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Health at Risk: Respiratory, Cardiovascular, and Neurological Impacts of Air Pollution

Md Habibur Rahman[1,*], Sadia Afrin Dipa[2], Kamrul Hasan[3], Md Minzamul Hasan[4]

[1] Department of Management, International American University, USA; rahman@aub.ac.bd.
[2] Department of Mathematics, The University of Texas at Arlington, USA; dipacoumath@gmail.com.
[3] Department of Economic Data Analytics, The University of Texas at Arlington, USA; kamrul.hasan@uta.edu.
[4] Department of Business Administration, International American University, USA; m.hasan.2958@westcliff.edu.

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Abstract

Air pollution has become one of the most pressing issues in the twenty-first century, with massive effects on the environment and human health. Air pollution is a complex cause of morbidity and mortality that contributes to respiratory and cardiovascular diseases, cancer, neurological impairments, and adverse perinatal outcomes. Air quality can be compromised by Particulate Matter (PM), ground-level ozone, nitrogen oxides, sulfur dioxide, carbon monoxide, Volatile Organic Compounds (VOCs), heavy metals, and persistent organic pollutants, which contribute to climate change and ecosystem instability. The effects extend beyond individual health to affect agricultural productivity, biodiversity, and the distribution of infectious diseases. Solving this crisis correlates with several United Nations Sustainable Development Goals (SDGs), including SDG 3 (Good health and well-being), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on land). Despite international policies like the Paris Climate Accord, a gap persists between high- and low-income nations in exposure, vulnerability, and adaptive capacity. Technological innovations, regulations, and community interventions have shown potential for cutting emissions, but must be included in larger sustainable development plans. This review summarizes evidence on the environmental and health consequences of air pollution, highlighting the need for interdisciplinary methods that combine population health, environmental science, and policy. The world needs a response to enhance environmental governance, ensuring equal access to clean energy and public consciousness to reduce air pollution as a health hazard and environmental determinant. Air pollution affects ecosystems and people and remains key to meeting the SDGs and achieving a sustainable future.

Keywords: Air pollution, Sustainable development goals, Climate change, Environmental policy, Global health equity.

1 | Introduction

Air pollution has become one of the defining issues of the current century, with far-reaching and interrelated impacts on human health, ecosystems, and sustainability worldwide. The rates of industrialization,

Corresponding Author: rahman@aub.ac.bd
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urbanization, and energy consumption have hastened the emission of pollutants, including Particulate Matter (PM), ozone, nitrogen oxides, sulfur dioxide, Volatile Organic Compounds (VOCs), heavy metals, and dioxins [1–3]. These chemicals accumulate in the atmosphere and interact with the climate system, exacerbating the twin risks of environmental degradation and climate change. The medical effects are far-reaching, with acute respiratory infections and cardiovascular incidents, as well as chronic diseases such as asthma, Chronic Obstructive Pulmonary Disease (COPD), cancer, and neurodevelopmental disorders [4–6]. The worldwide cost is mind-boggling, as it is estimated that the health burden of air pollution costs approximately nine million deaths annually worldwide, making air pollution one of the most significant environmental factors of health and disease in the world. In developing countries, the populations at higher risk are those who are vulnerable, such as children, the elderly, and low-income populations, due to increased exposure and low adaptive capability [7], [8]. In addition to health, air pollution interferes with agricultural productivity, biodiversity, and food security, causes extreme climate events, and changes the patterns of infectious diseases [6], [9]. Consequently, air pollution has not only been a local environmental risk but also a global crisis, which is directly defying the gains made towards sustainable development.

Air pollution has complex origins, mainly due to human activities such as the burning of fossil fuels, industrial activities, transport, farm activities, and household energy consumption. Motor vehicles contribute to a significant portion of emissions in urban areas; however, industrial facilities, power plants, and residential biomass burning contribute large fractions of PM, carbon monoxide, sulfur dioxide, and nitrogen oxides [10–12]. This is also caused by natural occurrences such as volcanic eruptions, dust storms, and forest fires, but their comparative significance is not as significant as the continuing human-induced causes. Indoor air pollution is an acute issue in low-income areas due to cooking and heating with solid fuels, which exposes women and children to extended exposure to toxic particulates [13], [14]. These emissions have far-reaching and compounding effects. There is acute respiratory distress, increased hospitalization, and diminished productivity due to short-term exposure and chronic respiratory disease, cardiovascular morbidity, adverse pregnancy outcomes, neurodevelopmental delays, and premature mortality, which are closely linked to long-term exposure. In addition to its impact on health, air pollution disrupts ecological stability by acidifying soil and water, reducing crop production, and contributing to biodiversity loss [15–17]. It also increases the rate of climate change and extreme weather events, as well as alters the pattern of infectious diseases. This tenacity and increase in air pollution levels are factors that warrant a new form of scientific interest, as the effects of air pollution are coming to the fore and intersect with the growing crisis of climate change [18–20].

Despite regulatory progress, global emissions remain alarmingly high, and the disparity between developed and developing nations is widening. Disproportionate exposure and health risks are caused in low-and middle-income countries that lack environmental infrastructure, have a high dependency on biomass fuels, and are characterized by rapid urbanization [21], [22]. Meanwhile, even high-income countries are facing issues such as traffic overload, industrial emissions, and an increase in greenhouse gas levels. This dichotomy emphasizes the international and acute nature of the issue [23], [24]. This review can be explained in two ways. First, air pollution not only causes ill health but also ecological imbalance and climate disruption. Pollutants such as PM, sulfur oxides, and black carbon exacerbate global warming and degrade natural systems [25–27]. Second, direct measures against air pollution promote several of the United Nations Sustainable Development Goals (SDGs): SDG 3 (Good health and well-being) through decreasing morbidity and mortality, SDG 11 (Sustainable Cities and Communities) through cleaner urban areas, SDG 13 (Climate Action) through the reduction of emissions, and SDG 15 (Life on land) by protecting the ecosystem [14], [21], [28], [29]. Thus, it is necessary to synthesize the existing evidence to inform integrated approaches that connect health, the environment, and sustainability.

The overall goal of this review is to develop an in-depth synthesis of existing information regarding the environmental and health effects of air pollution, and specifically focus on its interrelatedness with climate change and sustainable development. This study aims to elucidate the multifaceted burden of air pollution by synthesizing evidence on the sources of pollutants, their exposure pathways, and their far-reaching impacts on human health and ecosystems. It is not only descriptive but also analytical in its goal of pointing out how air pollution damages the achievement of several SDGs. In particular, the review highlights contributions to SDG 3 (Good health and well-being) in the form of disease prevention, SDG 11 (Sustainable cities and communities) in the form of better air quality in cities, SDG 13 (Climate action) in the form of reduced emissions, and SDG 15 (Life on Land) in the form of preserved biodiversity and ecosystems [30–33]. By doing so, this paper seeks to educate policymakers, researchers, and other professionals in the field of public health about the dire need for integrated, interdisciplinary approaches that cut across health, environmental governance, and social equity. Finally, the review places air pollution as a topical community health concern, but also as one of the key obstacles on the way to a sustainable and resilient future.

2 | Approach to the Problem

Pollution can be defined as the introduction of dangerous materials into the atmosphere in quantities that endanger human health, ecosystems, and the general state of the environment [2], [34]. These materials can be found in solid, liquid, or gaseous forms and can be either natural or anthropogenic. The common types of pollutants include primary and secondary pollutants. Primary pollutants are emitted directly by identifiable sources, such as combustion engines, industrial activities, or biomass burning, and secondary pollutants result when the influences of primary pollutants undergo chemical reactions, such as ozone or fine PM [3], [4], [8]. Pollution manifests in several forms from an environmental perspective. Air pollution is defined by the presence of the following pollutants: PM, nitrogen oxides, sulfur dioxide, carbon monoxide, VOCs, and aerosols that harm atmospheric quality [18]. Water pollution occurs when the level of organic, inorganic, or biological loads exceeds the limits of nature and affects aquatic ecosystems and safe human consumption [7], [10]. Heavy metals, hydrocarbons, and pesticides are deposited in the soil, causing pollution, altering soil chemistry, and lowering fertility [12], [13]. Other notable forms of pollution include radioactive pollution, which is caused by accidents or waste at nuclear plants, and polluted air, soil, and water [13], [22], and noise pollution, caused by industry and transportation, which has its own impact on the health of the population [19]. Collectively, these forms of pollution underscore their multidimensional character and profound consequences for sustainability and human well-being.

The process of increasing environmental pollution may be dated back to the Industrial Revolution, as the process of mechanizing, burning coal in large amounts, and urbanization became a turning point in human relations with the environment [15], [16]. Although industrialization has revolutionized economies and societies through increased technological innovation and service delivery, it has produced unprecedented amounts of pollutants that have been released into the air, water, and soil [11]. To a large extent, these emissions were uncontrollable in the initial phases of industrialization, resulting in serious health crises and ecological deterioration. The most notable case is the Great London Smog of 1952, where accumulated sulfur dioxide and smoke cost the lives of approximately 4,000 people in a few days [17], [25]. This and other pollution-related death incidents were reported later in New York City in 1963, where hundreds of people died after exposure to toxic mats [29]. The problem became more complicated as industrialization spread worldwide. Urbanization and the large-scale use of fossil fuels as a means of transportation and energy production have worsened the emission of PM, nitrogen oxides, and VOCs [3], [10]. Pollutants not only destroy respiratory and cardiovascular functions but also cause climate change, biodiversity loss, and agricultural decline [5], [25]. At the end of the twentieth century, air pollution became a worldwide health crisis among the population, and its effects are deeply connected with social and economic growth. The impacts of industrialization are still visible today, as industrial activity, energy demands, and urbanization still determine the magnitude and intensity of air pollution in numerous parts of the world [14], [35].

Air pollution is a major environmental determinant of disease and early death worldwide. Current estimates indicate that the number of deaths due to anthropogenic air pollution is approximately nine million per year, making it a significant global health crisis [2]. Acute respiratory and cardiovascular complications linked to short-term exposure to high concentrations of pollutants, such as atmospheric particles PM, sulfur dioxide, and ozone, have been repeatedly associated with elevated hospitalization rates [26], [31]. This burden is further increased by the fact that long-term exposure contributes to chronic diseases such as asthma, COPD, cardiovascular disease, diabetes, and even cancer [1], [12], [36]. The load is not evenly distributed over the areas. Unchecked urbanization, dependence on biomass energy in households, and a lack of environmental control expose developing nations to the increased dangers of indoor and outdoor air pollution [22], [29]. Conversely, in developed countries, even with more robust regulatory frameworks, high mortality is still associated with fine PM and traffic-related emissions [15], [37]. A direct relationship has been demonstrated between daily mortality rates and daily particulate concentrations in various geographic settings, both past and present [9]. This fact shows the harsh and persistent impact of air pollution on health on the planet, stressing that it is a local and transboundary risk factor that increases social and economic inequalities and hampers sustainable development.

Air pollution is a heavy burden that is closely connected to the trends of social inequity, high-speed urbanization, and sustainability issues. Low- and middle-income countries are at greater risk because of overpopulation, rapid industrialization, and dependence on solid fuels to meet household demands, placing women and children at a disproportionately high risk of indoor air pollution [10], [15]. Biomass heating and cooking in places such as India and Nepal continue to be a significant source of respiratory diseases and early mortality, with women and young children suffering the most health burden [32], [33]. Similarly, major cities such as New Delhi have unhealthy air, which is caused by industrialization, automobile pollution, and weather patterns that lead to severe pollution events [18], [15]. Conversely, developed countries record increased rates of cardiovascular diseases related to prolonged exposure to pollution, which highlights that exposure levels are not the only factor that influences vulnerability and that it is also influenced by the socioeconomic environment [34]. Such inequalities demonstrate how environmental pollution has increased social inequities and restricted access to clean air and healthy environments. In addition, unregulated urbanization and reliance on fossil fuels have a direct negative impact on sustainability, undermining progress in SDG 3 (Good Health and Well-Being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Therefore, to address air pollution, solutions must combine equity, urban planning, and sustainable development.

3 | Sources of Exposure

Most air pollutants result from large-scale human activities, with the main sources being industry, transport, agriculture, and households. Industrial processes such as power generation, oil refining, petrochemical production, fertilizer and metallurgical industries, and municipal waste incineration release significant volumes of sulfur dioxide, nitrogen oxides, PM, and heavy metals into the atmosphere [3], [7], [37]. Another essential source is transportation emissions, as automobiles, railways, and air traffic contribute almost 80% of the current air pollution in urban centers [4], [20]. Road traffic produces fine and ultrafine particulates, nitrogen oxides, and VOCs that accumulate in highly populated cities and have a direct effect on respiratory and cardiovascular health [14], [19]. Field cultivation practices, animal farming, and the use of fertilizers and pesticides in agriculture also contribute to this, as they emit ammonia, methane, and other reactive gases into the air [24]. Another burden is household activities, particularly in low- and middle-income countries. The extensive use of solid fuel cooking and heating-wood, coal, and crop residues–subjects women and children to extended health risks by exposing them to dangerous levels of indoor air pollutants [25], [26], [38]. Together, these human-made sources underline that the combination of industrialization, urban transport, agricultural intensification, and energy poverty all combine to fuel the increasing air pollution burden around the world.

Despite the overwhelming presence of anthropogenic sources that dominate air pollution on the planet, natural sources are also significant contributors to atmospheric quality. Volcanic eruptions cause a significant amount of gases, such as sulfur dioxide, carbon dioxide, and PM, which may then be distributed over a vast space and in the process cause short-term respiratory issues and long-term climatic impacts [6]. Naturally occurring forest fires and those caused by humans release smoke containing carbon monoxide, nitrogen oxides, VOCs, and fine particulates, which may travel over long distances and compromise the air quality in a region [17]. Likewise, dust storms formed in arid and semi-arid areas contain mineral particles that influence visibility, respiratory well-being, and even climatic patterns. Agricultural burning seasonally is also included here and therefore leads to acute pollution episodes that unite natural processes with human activities [7], [8]. Although the rate and intensity of these natural occurrences differ across geographical distributions and times, their health and environmental effects are serious, especially when coupled with anthropogenic emissions. Volcanic eruptions, massive wildfires, and dust storms may disproportionately affect local ecosystems and health care, highlighting the fact that natural sources still contribute to the global air pollution threat [3].

Air pollution is traditionally divided into outdoor (Ambient) and indoor categories, each of which has different sources and health outcomes. Industrial practices, electricity and power production, transport, and extensive farming activities are the major contributors to outdoor pollution, releasing pollutants such as PM, nitrogen oxides, sulfur dioxide, ozone, and VOCs into the air [22], [27], [39]. The emissions are more concentrated in cities where vehicles and industrial clusters increase exposure levels and tend to exceed the recommended air quality guidelines [13], [20]. Its health impacts include hospitalization due to respiratory and cardiovascular diseases, long-term chronic illness development, and early death [11], [40]. Although it is not widely acknowledged, indoor pollution is a significant threat, particularly in low- and middle-income nations. Reliance on biomass fuels, such as wood, coal, and crop residues, for cooking and heating exposes households to hazardous concentrations of smoke and fine particulates [29], [33]. Women and young children are disproportionately affected, as they spend more time indoors and experience acute lower respiratory infections, chronic obstructive respiratory diseases, and lung cancer [12]. Indoor pollution in most developing areas is usually higher than outdoor pollution, which explains its importance as a global health burden. Collectively, indoor and outdoor pollution depict the ubiquity of air pollution in environments.

The effects of air pollution highlight noticeable differences between developed and developing nations, demonstrating disparities in industrialization, energy consumption, and regulatory frameworks. Poor air quality in developing countries is mainly due to uncontrolled urbanization, a high rate of population increase, and the use of biomass fuels as a source of domestic energy [37], [40]. Of special interest is indoor air pollution, where women and children are exposed to smoke produced by solid fuels, and there is a high prevalence of respiratory diseases and chronic illnesses [24], [31]. Countries such as India document dangerous concentrations of PM, with concentrations in the northern parts being significantly higher than those in the southern parts due to climatic variations and heating requirements [12], [15]. Likewise, it has been reported that the increased mortality of lung cancer related to fine particles is attributed to the rapid industrialization of China [7], [9]. Conversely, developed nations tend to enjoy the advantage of more stringent regulations and cleaner energy technology systems, but still report large amounts of health costs. Fine PM and traffic-related emissions are strongly related to cardiovascular morbidity and mortality in high-income countries [17], [19]. These inequalities demonstrate the influence of socioeconomic status, policies, and technology on the air pollution load worldwide. Such inequities must be addressed to promote environmental justice and SDGs.

Air pollution is facilitated by a highly complex set of chemical and physical factors out of which the most facet of it is posed by the PM, ground-level Ozone (O3), Carbon Monoxide (CO), Nitrogen Oxides (NO2) and sulfur dioxide (SO2), lead, VOCs, PAHs, and dioxins, which constitute the most severe threats to human health and the environment. PM, particularly fine and ultrafine fractions (PM2.5 and PM10), infiltrates long distances into the lungs and even the bloodstream, leading to acute respiratory illnesses, cardiovascular diseases, and chronic risks, such as COPD, cancer, and infant deaths [10], [12]. Likewise, although beneficial in the stratosphere, ozone is toxic at low altitudes, exacerbating respiratory and cardiovascular morbidity, decreasing agricultural productivity, and causing ecosystem disturbances [2], [22], [40]. Carbon monoxide is an invisible gas that occupies hemoglobin to a greater extent than oxygen, producing hypoxia, nervous system harm, and cardiovascular illness, and excessive exposure results in acute toxicity [23], [41]. Massive amounts of nitrogen oxides released by motor engines irritate the lungs and weaken the immune system, in addition to harming crops and worsening visibility [34]. Sulfur dioxide is formed mainly when fossil fuels are burned; it causes bronchospasm, irritation to the eyes and skin, acid rain, acidification of soil, and loss of crops [26], [38]. Together, these pollutants undermine human health, disrupt climate regimes, enhance extreme weather, and hasten the loss of ecosystems.

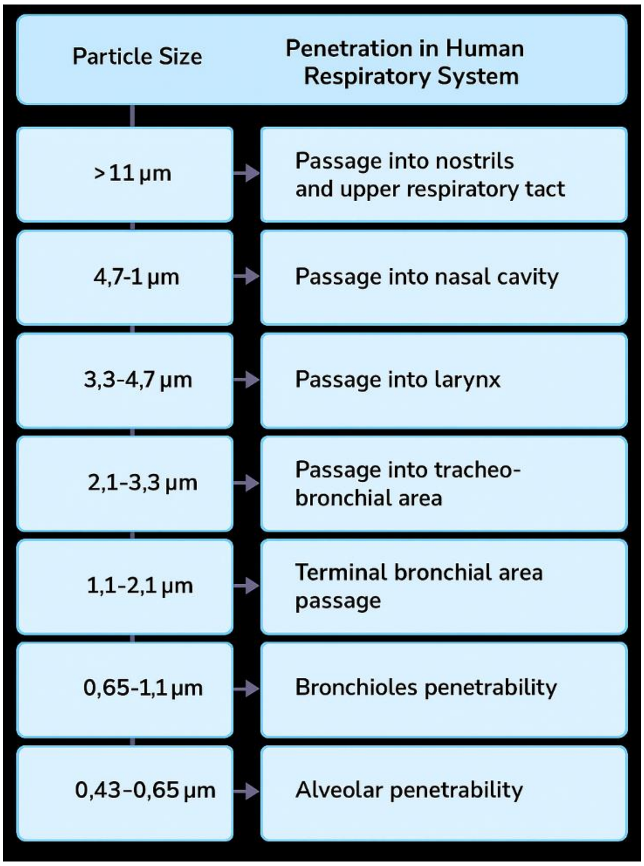

Fig. 1. Penetrability according to particle size.

In addition to gaseous pollutants, heavy metals and persistent organic compounds pose severe long-term risks. Lead, which is still emitted from specific industrial processes and small-scale engines, accumulates in the blood, soft tissues, and bones, causing neurodevelopmental disorders in children, impaired memory, cardiovascular disease, and reproductive toxicity [14], [19], [26]. Prenatal exposure is particularly dangerous, as lead crosses the placenta and disrupts fetal brain development [28]. Polycyclic Aromatic Hydrocarbons (PAHs), which are generated through the incomplete combustion of organic matter, are widespread in air, soil, and water. Compounds such as benzopyrene are recognized as mutagenic and carcinogenic and are strongly linked to lung cancer [33]. VOCs, including benzene, toluene, and xylene, accumulate indoors and outdoors, causing mucosal irritation, neurological symptoms, and elevated cancer risk [25], [30]. Dioxins, which originate from industrial activities, forest fires, and volcanic eruptions, bioaccumulate in animal fat and human tissues, causing skin lesions, endocrine disruption, reproductive disorders, and cancer [40]. The persistence of these pollutants in air, soil, and water exemplifies the transboundary nature of environmental hazards, illustrating how air pollution undermines multiple SDGs by threatening health (SDG 3), ecosystems (SDG 15), food security (SDG 2), and climate stability (SDG 13). Addressing these pollutants requires coordinated regulation, technological innovation, and global cooperation to mitigate both immediate health risks and long-term environmental damage caused by these pollutants.

Table 1. Types and sizes of PM.

Type of PM	Size Range (μm)	Characteristics/Behavior
Coarse particles (PM_{10})	2.5 – 10 μm	Deposited in the upper airways (Nose, throat); less able to reach the alveoli
Fine particles ($PM_{2.5}$)	≤ 2.5 μm	Penetrate deeply into bronchioles and alveoli; associated with respiratory and cardiovascular diseases
Ultrafine particles ($PM_{0.1}$)	≤ 0.1 μm	Pass through alveolar walls into the bloodstream; reach multiple organs, including the brain and heart
Total Suspended Particles (TSP)	≤ 100 μm	Includes all airborne particles; larger ones settle quickly, smaller remain suspended longer

4 | Health Impacts of Air Pollution

Air pollution has both short- and long-term impacts on human health, and it has been proven to be a contributing factor to a broad range of respiratory and cardiovascular diseases, as well as neurological and reproductive illnesses. Acute symptoms (Coughing, wheezing, chest tightness, asthma attacks, and shortness of breath) have been linked to short-term exposure to high levels of pollutants such as PM (PM2.5, PM10), nitrogen oxides, ozone, and sulfur dioxide [5], [8]. The effects are especially severe in vulnerable populations, including children, the elderly, and people with underlying conditions, which tend to lead to higher hospitalization and death rates among people and groups during periods of poor air quality [2], [11], [20]. In addition to respiratory effects, cardiovascular effects, including hypertension, stroke, and arrhythmia, have been observed to be caused by short-term exposure to high levels of PM and gaseous pollutants [1], [14]. In addition, there is the development of transient neurological symptoms that include feeling dizzy, headaches, and fatigue, which is a common occurrence in regions of high air pollution, especially with high amounts of carbon monoxide [31]. Such acute reactions emphasize the widespread and direct menace of unclean air on human health, as daily changes in pollutant concentrations can be directly converted into morbidity and mortality.

Excessive exposure to air pollution over long periods adds to the burden of disease by augmenting the development of chronic and frequently irreparable illnesses. Sustained exposure to PM, traffic emissions, and industrial pollutants is associated with epidemiological evidence of COPD, pulmonary insufficiency, and lung cancer [16], [34]. Cardiovascular outcomes are also of high importance, where chronic exposure to fine particulates and nitrogen oxides is linked to coronary arteriosclerosis, myocardial infarction, and heart failure [10], [20]. Neurodegenerative diseases such as Alzheimer's and Parkinson's diseases, cognitive decline, and developmental delays in children have also been implicated in neurological outcomes due to air pollution [2], [6]. Mechanistic pathways include oxidative stress, systemic inflammation, mitochondrial damage, and protein aggregation inside neurons, which have been identified in human and animal research [1], [3], [5]. Notably, maternal exposure during pregnancy is linked to poor fetal development, low birth weight, and a high likelihood of autism spectrum disorders, whereas early childhood exposure leads to behavioral disorders, low intelligence, and hyperactivity, especially with lead exposure [24], [40]. These results provide insight into the long-term effects that not only have on individuals throughout their lives but also lead to the continuation of health inequities across generations. The extent of health outcomes also includes dermatological and ocular diseases, immune dysfunction, systemic disorders, and respiratory, cardiovascular, and neurological diseases.

Pollutants caused by traffic, including PAHs, VOCs, and fine particulates, also cause skin aging, pigmentation, acne, eczema, psoriasis, and, in the extreme, skin cancer [28], [38]. Similarly, exposure to suspended particulates and chemical irritants is linked to eye irritation, retinopathy, and dry eye syndrome [10], [19]. Air pollutants have also been demonstrated to impair immune activity by changing antigen presentation and upregulating inflammatory responses, thus predisposing people to infections and autoimmune diseases [25], [26]. Psychological and developmental effects are also becoming critical and have been associated with autism, depression, and other behavioral issues that emerge in children, which are aggravated mainly by the socioeconomic gap that hinders access to protective measures [30], [31]. These results lead to the conclusion that the health burden of air pollution is not limited to certain systems but is multidimensional and systemic, and it concerns almost all organs of the human body.

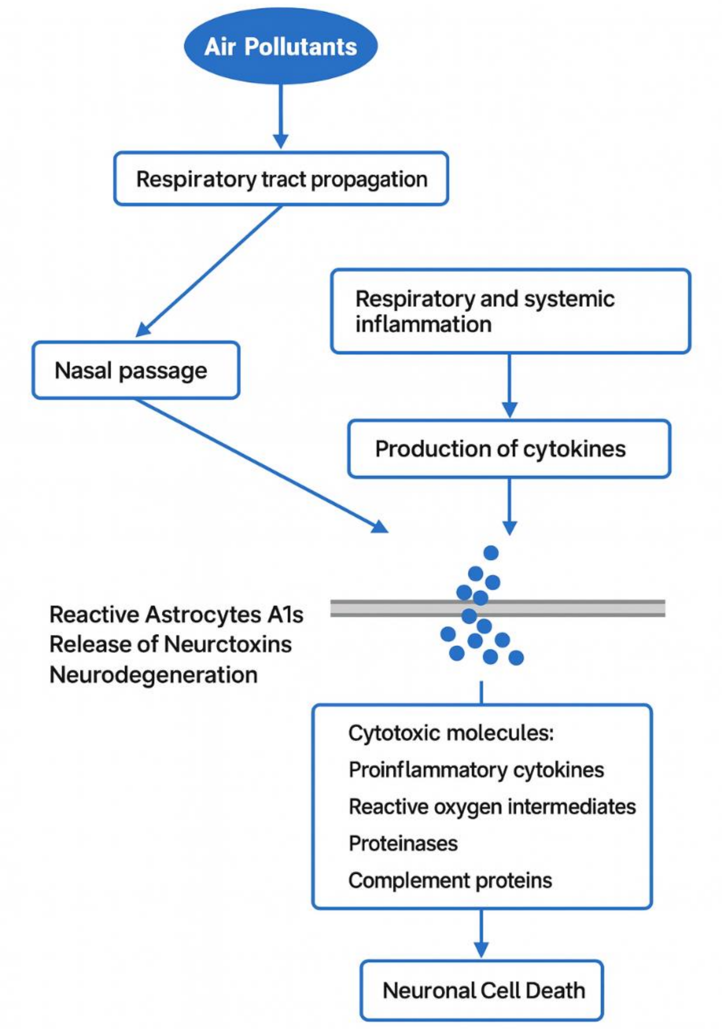

Fig. 2. Impact of air pollution on the brain.

This complexity highlights why air pollution is now recognized as a "silent public health emergency" [6], undermining progress toward SDGs by increasing premature mortality (SDG 3), deepening inequality (SDG 10), and straining healthcare systems globally.

5 | Environmental Impacts of Air Pollution

The natural environment is greatly affected by air pollution, which can result in a lack of atmospheric chemistry, soil fertility, water quality, and stability of ecosystems. A more important consequence is the production of acid rain, caused by the interactions of sulfur Dioxide (SO2) and nitrogen Oxides (NO2) with water vapor to form sulfuric and nitric acids [19], [22]. Acid rain is harmful to plants and trees and makes lakes and rivers acidic, where aquatic life and biodiversity could be in danger. Food security is another issue that causes widespread damage to agricultural output as a result of the leaching of nutrients from soils when they are exposed to acid rain, which poses a greater burden on agricultural production, disproportionately impacting low-income groups [14], [15]. Furthermore, the formation of smog, especially photochemical smog caused by ozone in the atmosphere at ground level, lowers visibility and destroys natural and artificial surroundings. The long-term effects of high ozone concentrations on the physiology of crops hinder the growth and yield of major staple crops, including wheat, rice, and maize [27], [41]. The direct effects are agricultural sustainability and food supply chains, which tie air pollution to environmental and economic instability at a wider level. Moreover, atmospheric radiation balance is also disturbed by pollutants such as PM and black carbon, which affect how temperature is regulated and how precipitation is distributed, thus accelerating climate variability and severe weather [7], [37].

In addition to atmospheric interactions, chronic contaminants, including heavy metals, PAHs, VOCs, and dioxins, pose a long-term danger to soil and water systems. Lead, mercury, and cadmium are deposited in soils and reach food chains, resulting in bioaccumulation and biomagnification in plants and animals, and eventually in humans [33], [40]. Long-lasting organic pollutants, such as dioxins and PAHs, pose a threat to soil, sediment, and aquatic environments, where they persist for decades because of their chemical stability [35], [36]. These chemicals interfere with reproduction and endocrine processes in wild animals, cause genetic mutations, and threaten aquatic biodiversity in terms of growth, reproduction, and survival [14], [18]. The deposition of airborne particulates on the earth and water bodies also inhibits the photosynthetic process of plants and phytoplankton, contaminating ecosystem productivity and carbon sequestration potential. These disturbances undermine the resilience of ecosystems and increase the difficulty of climate change (Biodiversity loss), directly connecting air pollution to the decline in ecosystem services vital to human livelihoods [6], [13], [17].

The ecological impacts of air pollution also overlap with the greater problems of sustainable development and climate change. Short-lived climate forcers, including black carbon and ozone, contribute to global warming, and aerosols and particulates affect cloud formation and precipitation cycles, causing regional climate imbalances [42], [33]. The loss of biodiversity caused by acid rain, ozone, and toxic pollutants affects SDG 15 (Life on Land). It leads to low crop yields and aquatic deterioration, which hinders the achievement of SDG 2 (Zero Hunger). In addition, air pollution increases the susceptibility of disadvantaged groups, especially those who rely on subsistence farming, fisheries, and forest ecosystems to support their lives. By doing so, the environmental effects of air pollution go beyond ecological degradation to include aspects of poverty, inequality, and climate resilience, directly undermining the achievement of a variety of SDGs, such as SDG 3, SDG 11, SDG 13, and SDG 15. These issues need to be handled through a unified system involving not only emission mitigation but also ecosystem restoration and climate adaptation measures so that environmental sustainability and human welfare work in harmony.

6 | Discussion

The evidence presented in this review underscores the multifaceted nature of air pollution, which is both a public health crisis and an environmental threat. The findings reveal that air pollution is not confined to a single region, pollutant, or health outcome, but instead represents a globalized, systemic challenge. Short-term exposures trigger acute respiratory and cardiovascular events, while long-term exposures drive chronic diseases, neurological decline, and intergenerational health inequities [1], [6], [30]. Simultaneously, pollutants degrade ecosystems through acid rain, crop loss, biodiversity decline, and climate destabilization [15], [40], [31]. What emerges is a picture of air pollution as a silent but pervasive determinant of global health, environmental sustainability, and social equity. This underscores why air pollution is described as both a local hazard—disproportionately burdening marginalized groups—and a transboundary issue that crosses national borders, impacting regional and global systems alike [37], [20].

A key insight is the interplay between urbanization, inequality, and environmental governance. Rapidly expanding megacities in low- and middle-income countries face critical challenges as industrial growth and reliance on solid fuels intersect with weak regulatory enforcement, resulting in extreme levels of indoor and outdoor pollution [10], [12]. Meanwhile, even high-income nations with established environmental regulations continue to struggle with traffic-related emissions, fine particulate exposure, and the chronic health burden of air pollution [29], [24]. These disparities highlight air pollution not only as an environmental determinant but also as a reflection of structural inequality. Vulnerable populations—women, children, older adults, and those in lower socio-economic strata—are consistently at higher risk, revealing air pollution as a matter of environmental justice as much as public health. Integrating air quality interventions with equity-focused policies thus becomes essential for sustainable progress.

Moreover, the linkages between air pollution and the SDGs provide a broader framework for understanding its urgency. Reducing air pollution directly advances SDG 3 (Good Health and Well-being) by lowering mortality and morbidity, SDG 11 (Sustainable Cities and Communities) through cleaner urban planning, SDG 13 (Climate Action) by mitigating short-lived climate forcers such as black carbon, and SDG 15 (Life on Land) by protecting ecosystems. The cross-sectoral nature of air pollution suggests that interventions yield co-benefits. For example, transitioning to renewable energy reduces both greenhouse gas emissions and particulate pollution, while sustainable agriculture protects food systems and reduces ammonia emissions [39], [34]. This multidimensional perspective underscores that combating air pollution cannot be siloed; it necessitates interdisciplinary strategies that integrate public health, environmental science, urban planning, and climate policy.

6 | Policy Response and Governance

Efforts to reduce air pollution have taken shape at both the international and national levels, reflecting a growing recognition of its pervasive health and environmental consequences. Internationally, agreements such as the Kyoto Protocol and the Paris Climate Accord have emphasized the reduction of greenhouse gas emissions, indirectly targeting pollutants like black carbon, nitrogen oxides, and sulfur dioxide that contribute simultaneously to climate change and poor air quality [8], [32]. At the same time, the World Health Organization (WHO) has developed global air quality guidelines, providing evidence-based benchmarks for pollutant concentrations to protect human health [4], [16]. These frameworks highlight the importance of aligning air quality management with climate policies, as reducing fossil fuel combustion yields immediate co-benefits for both public health and climate stabilization. However, despite these global initiatives, enforcement remains uneven, with significant gaps between high-income and low- and middle-income countries. Developed regions often implement robust emission standards and monitoring networks, while resource-constrained nations continue to struggle with regulatory capacity, resulting in persistently high exposures [3], [8]. This divergence underscores the importance of international cooperation, financial support, and technology transfer to bridge inequalities and enable sustainable progress across diverse socio-economic contexts.

At the national and local levels, governments have employed a variety of regulatory, technological, and behavioral interventions to mitigate air pollution. Regulatory measures include emission standards for vehicles and industries, fuel quality regulations, and bans on biomass burning in urban areas [7], [9], [11]. Technological solutions, such as catalytic converters, renewable energy adoption, and waste-to-energy conversion, have demonstrated measurable reductions in pollutant loads. Innovations in air quality monitoring and satellite-based surveillance have also enhanced accountability [1], [5], [17]. Public health campaigns and community-based interventions also play a vital role, particularly in reducing indoor pollution by promoting cleaner cooking technologies, such as liquefied petroleum gas or solar energy, in low- and middle-income countries [2], [3], [6]. Yet, challenges persist: urban traffic congestion, uncontrolled industrial growth, and reliance on fossil fuels undermine policy effectiveness, while weak governance structures often hinder enforcement. Moreover, the health and economic costs of air pollution—ranging from increased healthcare expenditures to reduced workforce productivity—are often undervalued in policy prioritization, leading to slow progress.

To achieve long-term sustainability, governance approaches must adopt an integrated and equity-focused framework that aligns environmental protection with social development. Air pollution reduction should not be viewed solely as an environmental challenge but as a pathway to achieving multiple SDGs. For example, transitioning to renewable energy simultaneously reduces greenhouse gas emissions and improves air quality (SDG 7 and SDG 13), while sustainable urban planning enhances livability and equity in cities (SDG 11). Strengthening global and regional governance, fostering interdisciplinary collaboration, and promoting active public participation are critical to ensuring that policies are both practical and equitable. Importantly, addressing air pollution requires recognizing it as a matter of environmental justice, where vulnerable groups deserve targeted protection and access to cleaner energy, transportation, and healthcare resources. Without such integrated action, air pollution will continue to undermine health, accelerate climate change, and hinder sustainable development globally.

7 | Conclusion and Future Research Directions

Air pollution remains one of the most pressing global challenges of the twenty-first century, with consequences that extend across human health, ecosystems, and climate systems. Both short-term and long-term exposures to pollutants such as PM, ozone, nitrogen oxides, sulfur dioxide, and persistent organic compounds contribute to a wide range of health outcomes, including respiratory and cardiovascular disease, cancer, neurological disorders, and adverse pregnancy outcomes. Beyond its impact on health, air pollution destabilizes ecosystems through acid rain, crop yield losses, biodiversity decline, and climate forcing, further threatening food security and environmental sustainability. The burden is not evenly distributed: low- and middle-income countries experience disproportionately higher exposures due to reliance on biomass fuels, weak regulation, and rapid urbanization, while even high-income nations continue to face the health costs of traffic and industrial emissions. These findings highlight that air pollution is both a transboundary hazard and a matter of environmental justice, directly undermining progress toward the SDGs, particularly those related to health, sustainable cities, climate action, and ecosystem protection.

Looking ahead, future research and policy must move beyond sectoral approaches to embrace integrated, interdisciplinary, and equity-driven strategies. Investments in renewable energy, clean transportation, and sustainable agriculture not only mitigate emissions but also yield co-benefits for public health, climate resilience, and economic productivity. Strengthening governance through robust regulatory frameworks, global cooperation, and technology transfer is crucial for bridging the disparities between developed and developing regions. At the same time, expanding monitoring systems, including the use of satellite technologies and machine learning approaches, can enhance data-driven decision-making and accountability. Public awareness and community-level interventions remain critical, particularly in reducing indoor air pollution and protecting vulnerable populations. Ultimately, tackling air pollution is not only about improving air quality but about securing a healthier, fairer, and more sustainable future. Recognizing its intersection with multiple SDGs underscores that reducing air pollution is both a public health imperative and a cornerstone of sustainable development.

Conflict of Interest Disclosure

The authors declare they have no competing interests as defined by the journal, or other interests that might be perceived to influence the results reported in this paper.

Data Access

Anonymized data can be requested from the corresponding author following journal data sharing policies.

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References

[1] Ridwan, M., Al Jubayed, A., Kayser, K. A., Ahmed, M. E., Chowdhury, R. R., Hassan, M. R., … & Kanij, H. N. (2025). Examine the role of political stability and education toward green economy: An empirical evidence for bangladesh. *Environment, innovation and management*, *1*, 2550011. https://doi.org/10.1142/S3060901125500115

[2] Uddin, M. K., Akter, S., Das, P., Anjum, N., Akter, S., Alam, M., … & Pervin, T. (2024). Machine learning-based early detection of kidney disease: a comparative study of prediction models and performance evaluation. *International journal of medical science and public health researc*, 5(12), 58-75. https://doi.org/10.37547/ijmsphr/Volume05Issue12-05

[3] Hasan, M., & Sifat, A. I. (2025). Influencers' impact on consumer engagement and sales conversion on social media: Facebook vs Instagram. *American journal of economics and business innovation (Ajebi)*, *4*(1), 20–30. https://www.researchgate.net

[4] Hasan, M. M., Riaz, M. H., Ahmed, Z., Islam, S., Uddin, M. S., Roshid, M. M., … & Atasoy, F. G. (2025). Decarbonizing Bangladesh: The Roles of technological innovation, energy transition, and urban-industrial dynamics in greenhouse Gas emissions. *Environment, innovation and management*, *1*, 2550019. https://doi.org/10.1142/S306090112550019X

[5] Rahman, M., Al Amin, M., Hasan, R., Hossain, S. M. T., Rahman, M. H., & Rashed, R. A. M. (2025). A Predictive AI framework for cardiovascular disease screening in the us: Integrating EHR data with machine and deep learning models. *British journal of nursing studies*, *5*(2), 40–48. https://doi.org/10.32996/bjns.2025.5.2.5

[6] Sweet, M. M. R., Arif, M., Uddin, A., Sharif, K. S., Tusher, M. I., Devi, S. (2024). Credit risk assessment using statistical and machine learning: Basic methodology and risk modeling applications. *International journal on computational engineering*, *1*(3), 62–67. https://doi.org/10.62527/comien.1.3.21

[7] Urbee, A. J., Hasan, M. A., Ridwan, M., & Dewan, M. F. (2025). Adaptation and resilience in the face of climate-induced migration: Exploring coping strategies in the urban economy of barishal metropolitan city. *Environment, innovation and management*, *1*, 2550005. https://doi.org/10.1142/S306090112550005X

[8] Rahat, S. K. R. U. I., Rahman, M. D. H., Arafat, Y., Rahaman, M., Hasan, M. M., & Al Amin, M. (2025). Advancing diabetic retinopathy detection with AI and deep learning: Opportunities, limitations, and clinical barriers. *British journal of nursing studies*, *5*(2), 1–13. https://doi.org/10.32996/bjns.2025.5.2.1

[9] Ridwan, M., Tahsin, M. S., Al-Absy, M. S. M., Eleais, M., Ridzuan, A. R., & Mukthar, K. P. J. (2025). Economic alchemy: Unraveling the nexus between trade openness, inflation, exchange rates, and economic growth in bangladesh. *International journal of economics and financial issues*, *15*(3), 244. https://doi.org/10.32479/ijefi.17779

[10] Gharbi, I., Rahman, M. H., Muryani, M., Esquivias, M. A., & Ridwan, M. (2025). Exploring the influence of financial development, renewable energy, and tourism on environmental sustainability in Tunisia. *Discover sustainability*, *6*(1), 127. https://doi.org/10.1007/s43621-025-00896-5

[11] Zare, Z., Sifat, A. I., & Karatas, M. (2025). A Review of data analytics and machine learning for personalization in tech sector marketing. *Journal of soft computing and decision analytics*, *3*(1), 92–111. https://doi.org/10.31181/jscda31202562

[12] Raihan, A., Bala, S., Akther, A., Ridwan, M., Eleais, M., & Chakma, P. (2024). Advancing environmental sustainability in the G-7: The impact of the digital economy, technological innovation, and financial accessibility using panel ARDL approach. *Journal of economy and technology*. https://doi.org/10.1016/j.ject.2024.06.001

[13] Akther, A., Tahrim, F., Voumik, L. C., Esquivias, M. A., & Pattak, D. C. (2025). Municipal solid waste dynamics: Economic, environmental, and technological determinants in Europe. *Cleaner engineering and technology*, *24*, 100877. https://doi.org/10.1016/j.clet.2024.100877

[14] Arif, M., Hasan, M., Al Shiam, S. A., Ahmed, M. P., Tusher, M. I., Hossan, M. Z. (2024). Predicting customer sentiment in social media interactions: Analyzing amazon help twitter conversations using machine learning. *International journal of advanced science computing and engineering*, *6*(2), 52–56. https://doi.org/10.62527/ijasce.6.2.211

[15] Sifat, A. I. (2025). The algorithmic consumer: A conceptual investigation of AI's influence on consumer preferences and decisions. *Asian management and business review*, *5*(2), 471–486. https://dx.doi.org/10.20885/AMBR.vol5.iss2.art14

[16] Mohaimeen-Ul-Islam, M. (2019). A study on diesel engine combustion. *Proceedings of the 2nd international conference on industrial and mechanical engineering and operations management (IMEOM), 118-122. http://dx.doi.org/10.6084/m9.figshare.13055228.v1*

[17] Zare, Z., Sifat, A. I., & Zadeh, A. (2025). Leveraging AI for sports fan engagement: Comparing traditional and transformer-based models. *Intelligent decision technologies*, 18724981251364376. https://doi.org/10.1177/18724981251364377

[18] Ridwan, M. (2023). Unveiling the powerhouse: Exploring the dynamic relationship between globalization, urbanization, and economic growth in Bangladesh through an innovative ARDL approach. *Asian journal of economics and business management, 2*(2), 283 – 291 https://doi.org/10.53402/ajebm.v2i2.352

[19] Ahmad, S., Raihan, A., & Ridwan, M. (2024). Role of economy, technology, and renewable energy toward carbon neutrality in China. *Journal of economy and technology*, *2*, 138–154. https://doi.org/10.1016/j.ject.2024.04.008

[20] Mozumder, M. A. S., Nguyen, T. N., Devi, S., Arif, M., Ahmed, M. P., Ahmed, E., … & Uddin, A. (2024). Enhancing customer satisfaction analysis using advanced machine learning techniques in fintech industry. *Journal of computer science and technology studies*, *6*(3), 35–41. https://doi.org/10.32996/jcsts.2024.6.3.4

[21] Ridwan, M., Urbee, A. J., Voumik, L. C., Das, M. K., Rashid, M., & Esquivias, M. A. (2024). Investigating the environmental Kuznets curve hypothesis with urbanization, industrialization, and service sector for six South Asian Countries: Fresh evidence from Driscoll Kraay standard error. *Research in globalization*, *8*, 100223. https://doi.org/10.1016/j.resglo.2024.100223

[22] Raihan, A., Ridwan, M., Sarker, T., Atasoy, F. G., Zimon, G., Bari, A. B. M. M., … & Mohajan, B. (2025). The influence of different environmental factors toward Vietnam's net-zero emissions goal. *Innovation and green development*, *4*(3), 100229. https://doi.org/10.1016/j.igd.2025.100229

[23] Polcyn, J., Voumik, L. C., Ridwan, M., Ray, S., & Vovk, V. (2023). Evaluating the influences of health expenditure, energy consumption, and environmental pollution on life expectancy in Asia. *International journal of environmental research and public health*, *20*(5), 4000. https://doi.org/10.3390/ijerph20054000

[24] Rahman, J., Rahman, H., Islam, N., Tanchangya, T., Ridwan, M., & Ali, M. (2025). Regulatory landscape of blockchain assets: Analyzing the drivers of NFT and cryptocurrency regulation. *BenchCouncil transactions on benchmarks, standards and evaluations*, 100214. https://doi.org/10.1016/j.tbench.2025.100214

[25] Rahman, M. H., Das, A. C., Shak, M. S., Uddin, M. K., Alam, M. I., Anjum, N., … & Alam, M. (2024). Transforming customer retention in fintech industry through predictive analytics and machine learning. *The american journal of engineering and technology*, *6*(10), 150–163. https://doi.org/10.37547/tajet/Volume06Issue10-17

[26] Ahmad, S., Raihan, A., & Ridwan, M. (2024). Pakistan's trade relations with BRICS countries: Trends, export-import intensity, and comparative advantage. *Frontiers of finance*, *2*(2), 6551. https://doi.org/10.59429/ff.v2i2.6551

[27] Hossain, M. N., Anjum, N., Alam, M., Rahman, M. H., Taluckder, M. S., Al Bony, M. N. V., … & Jui, A. H. (2024). Performance of machine learning algorithms for lung cancer prediction: A comparative study. *International journal of medical science and public health research*, *5*(11), 41–55. https://doi.org/10.37547/ijmsphr/Volume05Issue11-05

[28] Onwe, J. C., Ridzuan, A. R., Uche, E., Ray, S., Ridwan, M., & Razi, U. (2024). Greening Japan: Harnessing energy efficiency and waste reduction for environmental progress. *Sustainable futures*, *8*, 100302. https://doi.org/10.1016/j.sftr.2024.100302

[29] Mohaimeen-Ul-Islam, M. (2019). Pollutants from inland vessels of Bangladesh-A threat to the environment. *Proceedings of the 2nd international conference on industrial and mechanical engineering and operations management (IMEOM)*, 123-127. https://www.ieomsociety.org/imeom/62.pdf

[30] Ridwan, M., Akther, A., Dhar, B. K., Roshid, M. M., Mahjabin, T., Bala, S., & Hossain, H. (2025). Advancing circular economy for climate change mitigation and sustainable development in the Nordic Region. *Sustainable development*,1-20. https://doi.org/10.1002/sd.3563

[31] Rahman, M. D. H., Rahaman, M., Arafat, Y., Rahat, S. K. R. U. I., Hasan, R., Rimon, S. M. T. H., & Dipa, S. A. (2025). Artificial intelligence for chronic kidney disease risk stratification in the USA: Ensemble vs. deep learning methods. *British journal of nursing studies*, *5*(2), 20–32. https://doi.org/10.32996/bjns.2025.5.2.3

[32] Orthi, S. M., Rahman, M. H., Siddiqa, K. B., Uddin, M., Hossain, S., Al Mamun, A., & Khan, M. N. (2025). Federated learning with privacy-preserving big data analytics for distributed healthcare systems. *Journal of computer science and technology studies*, *7*(8), 269–281. https://doi.org/10.32996/jcsts.2025.7.8.31

[33] Raihan, A., Voumik, L. C., Ridwan, M., Akter, S., Ridzuan, A. R., Wahjoedi, … & Ismail, N. A. (2024). Indonesia’s path to sustainability: Exploring the intersections of ecological footprint, technology, global trade, financial development and renewable energy. In *Opportunities and risks in ai for business development: volume 1* (pp. 1–13). Springer. https://doi.org/10.1007/978-3-031-65203-5_1

[34] Raihan, A., Rahman, S. M., Ridwan, M., Sarker, T., Ben-Salha, O., Rahman, M. M., … & Munira, S. (2025). Dynamic influences of different energy sources, energy efficiency, technological innovation, population, and economic growth toward achieving net zero emissions in the United Kingdom. *Innovation and Green Development*, *4*(4), 100273. https://doi.org/10.1016/j.igd.2025.100273

[35] Ridwan, M., Akther, A., Tamim, M. A., Ridzuan, A. R., Esquivias, M. A., & Wibowo, W. (2024). Environmental health in BIMSTEC: The roles of forestry, urbanization, and financial access using LCC theory, DKSE, and quantile regression. *Discover sustainability*, *5*(1), 429. https://doi.org/10.1007/s43621-024-00679-4https://doi.org/10.1007/s43621-024-00679-4

[36] Sifat, A. I., & Elahi, M. A. (2025). Elasticity-driven fare optimization in US air travel segments. *Challenges and issues of modern science*, 133. https://doi.org/10.15421/cims.4.316

[37] Kurniawati, T., Rahmizal, M., Ridwan, M., Aspy, N. N., Mahjabin, T., Eleais, M., & Ridzuan, A. R. (2025). Reassessing the load capacity curve hypothesis in ASEAN-5: Exploring energy intensity, trade, and financial inclusion with advanced econometric techniques. *International journal of energy economics and policy*, *15*. https://doi.org/10.32479/ijeep.17328

[38] Islam, M. M. U. (2019). Acceleration analysis of transversely vibrated cracked shafts. *Proceedings of the 2nd international conference on industrial and mechanical engineering and operations management (IMEOM)*, 128-131. http://dx.doi.org/10.6084/m9.figshare.13088390.v1

[39] Akash, M. A., Riaz, M. H., Uddin, M. N., Ridwan, M., Akinpelu, A. A., & Akter, R. (2025). Analyzing the drivers of ecological footprint toward sustainability in BRICS+. *Environment, innovation and management*, *1*, 2550017. https://doi.org/10.1142/S3060901125500176

[40] Islam, M. M. U. (2025). Numerical analysis of particle sorting by acoustic waves in microfluidics. *Bangladesh army university of engineering, 2*(4), 1-7. https://doi.org/10.59321/BAUETJ.V4I2.1

[41] Ridwan, M., Aspy, N. N., Bala, S., Hossain, M. E., Akther, A., Eleais, M., & Esquivias, M. A. (2024). Determinants of environmental sustainability in the United States: Analyzing the role of financial development and stock market capitalization using LCC framework. *Discover sustainability*, *5*(1), 319. https://doi.org/10.1007/s43621-024-00539-1

[42] Shak, M. S., Uddin, A., Rahman, M. H., Anjum, N., Al Bony, M. N. V., Alam, M., … & Pervin, T. (2024). Innovative machine learning approaches to foster financial inclusion in microfinance. *International interdisciplinary business economics advancement journal*, *5*(11), 6–20. https://doi.org/10.55640/business/volume05issue11-02