues, increased susceptibility to respiratory and cardiovascular diseases, increased absenteeism, and poorer cognitive or academic performance, indicating a need for improved indoor air quality (Thoua et al., 2022). Studies in 40 developed nations have revealed that certain airborne pollutants are more prevalent in schools than in homes and commercial buildings (Sadrizadeh et al., 2022). Exposure to air pollutants in school buildings poses a significant health risk to students, as they inhale a larger volume of air compared to adults. Most schools lack natural ventilation systems, leading to insufficient indoor air quality due to contaminants like moulds, bacteria, and trace metals (Sadrizadeh et al., 2022). Over the years, global studies reveal that many schools are not adequately addressing indoor air quality issues like PM, VOCs, and ventilation rates, which are crucial for students' health and academic performance (Thoua et al., 2022; Matilla et al., 2023).

Indoor air pollution is a significant environmental risk affecting human health and well-being in both the developing and industrially developed countries. In the developing countries, people are exposed to high levels of particulate matter from vehicle exhaust, industrial emissions, fossil fuel combustion, and firewood, among other anthropogenic emissions. Despite the absence of typical indoor PM sources like smoking and cooking in the school environment, many children are present in a limited space for several hours per day (de Gennaro et al., 2014). In developing countries, most school children are exposed to high levels of air pollutants from various sources, necessitating more empirical evidence on indoor air quality in school classrooms. In a study, a group researchers examined the indoor air quality in schools in Akwa Ibom State, Nigeria, focusing on parameters like particulate matter, carbon monoxide, CO2, temperature, and relative humidity (Ite et al., 2019).

Results showed that naturally ventilated classrooms in the industrial zone had significantly higher concentrations of PM1, PM2, PM5, and PM10 during both rainy and dry seasons (Ite et al., 2019). The concentrations of PM_{10} were found to be much lower than the ambient maximum contaminant level for airborne PM_{10} standards promulgated by the United States Environmental Protection Agency (US–EPA) and World Health Organisation (WHO) PM_{10} guidelines. Although most schools lack adequate natural ventilation systems around the world, the low concentrations of CO and CO_2 measured indicated adequate air exchange and effective ventilation in the naturally ventilated classrooms in the study area (Sadrizadeh et al., 2022; Ite et al., 2019).

The study highlights the crucial role of ventilation in enhancing indoor air quality in classrooms, providing valuable insights into airborne PM distribution patterns, which can aid in developing public health policies in Nigeria (Ite et al., 2019). In a review, a group researchers reported that African school children are frequently exposed to $PM_{2.5}$ and PM_{10} levels exceeding World Health Organization guidelines (Kalisa et al., 2023). The review emphasises the need for more air quality measurements and intervention studies in African schools to mitigate air pollution exposure, highlighting the significance of education in environmental science and policy (Kalisa et al., 2023).

2.3 Nitrogen Oxides

Oxides of nitrogen (NO_x) are a ubiquitous group of air pollutants that may be found in both outdoor and indoor environments. Among the different atmospheric nitrogen oxides, nitric oxide (NO) and nitrogen dioxide (NO_2) are the most important in relation to their effects on materials, vegetation, and human health. Nitrogen dioxide is primarily produced by automobile exhaust, power plants, and other fossil fuel-burning industries, with a significant portion of it entering the atmosphere due to combustion. Indoor NO_2 emissions are primarily from combustion processes, such as unvented appliances like furnaces, stoves, and water heaters (Tran et al., 2020). These emissions can be minimal when well vented but can become significant if unvented or poorly vented.

The degree of venting for gas stoves depends on the effectiveness of the range hood exhaust fan and cooking usage. Indoor NO_2 levels vary significantly between homes due to differences in exterior and interior sources. Therefore, it is crucial to ensure proper ventilation to minimise indoor NO_2 emissions. Home levels without combustion appliances are half that of outdoor levels, while those with gas stoves, kerosene heaters, or unvented gas space heaters often exceed outdoor levels. The higher oxides of nitrogen oxides, particularly nitrogen dioxide and nitric oxide, pose significant adverse human health risks in certain occupational settings worldwide. NO_2 exposure in workplaces like electroplating, acetylene welding, agriculture, space exploration, explosive detonation, military activities, and burning nitrogen-containing propellants has been reported (Mohsenin, 1994).

Exposure concentrations in armoured vehicles during live-fire tests can be high, with peak NO_2 concentrations over 2,000 ppm, and these concentrations decrease to 500 ppm after 1 minute and 20 ppm within 5 minutes (Mayorga, 1994). Nitrogen oxide (NO) is produced in high temperature combustion reactions where nitrogen (N) reacts with oxygen (O_2) and is rapidly converted to nitrogen dioxide (NO_2). Both fuel and air nitrogen can participate in these reactions. NO_2 is one of the highly reactive gases, a strong oxidant, and a major constituent of ambient air pollution that is harmful due to its significant adverse health impact.

Oxides of nitrogen are produced during the burning of fuels, including tobacco, by combining nitrogen and oxygen in the air; the amount increases as the combustion temperature rises. The oxides of nitrogen (NO, NO_2, N_2O, and others) are irritating gases that can harm human health. Over the years, emissions of oxides of nitrogen have typically grown, resulting in a variety of research dealing with dioxides of nitrogen exposure (Mayorga, 1994; Mohsenin, 1994; Cyrys et al., 2000; Dennekamp et al., 2001; García-Algar et al., 2003; Kumie et al., 2009; Vilcekova, 2011; Gubb et al., 2022). In a study, authors investigated indoor and outdoor concentrations of NO_2 for Hamburg (west Germany) and Erfurt (east Germany), with gas cooking ranges and smoking identified as important indoor sources (Cyrys et al., 2000). Findings from the study have shown that residences in Hamburg had slightly higher NO_2 levels compared to Erfurt, with gas cooking being the major indoor source of NO_2 in both cities (Cyrys et al., 2000).

According to a study, factors like ventilation, outdoor NO_2 levels, and gas usage for cooking significantly influenced indoor NO_2 concentrations (Cyrys et al., 2000). In a related study, a group researchers investigated the relationship between indoor and outdoor NO_2 concentrations, housing, and occupant characteristics in Barcelona, Spain, during 1996 – 1999 (García-Algar et al., 2003). The study found that indoor NO_2 concentrations were primarily caused by gas cooker use, lack of extractor fan, and cigarette smoking. According to a study, the absence of central heating was linked to higher NO_2 concentrations, with each ppb increase in outdoor NO_2 causing a 1% increase in indoor concentrations (García-Algar et al., 2003). The study highlights the importance of addressing indoor and outdoor NO_2 pollution in housing and occupant characteristics.

In developing countries, unprocessed biomass fuel continues to be the primary source of indoor air pollution and has been linked to acute respiratory infections (Bruce et al., 2000; Ezzati and Kammen, 2001; Lavric et al., 2004; Kumie et al., 2009; Sanbata et al., 2014; Ofori et al., 2018; Ogaji et al., 2022). In a study, a group researchers assessed 17,215 air samples in rural Ethiopia and found wood and crops as primary household energy sources, with biomass fuel characteristics strongly correlated with indoor NO_2 concentration (Kumie et al., 2009). Indoor NO_2 concentration is predicted by factors such as highland setting, wet season, cooking, fire events, cooking frequency, and ecology-season interaction over time (Kumie et al., 2009). However, housing unit volume and kitchen presence showed little relevance in NO_2 concentration levels (Kumie et al., 2009). In a related study, a studied the concentration of harmful gases in residential apartments in Port Harcourt, Nigeria, revealing significant differences in concentrations across time and locations, with CO being the highest (Ogaji et al., 2022).

According to the concentrations of NO_2 and SO_2 were higher than the WHO limit, while CO, CH_4, NH, and O_3 were below the WHO limit (Ogaji et al., 2022). The study found that CO concentrations were highest in the morning, while NO_2 and SO2 concentrations were highest in the evening, and CH_4, NH_4, NO_2, and SO_2 were higher during the dry season (Ogaji et al., 2022). The use of biomass fuels in households is linked to acute respiratory infections in children in developing countries, and there is a need for regular monitoring of pollutant levels to provide exposure advice to community dwellers on how to mitigate effects of indoor air pollution (Mishra, 2003; Sanbata et al., 2014).

Nitrogen dioxide (NO_2) is a widespread major indoor and outdoor contaminant that has been implicated in reduced lung function, airway inflammation, and serious respiratory diseases based on epidemiological evidence over the years (Smith et al., 2000; Jiang et al., 2019; Pettit et al., 2019; Gubb et al., 2022). Despite several epidemiological studies showing links between NO_2 exposure and harmful health consequences, there is paucity of information with regards to NO_2 indoor concentrations in the Niger Delta region of Nigeria. NO_2, which is a reddish-brown gas in colour, contributes to the formation of several other air pollutants, including ozone (O_3), nitric acid (HNO_3), and nitrate (NO_3^-)-containing particles that also form through photochemical reactions. NO_2 is an oxidising agent that is irritating to mucous membranes, and a study indicates that short-term exposure to NO_2 can lead to hypomethylation of *NOS2A* and *ARG2*, inflammation, and lung function impairment, potentially predicting its respiratory effects (Jiang et al., 2019).

Therefore, reduction in the concentrations of oxides of nitrogen in indoor air can be accomplished by: (1) reduction in the combustion sources; (2) reduction in the combustion temperature of combustion devices; (3) modification of burners in combustion devices; (4) venting of the combustion gases to the outside; (5) increase in the ventilation; and (6) exposing the oxides of nitrogen to reactive surfaces (Cooke, 1991). The mechanism behind the decay of nitrogen dioxide concentrations in indoor air is not fully understood, but it seems to be a reaction with oxidisable materials, as NO_2 is an oxidising agent. According to a study, potted plants can enhance indoor air quality, particularly in poorly ventilated and polluted spaces, but their effectiveness depends on building ventilation rates and NO_2 concentration gradients at the indoor-outdoor interface, which vary significantly between urban and rural areas (Gubb et al., 2022).

2.4 Environmental Tobacco Smoke

Environmental tobacco smoke (ETS), which is the major indoor source of pollutants of respirable size, is a mixture of exhaled mainstream smoke (MS) and side stream smoke (SS) released from the burning end of cigarettes and related tobacco products (Mueller et al., 2011; Rumchev et al., 2011; Stewart & Robinson, 2017; Baek, 2019). Both sources yield complex chemical mixtures rich in polyaromatic hydrocarbons and oxidants (Stewart and Robinson, 2017). ETS is a major source of multiple pollutants, especially in indoor environments, and it produces ultrafine particles, which are the most common and dangerous element of air pollutants for health (Afshari et al., 2005; Mueller et al., 2011; Müller et al., 2011; Kaunelienė et al., 2018; Obore et al., 2020). Tobacco smoke is an extremely complex mixture of chemicals that contains particulate phase compounds, gas/vapour phase compounds, and over 9000 chemicals, including many carcinogens and toxins, which is the leading cause of approximately 6 million preventable deaths annually worldwide (Kapp, 2005; Kivell and Danielson, 2016).

Tobacco–related gases and particles deposits onto surfaces such as walls, carpets, blankets, clothes, and furniture may lead to serious health problems, and the accumulated pollutants also cause discolouration as well as ageing. Since deposited environmental tobacco smoke (ETS) can be absorbed via the skin, there is further exposure to ETS when it is deposited onto interior surfaces in addition to inhalation (Hasager et al., 2021). In areas where smoking is permitted, deposited ETS is a major source of airborne particles that may be re-emitted back to the gas phase and/or are re-suspended long after active smoking ends. ETS contributes significantly to the amount of particle indoor air pollution since the great majority of its components, including nicotine and several carcinogens, are classified as particulate phase pollutants (Afshari et al., 2005; Mueller et al., 2011). Precursors and by-products can be re-emitted back to the gas phase, and airborne particles on indoor surfaces can be resuspended, leading to higher indoor ETS concentrations than outdoor ones (Matt et al., 2004).

Environmental tobacco smoke is a major source of indoor air contaminants such as carbon monoxide, carbon dioxide, nitrogen oxides, and particulate matter (Mueller et al., 2011; Manisalidis et al., 2020). The analysis of tobacco smoke has identified several toxicologically significant chemicals and groups, including polycyclic aromatic hydrocarbons, volatile compounds, tobacco specific nitrosamines, aldehydes, hydrogen cyanide, benzene, toluene, phenols, aromatic amines, respirable particles, etc. (Kapp, 2005). The health effects associated with tobacco smoke can be divided into: (1) acute, irritating, and immune effects; (2) respiratory effects; (3) cancer effects; and (4) cardiovascular effects. Exposure to ETS can cause acute irritation in the eyes, nose, and throat and can activate the immune system, raising concerns about its health significance due to its similar hazardous constituents to mainstream smoke (Kapp, 2005; Mueller et al., 2011; Stewart and Robinson, 2017).

ETS contributes to diseases of the airway lining and raises the risk of cancer through passive exposure, making it a major risk factor for the development of asthma (Stewart and Robinson, 2017). According to a group reseacher, nicotine has been employed as a tracer or marker for ETS since it is simple to analyse; however, in order to assess ETS, a marker unique to tobacco smoke that can be detected even at very low smoking rates is required (Baek, 2019). Although extensive research has been conducted towards understanding of the mechanism of action of ETS, 3-ethenylpyridine has been suggested to be an ideal marker of ETS constituents in the vapour phase and solanesol, a tobacco-specific compound for particulate-phase measurements (Stewart and Robinson, 2017; Baek, 2019).

2.5 Volatile and Semi-Volatile Organic Compounds

Exposure to volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) has been widely studied in indoor environments, and several adverse human health implications have been documented over the past decades (Wang et al., 2020; Liu & Folk, 2021; Zhang et al., 2021b; Liu, 2022; Sonne et al., 2022; Xiong et al., 2022). According to ASTM D8141-22 (2022), VOCs are organic compounds with boiling points between 50°C and 240°C, while SVOCs have boiling points between 240°C and 400°C, with higher boiling points and lower saturated vapour pressures. VOCs are highly volatile chemical species, making them difficult to manage in an individual's microclimate due to their physico-chemical properties (de Gouw and Warneke, 2007; Mo et al., 2021; Sonne et al., 2022). The exposure to VOCs is exacerbated by factors such as air conditioning, limited outdoor air exchange, and the infiltration of polluted outdoor air into the indoor environments.

Examples of VOCs include, but are not limited to: acetone, benzene, ethylene glycol, formaldehyde, methylene chloride, tetrachloroethylene (perchloroethylene), toluene, xylene, styrene, and 1,3-butadiene. Semi-volatile compounds are a subgroup of VOCs that have a moderate to low vapour pressure (volatility), typically occurring between 260 and 400 °C (Sonne et al., 2022). Examples of SVOCs include, but are not limited to: hydrocarbons, aldehydes, ethers, esters, phenols, organic acids, ketones, amines, amides, nitroaromatics, PCBs, PAHs, phthalate esters, nitrosamines, haloethers, trihalomethanes, pesticides, and some perflourinated substances (PFAS). These chemicals partition between the gas and particulate fractions, resulting in airborne particles, dust, and bulk deposition on surfaces and ventilation systems (Harrad et al., 2010; Pagonis et al., 2019).

Studies suggest that human exposure to toxic contaminants like BFR, PCBs, PFAS, and phthalates can negatively impact indoor air quality through inhalation and ingestion of settled indoor dust (Eichler and Little, 2020; Huang et al., 2021a; Huang et al., 2021b; Sonne et al., 2022). These substances, due to their slow chemical and biological degradation and long lifetimes of tens of hours, can remain almost inert in indoor environments for extended periods (Lucattini et al., 2018; Pagonis et al., 2019; Sonne et al., 2022).

The VOCs and SVOCs are found in the indoor environment through emissions and leaching from building materials, indoor structures, equipment, electronics, furniture materials, and human activities like cooking, cleaning, and using consumer products (Figure 4) (Demirtepe et al., 2019; Cao, 2022; Liu, 2022; Sonne et al., 2022; Xiong et al., 2022). Paints, cleaning products, cosmetics, degreasing, wall joints, furniture, photocopiers, printers, computers, and other common household items all emit volatile organic compounds (VOCs) into the air (Yue et al., 2021). VOCs are commonly used in furniture, carpets, laptops, wall joints, and artificial boards, which are medium-density fibre boards and plywood glued together using adhesives and resin glue (Goldstein et al., 2021).

Formaldehyde and benzene contribute to occupational and personal exposure in closed buildings, while outdoor air transportation, including traffic and industrial-related VOCs, is a significant source of indoor organic compounds (Miller et al., 2009; Mishra et al., 2015; Peng et al., 2022). SVOCs, found in consumer products, clothing, building materials, paint, furniture, electronics, and indoor articles, serve as plasticisers, flame retardants, solvents, pesticides, and coatings. Over time, they volatilise and release into indoor air and dust, which volatilise over time and release to indoor air and dust (Table 1) (Lucattini et al., 2018; Eichler et al., 2021; Wu et al., 2021; Sonne et al., 2022). SVOCs can be found in various ways in indoor environments, and these compounds may originate from sources such as pesticides and herbicides that contain phosphorus, sulphur, chlorine, or nitrogen. Over the years, the use of organochlorine pesticides (OCPs) for pest control indoors and outdoors has contributed towards contamination of the indoor environment with SVOCs in some countries (Jayaraj et al., 2016; Demirtepe et al., 2019).

Pesticides like pyrethroids are used to combat endemic diseases, fight insect-borne diseases like lice and scabies, and as household insecticides (Sonne et al., 2022). In Brazil, they are marketed to the retail sector for public usage, such as residual spraying and tissue impregnation (Guida et al., 2021). Some SVOCs, such as OCPs, can reach considerable distances from their emission sources, either in the gas-phase or ad/ab-sorbed by particles, facilitating long-range atmospheric transport (LRAT) through the atmosphere (Lohmann et al., 2007). A systematic review shows that other polycyclic aromatic hydrocarbons (PAHs), including PCDD/F, are a significant indoor source of SVOCs in households reliant on wood burning, personal care products, and their degradation products (Lucattini et al., 2018; Demirtepe et al., 2019). This is especially important in areas where people utilise wood waste processed with polyvinyl chloride (PVC) or pyrolysis of wood–PVC mixtures, which can release high levels of PCDD/F (Lavric et al., 2004).

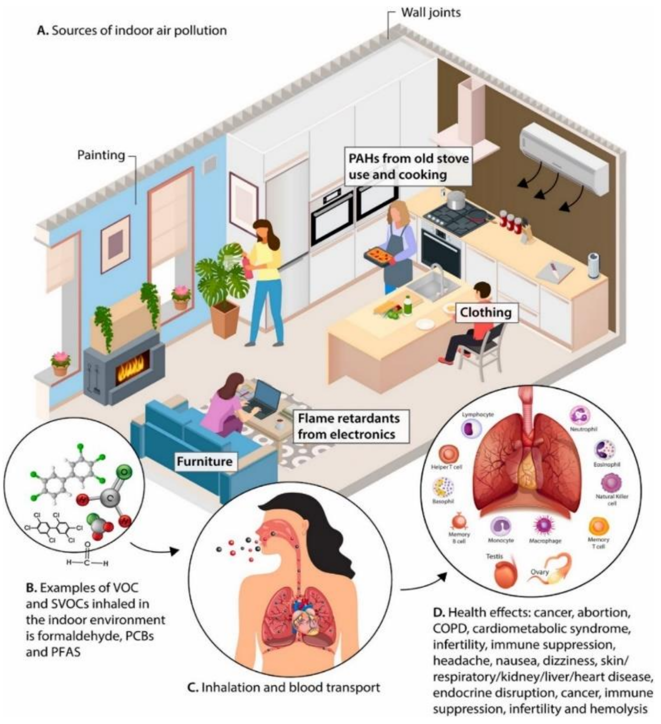

Figure 4: Indoor toxic volatile organic compounds and human health effects [Source: Sonne et al. (2022)]

SVOCs are easily sorbed onto interior surfaces due to their high surface/air partition coefficient, making the sorption effect significant and crucial for their transport, unlike VOCs, which have a lower sorption coefficient (Wang et al., 2020). VOCs like formaldehyde and benzene, found in various products, are linked to reproductive issues, respiratory complications, immune suppression, cancer, and dementia (Sonne et al., 2022). Indoor air pollution, characterised by neurotoxic chemicals, can lead to behavioural changes, learning disabilities, and locomotor impairments, posing significant health and socioeconomic challenges to individuals and societies. Solutions for indoor VOCs and SVOCs include reducing or eliminating sources, increasing removal, and utilising phytoremediation and metal-organic frameworks to decrease indoor concentrations (Sonne et al., 2022).

The urgent need is to regulate indoor concentrations of chemicals and develop solutions using advanced, sustainable materials, electronics, and technologies to mitigate their health effects. Understanding the emission and sorption mechanisms of VOCs and SVOCs is crucial for characterising their fate and transport in indoor environments and proposing strategies to reduce human exposure (Wang et al., 2020; Wu et al., 2021; Sonne et al., 2022).

2.6 Polycyclic Aromatic Hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are a group of chemical compounds with two to seven fused aromatic rings, which are toxic organic pollutants and potential carcinogens. PAHs are primarily derived from anthropogenic sources such as industrial activities, combustion engines, residential heating, biomass burning, traffic emissions, and incomplete combustion of industrial and domestic fuels (Ite, 2012; Abdel-Shafy and Mansour, 2016; Hussain et al., 2019; Zhang et al., 2021c). Indoor PAHs are partially generated by sources like smoking, cooking, domestic heating, and open fireplaces and partially transferred outdoors through air infiltration, intrusion, and soil shifts, consumer products, and indoor emissions sources such as leakage from wood-burning appliances, domestic heating, construction materials or furniture, an open fireplace, as well as other emission sources (Wang et al., 2013a; Ali et al., 2016; Hussain et al., 2019; Zhang et al., 2021c).

PAHs, when emitted into indoor environments, can disperse among various surfaces and matrices, reaching significant distances from their sources, leading to potential chronic exposure through inhalation, dust ingestion, and dermal contact (Li et al., 2008; Hussain et al., 2019; Wang et al., 2019b). PAHs, like other VOCs and SVOCs, are organic chemicals commonly adsorbent and bound to ambient particulate matter, a mixture of small particles and liquid droplets. Studies have shown that PM-bound PAHs have had adverse effects on human health due to their carcinogenicity and mutagenicity, with inhalation being the primary human exposure route (Yang et al., 2021). PAH compounds are commonly found in indoor environmental matrices like dust, airborne particulate phase, and gas phase, allowing them to absorb and achieve distribution equilibrium (Ali et al., 2016; Hussain et al., 2019). Understanding the behaviour of PM-bound PAHs in the atmosphere is crucial due to their varying concentrations among people, microenvironments, and areas.

Indoor samples are frequently analysed to understand PAH external exposure, but limited data exists on particulates and vapour phases of indoor air (Liu et al., 2018; Wang et al., 2019b; Zhang et al., 2021c). Over the years, various studies have documented the prevalence of PAHs in indoor dust, and several governments have launched investigations on PAHs in indoor aerosol particles (Wang et al., 2013a; Han et al., 2015; Błaszczyk et al., 2017; Madruga et al., 2019; Zhang et al., 2021c). PAHs can enter the human body through air inhalation, dust ingestion, and dermal contact, but there is limited information on their contribution to total human exposure and comparative studies on internal and external exposure in developed and developing countries (Li et al., 2008; Zhang et al., 2021c). According to a study, air quality has a significant influence on both individual and societal health, and it remains a major concern in industrialised regions such as southern Poland (Błaszczyk et al., 2017). PAHs like benzo[a]pyrene, benz[a]anthracene, and chrysene are probable carcinogens for humans and animals, and indoor pollutants pose risks to those who spend extended periods indoors (Li et al., 2008; Yury et al., 2018).

Human oxidative damage, cancer, mutagenicity, and cardiovascular disease are all strongly correlated with PAH exposure (Holme et al., 2019; Wang et al., 2019c). Indoor environments significantly impact human health and productivity due to exposure to organic chemicals and air pollutants, as most people spend most of their time indoors, and indoor air quality also significantly influences these exposures (Schwela, 2014; Mannan and Al-Ghamdi, 2021). The Niger Delta region of Nigeria lacks comprehensive data on PAHs and other SVOCs, including PCBs and legacy and current pesticides, in indoor environments. Therefore, an effective understanding of indoor sources and levels of PAHs and SVOCs is crucial for identifying human exposure routes, risks, and designing control and mitigation strategies.

2.7 Other Indoor Air Pollutants

There are several other toxic chemicals that have been identified in ambient air, and most of them are indoor air pollutants. These additional air toxics may be classified as toxic metal compounds, aromatic compounds, or non-aromatic toxic compounds. The majority of hazardous substances are released into the air through the burning of fossil fuels, biomass, industrial processes, solvent evaporation, and waste incineration (Smith et al., 2000; Ezzati and Kammen, 2001; Sorooshian et al., 2012; Tian et al., 2012). A significant fraction of these chemicals are traditional pesticides and herbicides, which are typically persistent organic pollutants (POPs). Exposure to several pollutants in built environments is becoming more important due to social advancements. It is necessary to understand the sources, transformation, transport, and fates of these additional air toxins in order to mitigate the risks of human exposure.

Some of these additional indoor air pollutants include biological contaminants, nonionising electromagnetic radiation, toxic metals, toxic aromatics, ozone, and humidity, as well as inorganic and non-aromatic organic toxic air pollutants. These compounds are mostly hydrocarbons containing the functional groups –OH, –C=O, –C(O)OH, $–NH_2$, –CN, –X, and –S. Inorganic toxins include CS_2, COS, CCl_4, Cl_2, HF, HCl, H_2S, P, $TiCl_4$, and inorganic cyanides. Radon, other radionuclides, mixtures of fine mineral fibres, and coke oven emissions are also toxic. Some of these additional indoor air pollutants will be briefly described below.

Biological contaminants (bio-contaminants) are pollutants of biological origin, including bacteria, fungi, algae, mites, insect debris, and animal epithelia, and their by-products, including endotoxins, mycotoxins, and volatile organic compounds, etc., are present in both indoor and outdoor environments (Nevalainen and Morawaska, 2009; Schwela, 2014; Tulchinsky and Varavikova, 2014; Kumar et al., 2021; Salami et al., 2022; Kumar et al., 2024). It has been reported that indoors and outdoors can be contaminated with biological contaminants including bacteria, spores, yeasts, fungi, and secondary metabolites such as bacterial endotoxins, peptidoglycans, volatile organic compounds, pollens, viruses, and protozoa (Nevalainen and Morawaska, 2009). Indoor environments like houses, hospitals, workplaces, educational institutions, and museums are highly susceptible to biological contaminants due to their activities.

Microorganism mixtures, including particles and gases, can cause various nonspecific health issues in indoor environments such as schools, hospitals, and workspaces (Schwela, 2014). These biological contaminants may cause direct detrimental effects on human health and well-being as well as serve as vectors for diseases. It has been suggested that biological agent exposures in indoor environments are linked to a variety of health outcomes that have a significant influence on public health, such as allergies, airway inflammation, neurological disorders, and acute toxic effects (Nevalainen and Morawaska, 2009). Some of these biological contaminants in indoor environments are known to cause allergic or inflammatory reactions or infectious diseases like aspergillosis, coccidioidomycosis, and cryptococcosis (Nevalainen and Morawaska, 2009; Schwela, 2014; Tulchinsky and Varavikova, 2014; Tran et al., 2020; Kumar et al., 2021; Salami et al., 2022).

Indoor biological contamination, despite lack of awareness, can spread infections and have pathogenic, toxicogenic, and allergenic health effects (Cooke, 1991; Kumar et al., 2021). Air circulation equipment, insulation, temperature, relative humidity, and duct maintenance are examples of abiotic factors that regulate indoor air quality and biological agents' survival (Kumar et al., 2021). Indoor air pollution control involves preventing conditions that promote biological agent growth (development), containing and removing such growth, and avoiding substrates that facilitate such growth. Reduction in the concentration of biological contaminants can be accomplished by reducing relative humidity in a building, and effective programmed hygiene and maintenance procedures are crucial for reducing human health risks and hazards (Cooke, 1991; Kumar et al., 2021).

Nonionising radiation, including optic and electromagnetic fields, is a type of radiation that does not have enough energy to ionise atoms or molecules. Optic radiation includes ultraviolet and infrared wavelengths, while electromagnetic fields, like microwaves or radio frequencies, are characterised by wavelengths or frequencies (Tulchinsky and Varavikova, 2014; Havas, 2017). Indoor nonionising radiation can be emitted from various electrical sources, including high voltage lines, phone base stations, radio/broadcast antennas, and various electrical appliances like televisions, computers, mobile phones, and so on (Cooke, 1991; Tulchinsky and Varavikova, 2014). Although nonionising radiation is essential to life in our modern world, occupational exposure and excessive personal exposures may cause potential health risks such as tissue damage and other adverse medical problems.

Nonionising radiation can cause photochemical, thermal, and electrical effects, potentially impairing tissue and organ function beyond certain thresholds (Tulchinsky and Varavikova, 2014). Acute effects, such as skin redness, hair loss, radiation burns, or acute radiation syndrome, can occur with more severe effects at higher doses and rates. UV radiation increases skin cancer risk, eye burns, cataracts, reduced immunity, blood vessel damage, and reduced immunity, while excessive infrared radiation exposure over long periods increases cataracts, impaired fertility, and tissue damage (Tulchinsky and Varavikova, 2014). Although it hasn't been confirmed, prolonged exposure to high-voltage power lines, radio and radar transmitters, and mobile phone use is hypothesised to increase the risk of cancer (Tulchinsky and Varavikova, 2014). Epidemiological studies suggest nonionising radiation exposure may pose significant health risks, including cancer and reproductive effects, although cause and effect have not been proven (Cooke, 1991; Tulchinsky and Varavikova, 2014; Havas, 2017). In general, legal restrictions and caution in their use are crucial due to their potential risks, and more research is needed in this area.

Indoor ozone emissions can pose human health risks and react with gaseous chemicals and building materials, resulting in by-products such as secondary organic aerosols that may significantly affect indoor air quality. Apart from ambient outdoor sources, indoor ozone emissions from indoor devices like ozone generators, disinfectors, air purifiers, laser printers, photocopiers, and other household devices are the primary sources of indoor ozone (Guo et al., 2019; Nazaroff and Weschler, 2022). Indoor emission sources have the potential to significantly raise indoor ozone concentrations, even though the majority of indoor ozone originates outdoors and enters through ventilation air (Nazaroff and Weschler, 2022). Ozone concentrations near photocopiers using ultraviolet light may pose a health hazard, despite their low concentrations in most indoor environments (Cooke, 1991). A group researchers reported measurements in around 2000 indoor environments that reveal a central trend of 4 – 6 ppb average indoor ozone concentration and a 25% indoor–to–outdoor concentration ratio (Nazaroff et al., 2022).

In a review, a group researchers reported that while the median ozone concentration in school and office environments was below the WHO guideline of 100 μg/m^3 for 8 hours, a wide range of average concentrations indicated that WHO values were exceeded (Salonen et al., 2018). Ozone, a potent oxidising gas, can significantly damage the tissues of the respiratory tract, causing inflammation and irritation, cardiovascular system problems, and other potential health risks (Guo et al., 2019). Ozone is not widely known due to its limited information on global and local exposures in various indoor environments, despite its potential for severe health consequences (Salonen et al., 2018; Khararoodi et al., 2022). Considering the health effects, increasing ventilation is typically effective in reducing indoor concentration and the concentration of ozone and ozone reaction products must be reduced in both indoor and outdoor environments.

Indoor humidity is not a health hazard, but condensation on cold surfaces can negatively impact air quality, leading to microbial development on surfaces and buildings (Cooke, 1991; Wolkoff, 2018). The relationship between perceived indoor air quality (IAQ), indoor air humidity, and related health impacts has long been a source of controversy. Indoor air humidity can improve perceived IAQ, eye symptoms, and work performance in offices (Wolkoff, 2018; Wolkoff *et al.*, 2021; Wolkoff, 2024). However, low humidity does not worsen sensory irritation in the airways. According to a study, humidified air reduces nasal symptoms in obstructive apnoea syndrome patients, but no improvement in voice production has been observed, except for vocal fatigue patients (Wolkoff, 2018). Low indoor air humidity leads to desiccation of airways and less efficient mucociliary clearance, causing common mucous membrane-related symptoms like dry and tired eyes, affecting work performance (Wolkoff et al., 2021).

Recently, findings from epidemiological and experimental studies have reconfirmed that low indoor air humidity, or dry air, increases the prevalence of acute eye and airway symptoms in offices, leads to lower mucociliary clearance, less efficient immune defense, and decreased work productivity (Wolkoff, 2024). Relative humidity is a crucial environmental parameter, and controlling it using air conditioners or dehumidifiers is a straightforward solution (Cooke, 1991).

Apart from outdoor sources, different indoor sources contribute to increased pollutant concentrations, including human activities, surface chemistry reactions, building materials, and emissions from furniture and electronic appliances. Therefore, indoor air quality is a complex system due to a heterogeneous mix of pollutants with varying toxicity levels, necessitating effective detection and characterisation of these pollutants at trace levels to quantify and mitigate their health risks (Rivas et al., 2019).

3. EXPOSURE AND HEALTH EFFECTS OF INDOOR AIR POLLUTANTS

Indoor air pollution is a significant environmental issue globally, particularly affecting the poorest nations, who often lack access to clean cooking fuels. Indoor air pollution levels can vary based on factors such as pollutants' types, sources, occurrence, sink presence, and mixing. Indoor concentrations may be higher or lower than outdoor levels, with outdoor pollutants lagging and having a lower peak. The time pattern of indoor air pollution concentration may also differ.

3.1 Exposure to Indoor Air Pollutants

Acute (short–term) and chronic (long–term) exposure to indoor or household air pollution (HAP) is associated with various adverse health problems, including chronic obstructive pulmonary disease (COPD), cardiovascular disorders, endocrine and nervous system malfunction, cognitive deficits, cancer, neurological effects, low birth weight, and infant mortality (Bruce et al., 2000; Almetwally et al., 2020; Ramya et al., 2021; Newell et al., 2022; Kumar et al., 2023a; Jones & Molina, 2024; Rybak & Pieśniewska, 2024). Indoor air pollution is a significant environmental issue globally, particularly affecting the poorest nations, who often lack access to clean cooking fuels. Indoor air pollution significantly impacts health in low-income countries, ranking among the worst risk factors (Ritchie and Roser, 2023).

According to a study, 90% of rural households in low- and middle-income countries use solid fuel, often in inefficient cookstoves without adequate ventilation, exposing them to high HAP (Newell et al., 2022). Indoor air pollution (IAP), which causes over 3 million deaths annually, is the leading cause of disability-adjusted life years globally (Ritchie and Roser, 2023; Rybak and Pieśniewska, 2024). It is expected that human exposure to some of these indoor air pollutants will remain due to their pattern of usage and persistent chemical characteristics, and as such, human health effects due to such exposures will also continue to be an issue of concern. In order to properly analyse chemical hazards and understand human health risks, several parameters, including air, soil, and water quality, need to be taken into account. Therefore, assessing the various routes of human exposure to indoor air pollutants often requires a combination of a sophisticated and multidisciplinary approach and experimental techniques.

The transformations and distribution of indoor pollutants in our surroundings are greatly influenced by atmospheric processes. There are two main pathways, either directly or indirectly, for human exposure to airborne indoor pollutants: (i) inhalation and (ii) ingestion (which is indirectly influenced by the environment in two ways) (Ite and Ite, 2024). Therefore, human exposure to indoor air pollutant concentrations is closely related to environmental contamination and/or pollution. In our environment, exposure to indoor air pollutants can occur through various sources, including drinking water, food, air, and dermal (skin) contact. For example, PAHs that are released into the atmosphere exist in two distinct states: a vapour phase and a solid phase, where they adsorbed onto particulate matter (Ravindra et al., 2008; Zhang and Tao, 2009; Wang et al., 2013b; Abdel-Shafy and Mansour, 2016).

Indoor particulate matter (PM) exposure, particularly PM2.5, is a significant health concern due to its large surface area, high adsorption capacity, and deeper penetration into alveolar sacs (Warwicker, 2010; Ite et al., 2019; Tran et al., 2020; Mannan and Al-Ghamdi, 2021; Dwivedi et al., 2022). Particulate-phase PAHs are primarily adsorbed onto fine particles, which can be transported over long distances and pollute even remote areas, depending on atmospheric conditions and chemical reactivity (Srogi, 2007; Abdel-Shafy and Mansour, 2016; Hussain et al., 2019). PAHs on particles less than 1 μm are reportedly derived from combustion and other high-temperature sources (Venkataraman et al., 1994).

Studies indicate that low-molecular-weight PAHs (two or three rings) exist in the vapour phase, multi-ringed PAHs (five rings) are bound to particles, and intermediate-molecular-weight PAHs (four rings) are divided between the vapour and particulate phases (Howsam et al., 2000; 2001; Srogi, 2007; Abdel-Shafy and Mansour, 2016). Indoor air quality is crucial for human health, as adults inhale 15 kg of air daily, which accounts for over 75% of the human body's daily mass intake (Zhang et al., 2022a). Therefore, poor indoor air quality may result in a variety of health problems and can lead to chronic health issues in individuals who spend 80 – 90% of their time indoors (Saini et al., 2020; Dwivedi et al., 2022; Saini et al., 2022).

3.2 Health Effects of Indoor Air Pollutants

The health effects associated with exposure to indoor air pollution are influenced by various factors and vary over time. Exposure to household air pollution may result in a broad range of health effects, from minor problems like annoyance to severe conditions like asthma, cancer, cardiovascular disease, and even premature mortality (Ahmed et al., 2019; Manisalidis et al., 2020; Samet et al., 2021; Hänninen et al., 2022). The often documented negative health effects of HAP that considerably increase the global health burden include respiratory infections, lung cancer, reduced lung function, chronic obstructive pulmonary disease (COPD), and immune system degradation (Ahmed et al., 2019; Schraufnagel, 2020; Samet et al., 2021; Wolkoff et al., 2021; Newell et al., 2022; Idowu et al., 2023; Lewis et al., 2023; Rybak and Pieśniewska, 2024).

According to a study, evidence from health risks revealed that indoor air pollutants caused 4.3 million deaths, of which 34% were caused by strokes, 26% by heart diseases, and 12% by respiratory disease in children (Figure 5) (WHO, 2014). Every stage of life is impacted by household air pollution, which has multi-systemic health impacts that are visible from early pregnancy to old age. It has been demonstrated that prenatal exposure to domestic air pollution has long-lasting health impacts (Apte and Salvi, 2016). Early childhood indoor air pollution exposures also frequently have long-term effects.

The effects on the brain system, endocrine system, and cardiovascular system are mainly understated, while the respiratory system experiences the most damage. Reduced sperm motility and low-quality zygotes are the results of increased oxidative stress, which contributes significantly to the rise in insulin resistance linked to polycystic ovarian disease, a leading cause of infertility (Kelly, 2003; Lodovici and Bigagli, 2011; Apte and Salvi, 2016). The development of certain cancer forms has also been linked to household air pollution (Apte and Salvi, 2016). Household air pollution is a significant global cause of disability-adjusted life years (DALYs), with at least sixty sources varying across countries, making it the third leading cause globally (GBD, 2015; Apte and Salvi, 2016; Reiner et al., 2022).

Exposure to ambient air pollutants can cause distinct toxicological effects on humans, particularly in indoor air quality (IAQ), which is crucial for health and well-being, and deteriorated IAQ can lead to severe health consequences (Samet et al., 2021; Sadrizadeh et al., 2022; Kumar et al., 2023a). These effects can include skin disorders, long-term chronic illnesses including cancer, neuropsychiatric problems, respiratory and cardiovascular ailments, and eye discomfort (Figure 5) (Ghorani-Azam et al., 2016; Kumar et al., 2023a). Household air pollution exposure, both short- and long-term, can raise morbidity and death from cardiovascular disease (CVD) and typically works in concert with other CVD risk factors (Apte and Salvi, 2016; Tran et al., 2020; Sagheer et al., 2024).

Exposure to household air pollutants increases cardiovascular and respiratory mortality rates, with a 10 μg/m^3 increase in indoor PM_{10} causing a 0.36% and 0.42% increase, respectively (Apte and Salvi, 2016). Indoor $PM_{2.5}$ levels of 10 μg/m^3 have been linked to a 0.63% increase in cardiovascular mortality and a 0.75% increase in respiratory mortality. It has been reported that every 10 μg/m^3 increase in household PM_{10} leads to a corresponding 23 – 67% increase in mortality risk in the long term exposure (Lu et al., 2015). According to a group researchers short exposures of aerodynamic diameters less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$) are positively associated with increases in mortality due to non-accidental causes such as cardiovascular disease and respiratory disease (Lu et al., 2015). In a study, reported that the monthly average levels of $PM_{2.5}$ and PM_{10} in selected areas of Nigeria were above the WHO guideline, indicating poor and unhealthy air quality, with $PM_{2.5}$ AQI levels ranging from 65.13 to 927.07 and PM_{10} AQI levels ranging from 73.51 to 256.65 (Lala et al., 2023). Although ambient air pollution, including $PM_{2.5}$ and PM_{10}, is a major environmental health problem in developing countries, there is insufficient evidence regarding constituent-associated health effects in Nigeria's Niger Delta region.

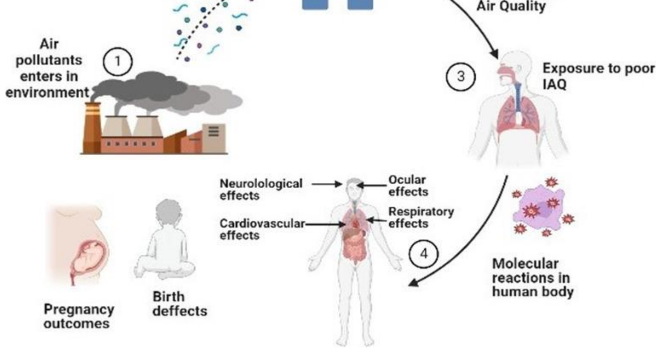

Figure 2: Health Effects associated with indoor air pollution [Source: (Kumar et al., 2023a)].

Some studies have shown that household air pollution has been linked to impairments in cognition and judgemental skills (Lang et al., 2008; Ailshire and Clarke, 2014; Apte and Salvi, 2016). Exposure to higher particulate matter concentrations can significantly impair cognitive function in older adults, potentially due to oxidative stress and activation of pro-inflammatory pathways (Apte and Salvi, 2016). Animal studies have demonstrated that particulate matter with a size of 2.5 μm or smaller can induce depressive responses, impaired spatial learning and memory, increase pro-inflammatory cytokine expression in the hippocampal axon, and alter neuronal morphology (Fonken et al., 2011; Hou et al., 2023).

Animal studies have suggested that chronic exposure to particulate air pollution in major cities (traffic-related PM) could be linked to depressive behaviours, altered affective responses, and cognitive impairments in urban populations (Ranft et al., 2009; Fonken et al., 2011). In a recent study, reported that long-term exposure to particulate air pollution in urban areas was associated with increased risks of schizophrenia spectrum disorder, depression, and anxiety disorders, supporting altered affective responses (Nobile et al., 2023). Environmental risk factors for cognitive function in older adults have been under researched in population-based studies, despite their significant social, economic, and health implications (Lang et al., 2008; Ailshire and Clarke, 2014). Furthermore, research evidence has shown mutations in over 68 genes that have been linked to an increased risk of small cell lung cancer in people who use coal for cooking and heating in their homes, which creates a lot of smoke (Yu et al., 2015b).

Animal and human studies have demonstrated that air particles can alter global and promoter-specific DNA methylation levels (Arita and Costa, 2011). A study in Boston, MA, found that ambient particulate matter decreases blood DNA methylation levels of *LINE-1* and *Alu* repetitive elements in older males' blood (Baccarelli et al., 2009). This suggests that changes in global DNA methylation may affect human health, as these changes are linked to the progression of cancer and cardiovascular disease (Castro et al., 2003). Over the years, household air pollution has significantly influenced the development and progression of various diseases such as asthma, lung cancer, ventricular hypertrophy, Alzheimer's, Parkinson's, psychiatric difficulties, autism, retinopathy, foetal growth, and low birth weight (Ghorani-Azam et al., 2016; Manisalidis et al., 2020).

Volatile organic compounds (VOCs) are harmful pollutants that can be toxic at low concentrations, causing adverse health effects ranging from minor irritations to chronic complications like asthma exacerbation, highlighting the need for proper management and prevention of these pollutants (Warwicker, 2010). VOCs, when inhaled, can enter the bloodstream and cause acute health issues like eye, nose, throat irritation, and headaches (Wang et al., 2019a; Yue et al., 2021). Chronic exposure to high concentrations can lead to reproductive problems, respiratory conditions, cardiovascular issues, immune system deterioration, allergic conditions, cancers, and dementia (Wang et al., 2019a; Yue et al., 2021; Sonne et al., 2022). Toxic indoor VOCs, including phthalates and PAHs, have caused diseases and endocrine disruptions, posing socio-economic burdens in both developed and developing countries, and are detrimental to human health due to their impact on the environment (Landrigan et al., 2018; Yue et al., 2021; Sonne et al., 2022).

Most chemicals are toxic to the immune system, potentially impacting the production of antibodies against viral infections (Grandjean et al., 2012). The COVID-19 lockdown underscored the need to enhance indoor air quality, especially in countries where the lockdown coincided with the cold season and the burning of wood and coal for heating (Zhang et al., 2022b). Therefore, action is needed to promote healthy indoor environmental quality (IEQ), reduce personal exposure to chemicals, and adopt controlled air circulation to remove aerosols from the indoor environments (Morawska et al., 2021; Wang et al., 2021; Sonne et al., 2022).

PAHs, found in petroleum and coal, pose significant environmental and occupational health risks due to their toxic, mutagenic, and carcinogenic properties (Abdel-Shafy and Mansour, 2016; Hussain et al., 2019; Gad and Gad, 2024). Over the years, humans have been exposed to PAHs with catastrophic consequences, and several biomarkers have been employed to detect susceptible populations to PAH-induced diseases (Banks et al., 2019). PAHs are considered hazardous pollutants, and 17 PAHs pose significant health risks due to their widespread diffusion and toxicological relevance. However, individual health effects vary, with some classified as known, possibly, or probably carcinogenic to humans by the International Agency for Research on Cancer (IARC, 2010).

PAHs, including benzo[a]pyrene, naphthalene, chrysene, benz[a]anthracene, benzo[k]fluoranthene, and benzo[b]fluoranthene, pose a significant health threat, including an increased risk of lung cancer (IARC, 2010; Kim et al., 2013). The acute health impacts of PAHs are primarily determined by their exposure duration, concentration, toxicity, and route of exposure, such as inhalation, ingestion, or skin contact (ACGIH, 2005). It has been reported that short–term exposure to PAH via dermal contact and inhalation can result in photosensitisation of the skin and eyes, producing erythema and other cutaneous consequences.

Additional side effects include central nervous system suppression, nausea, diarrhoea, and disorientation (Gad and Gad, 2024). PAHs, despite their low acute toxicity to humans, are highly carcinogenic and/or mutagenic in chronic exposure, with cancer being the most significant endpoint. Studies have linked PAHs to stomach, bladder, liver, lung, skin, and injection-site sarcomas in animals (Li et al., 2005; Oliveira et al., 2017; Rostami et al., 2019). Exposure to ultraviolet light increases toxic dermal effects, potentially leading to skin cancer if sun-exposed skin lesions progress. PAHs, which cause respiratory effects like cough, chronic bronchitis, and haematuria, have been linked to increased cancer rates in workers exposed to high airborne concentrations.

PAHs exposure is a global issue causing long-term damage, including inflammation, carcinogenic and mutagenic effects, infertility, and neurotoxicity to humans and wildlife, even at low concentrations (Abdel-Shafy and Mansour, 2016; Banks et al., 2019; Bollinger et al., 2020). Developmental behavioural problems have also been noted as children grow (Herbstman et al., 2012; Bandeira and Meneses, 2013). Long-term exposure to PAHs can lead to health issues like decreased immune function, cataracts, kidney and liver damage, breathing problems, asthma-like symptoms, and lung function abnormalities (Abdel-Shafy and Mansour, 2016; Bollinger et al., 2020).

Post-September 11, 2001 literature reviews studies on neural signaling pathways, primary targets of PAH toxicity, and toxicity modifiers, highlighting the potential health risks of repeated skin contact, redness, inflammation, and red blood cell breakdown (Bollinger et al., 2020). In a recent study, a group researchers used epidemiological data and animal data to explore potential pathways contributing to neurodevelopmental deficits in infants, toddlers, and children induced by PAH exposure (Bollinger et al., 2020). Due to its presence in the circulation and skin exposure, pyrene, which is prevalent in high concentrations in the environment, is a carcinogenic agent that can induce severe and permanent hyperplasia and metaplasia as well as immunodepression (Gad and Gad, 2024).

Indoor air contamination, primarily caused by bacteria, moulds, and yeast, poses significant health risks, especially to the respiratory system, negatively impacting human health and indoor air quality due to biological activities (Moldoveanu, 2015; Kumar et al., 2021; Kumar et al., 2023a; Kumar et al., 2024). Biological pollutants are classified according to whether they are allergenic, infectious, or capable of inducing toxic or inflammatory responses in human beings (Kumar et al., 2021). Biological pollutants cause health issues like sneezing, coughing, shortness of breath, dizziness, lethargy, fever, and digestive problems, with allergic reactions occurring after repeated exposure (Seltzer, 1994; Von Essen and Romberger, 2003; Kumar et al., 2021; Chawla et al., 2023; Kumar et al., 2024). Biological pollutants cause airway diseases, hypersensitivity reactions, and infections, while also acting as potential irritants and toxins, causing organ system injuries like dermatitis, flu-like symptoms, diarrhoea, and cancer (Seltzer, 1994).

Evidence suggests that indoor air exposure to biological pollutants can induce allergic reactions and may lead to neurological symptoms like headaches, fatigue, and forgetfulness (Moldoveanu, 2015). Exposure to poor indoor air quality and biological pollutants can lead to severe health issues, such as SBS (Joshi, 2008; Kumar et al., 2023a). Chronic airway illness is highly prevalent in agricultural workers, especially swine farmers, and is partially assumed to be caused by long-term inhalation of organic dust particles (Von Essen and Romberger, 2003). Organic dust of biological nature partly influences the immune system and has toxic and irritative effects. In the agricultural sector, the acute systemic reaction to inhalation of massive amounts of dust associated with the handling of mouldy agricultural products may be implicated in organic dust toxic syndrome (ODTS). Therefore, humans' indoor confinement has not only increased biological contaminants in microenvironments but has also contributed to the enhanced burden of diseases.

4. MITIGATION STRATEGIES

Source identification is crucial for mitigating indoor air pollution, and several studies reported significant sources of both indoor and outdoor origins. One of the most important steps in reducing pollutants and the health concerns they pose is accurately identifying the sources of indoor air pollutants (Chojer et al., 2024). The presence of a potential contaminant source does not guarantee exposure, as the extent of exposure depends on the source's physical nature or usage rather than the mere presence. Indoor pollutants can cause adverse effects in occupational and other environments, despite their unclear health significance. A group researchers propose a hybrid approach for source identification, combining traditional samplers and continuous monitoring methods for both preventive and reactive measures (Chojer et al., 2024). Human health is greatly affected by the presence of contaminants in indoor environments, and assessing the danger to human health requires regular evaluation of indoor air quality.

There are several mitigating strategies that have been developed to protect occupants from exposure and address the increased health risk caused by poor IAQ. Mitigation options include improved airflow distribution, photocatalytic oxidation techniques, and green indoor systems that use phytoremediation and biofiltration to remove pollutants from the environment (Ramya et al., 2021; Kumar et al., 2023b). Over the years, several technologies have been developed to eliminate indoor pollutants, including catalytic oxidisation, photocatalytic nano-based activated carbon filters, chemical sorbents, building materials as adsorbents, and phytoremediation by green wall biofilters. These sustainable remediation methods have proven popular in various fields, including environmental protection and health (Er et al., 2016; Grabchenko et al., 2018; Thevenet et al., 2018; Suarez et al., 2019; Darlington et al., 2001; Pettit et al., 2019; Lee et al., 2020; Bandehali et al., 2021; Teiri et al., 2022; Kumar et al., 2023b).

These sustainable remediation methods have proven popular in various fields, including environmental protection and health. In practice, remediating existing indoor contaminants comes after eliminating indoor air pollution through emission reduction in order to ensure effective mitigation strategies. In a study, reported that increased ventilation effectively reduces indoor air pollution concentrations, with particulate-bound PAH concentrations being 4-10 times lower in more ventilated households compared to unventilated ones (Downward et al., 2014). In a related study, a group researcher measured the first-time personal exposure level of polycyclic aromatic hydrocarbons (PAHs) during cooking hours in participants from three kitchen types using traditional and improved cookstoves (Sharma et al., 2020). Evidence from the study showed that kitchen characteristics and cookstoves type had a significant effect on personal exposure, and intervention of improved cookstoves resulted in 75 – 90% reduction in PAHs concentration (Sharma and Jain, 2020). Ventilation optimisation can improve indoor air quality in areas with high outdoor pollution, but it may not be effective due to common ventilation systems not filtering gaseous air pollutants (Tran et al., 2020). Indoor air contains fine particles and hazardous volatile organic compounds, known for their carcinogenic effects. Health authorities are concerned about their difficult and expensive removal methods, leading researchers to search for an economical and environmentally friendly technique.

Plants, like potted ones or green walls, can potentially improve indoor air quality and health levels in homes (Darlington et al., 2001; Pettit et al., 2019; Lee et al., 2020; Bandehali et al., 2021; Teiri et al., 2022; Kumar et al., 2023b). According to green wall systems, commonly referred to as "bio filters," "vertical gardens," or "living walls," are a significant breakthrough for the remediation of indoor and outdoor air pollution (Figure 6) (Kumar et al., 2023b). Green walls provide practical advantages over potted plants for pollution removal due to their greater plant density, vertical alignment, and efficient mechanically-assisted ventilation, which allows polluted air to pass through the substrate and roots (Pettit et al., 2019). It is known that their design allows for potential applications in high-pollution areas like traffic tunnels and carparks, as well as green buildings, achieving energy efficiency equivalent to ventilation and thermal comfort (Tudiwer and Korjenic, 2017).

As such, the use of active green walls in buildings allows for the biofiltration of air, thereby improving indoor air quality, rather than relying on traditional HVAC systems (Darlington et al., 2001). Affordable plant-based solutions, such as potted plants and green walls, can effectively control temperature, improve indoor air quality, and protect against health risks, as they can be combined with biofiltration for efficient air purification (Kumar et al., 2023b). Phytoremediation is a technique involving the use of living plants to remove pollutants from air, water, and soil, aiming to enhance air quality, reduce pollution, and promote soil health (Cunningham et al., 1995; Kumar et al., 2023b). In recent years, several researchers have discussed phytoremediation and its mechanism of cleaning indoor air (Bandehali et al., 2021; Ramya et al., 2021; Kumar et al., 2023a; Kumar et al., 2023b).

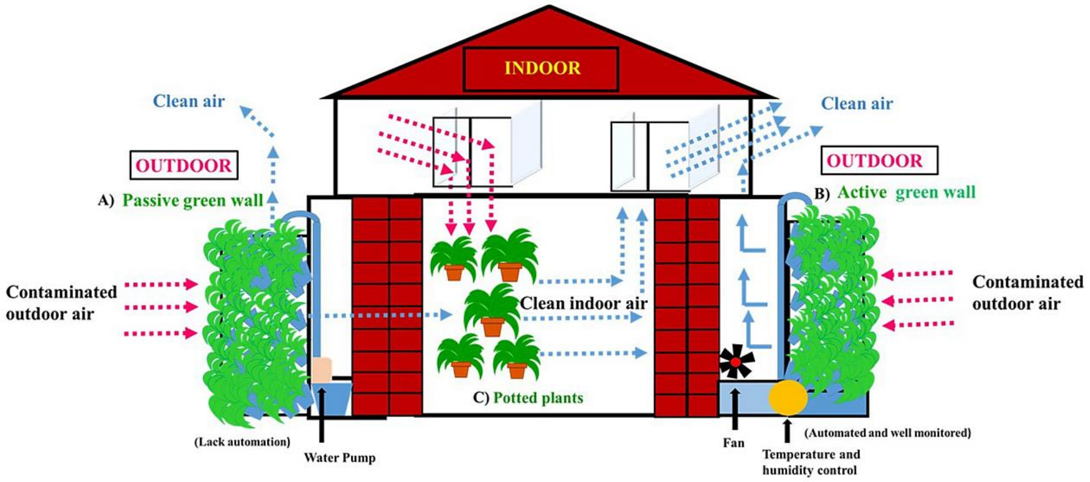

Figure 3: Schematic representation of the purification of outdoor/indoor air through vertical green walls and potted plants [Source: (Kumar et al., 2023b)].

Phytoremediation is a process where plants' aerial parts and phyllosphere microorganisms interact to remove air pollutants via adsorption and biodegradation, thereby enhancing the overall air quality (Kumar et al., 2023b; Maurya et al., 2023). Phytoremediation involves the rhizosphere of plants to remove air pollutants from soil during leaf fall and precipitation, involving mechanisms like phytovolatilisation, phytodegradation, phytostabilisation, rhizodegradation, and rhizofiltration (Lee et al., 2020; Kumar et al., 2023b; Maurya et al., 2023). It is well recognised that plants, microorganisms, and their mutualistic relationships may break down and remove harmful pollutants in the phyllosphere and rhizosphere by using a variety of remediation mechanisms (Maurya et al., 2023).

Plants offer a vast surface area for indoor pollution removal, either through passive systems like potted plants or active green walls, or active systems like plant biofiltration or active green walls, where plants and microbes work together to eliminate gases (Guieysse et al., 2008; Xu et al., 2011; Kumar et al., 2023b; Maurya et al., 2023). Potted plants, live green walls, and green walls in hydroponic systems are just a few of the ways that plants may be used to enhance air quality and offer environmentally friendly solutions (Teiri et al., 2022; Kumar et al., 2023b). In a study, author used a dynamic chamber technique to access the formaldehyde removal capabilities of potted spider plants, aloe, and golden pothos with potted soils (Xu et al., 2011). Findings from the study showed that these systems could remove formaldehyde from air for extended periods, with spider plant-soil systems having the highest removal capacity.

This suggests that daytime metabolisms in plants and microorganisms may contribute to these higher removal capacities (Xu et al., 2011). In a related study, it has been reported that formaldehyde, an indoor pollutant, has been decreased in the environment utilising a combination phytoremediation system of *Bacillus cereus* ERBP and *Clitoria ternatea* (Khaksar et al., 2016). Therefore, plants, microbes, and their mutualistic associations can be green solutions for improving indoor air quality. According to a study, investigation of modern omics technologies is essential for effective understanding of the molecular processes behind plant-based indoor air pollution reduction, and low-cost technologies need to advance further to assure reliability (Kumar et al., 2023b).

Indoor air pollution, including VOCs and fine particulate matter, poses significant health risks, including cancer, leukaemia, and abortion, necessitating the development of technologies to minimize its negative effects. Plants play a significant role in removing VOCs, as they absorb a significant amount of these pollutants (Yue et al., 2021; Maurya et al., 2023). Recent advancements in adsorption materials, such as traditional biochar and metal-organic frameworks, have led to the efficient removal of VOCs and $PM_{2.5}$ using technologies such as adsorption and photocatalytic oxidation (Yue et al., 2021). The effectiveness of biochar and metal–organic frameworks in mitigating volatile organic compounds (VOCs) in indoor air pollution, including photocatalytic oxidation, and the parameters affecting indoor air pollution removal efficiency have been reviewed (Yue et al., 2021).

Indoor exposure to VOCs and SVOCs can negatively impact health, necessitating mitigation efforts using innovative technologies and materials. The development of sustainable materials is a significant challenge in reducing indoor ornamentation containing VOC/SVOC, such as carpets and artificial boards (Yue et al., 2021). The use of bioresidues like sawdust and formaldehyde-free wood composites in hot-pressed self-bonding boards as an alternative to traditional artificial boards is promising (Yue et al., 2021).

Ozone exposure can cause health issues, and addressing indoor ozone levels is crucial to reducing exposure to ozone due to the predominant role of indoor environments in human activity patterns. To decrease indoor ozone levels without indoor sources, two methods can be used: removing ozone from the air and reducing indoor ozone concentration once present (Abbass et al., 2017). Activated carbon-based filters can be used to remove ozone from ventilated indoor air, but the main issue is carbon exhaustion due to irreversible reactions with ozone (Khararoodi et al., 2022). There have been few studies on ozone absorption by indoor plants, including estimates of deposition velocities. In a study, investigated the effectiveness of indoor plants for passive removal of indoor ozone, and the number of plants required for effective ozone removal depends on their size and the leaf surface area they provide (Abbass et al., 2017). Indoor plants have been shown to effectively remove pollutants, including ozone, but their use in ozone removal is a strategy with limited quantitative research (Abbass et al., 2017).

5. CONCLUSION

The continuous discharge of indoor air pollutants, without effective preventative controls and/or regulatory measures, has deteriorated household air quality in various developed and developing countries globally. Indoor air pollutants can significantly increase personal exposure due to prolonged indoor activities like cooking, cleaning, and dust resuspension, and chemical reactions initiated by reactive species like O_3 can also contribute to poor indoor air quality. Indoor sources emit a wide range of pollutants, including gaseous pollutants, inorganic particles, and organic particles, resulting in different toxicities. Although some components of indoor air pollutants are harmless, the detection and characterisation of IAQ are crucial for quantifying health risks due to the scale of exposures, which can be long periods or high concentrations.

Considering the human health effects associated with the sublethal effects of these pollutants, there is a devastating need for time to formulate sustainable, efficient, and eco-friendly technologies to reduce indoor air pollutants for sustainable environmental management. The use of clean fuels and technologies, such as solar, electricity, biogas, LPG, natural gas, alcohol fuels, and biomass stoves, is crucial for reducing household air pollution and protecting health. Addressing indoor air quality in developing countries like Nigeria requires awareness, research, and policy measures. Prioritising health recommendations, supporting environmental government programs, educating the public about clean air benefits, and working with international authorities are essential. Reducing indoor emissions, adopting air pollution prevention and control policies, and developing effective risk mitigation strategies are necessary for a sustainable environment.

Understanding the sources and occurrence of adverse impacts on the environment, human health, and economic burden of poor indoor air quality is crucial for developing effective preventative controls and mitigation strategies. Long-term air quality monitoring is necessary for sustainable environmental management and risk mitigation strategies. The detection and characterisation of some of these indoor air pollutants at trace levels will enable researchers to understand the environmental fate and behaviour of various indoor air pollutants. The detection and characterisation of indoor air pollutants will begin with the development of sensitive and cost–effective, robust methods and long-term monitoring for sustainable environmental management and cost-effective risk mitigation strategies. Sustainable environments necessitate reducing indoor emissions, implementing air pollution prevention and control policies, and developing effective risk mitigation strategies by both developed and developing countries. Therefore, there is a need for governments worldwide to promote clean air policies, strategies, and plans that can reduce air pollution emissions and consequently improve indoor air quality.

CONFLICT OF INTEREST

i. The authors declare that they have no conflict of interest.

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