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The Interrelationship between Metabolic Conditions, Environmental Pollution, and Climate Change: A Syndemic Approach to Understanding Diabetes in Urban Populations

Ezugwu Ifeanyi J.K.

Department of Biochemistry University of Nigeria, Nsukka, Enugu State, Nigeria.

ABSTRACT

Diabetes is a growing global health concern, particularly within urban populations exposed to high levels of environmental pollution. This study explores the syndemic relationship between metabolic conditions, specifically type 2 diabetes (T2D), and environmental factors such as air pollution and climate change. By integrating data from various studies, this review highlights the mechanisms through which air pollution exacerbates diabetes and examines the compounded risks faced by economically disadvantaged urban communities. It also suggests potential public health interventions and policy measures aimed at mitigating these risks and improving diabetes management in polluted urban environments.

Keywords: Diabetes, Type 2 Diabetes, Air Pollution, Climate Change, Environmental Health and Urban Health Syndemic

INTRODUCTION

Metabolic conditions, environmental pollution and climate-related changes, and the association between them should matter to everyone affected individually as they are interrelated and identified as syndemic factors [1-4]. Generally, the areas that are most prone to environmental degradation are the more at-risk communities. Community members exposed to environmental burdens often lack economic resources to adapt. As pollutants in the air can worsen diabetes patients' control, those without disease management resources (e.g., financial, knowledge or healthcare resources) have a lower quality of life and run the risk of developing diabetes complications, disease-related worse outcomes, and, ultimately, premature death. Published by the American Diabetes Association in 2021, the "Diabetes Atlas" reported that nearly 10% of the global population has diabetes, a complex metabolic disorder categorized by hyperglycemia [5-6]. The report expressed increasing rates of diabetes globally, with over 537 million individuals currently living with the disease and over 1.1 million diabetes-related deaths annually. Research has shown air pollution is associated with increased prevalence of diabetes [7-9]. Ambient particle matter pollution can increase the risk of diabetes, and people with diabetes exacerbate the effects of air pollution [8-9]. Research indicates excess body weight need not be present for adverse effects of exposure to air pollution on diabetes to occur [8]. Type 1 diabetes is not as strongly associated with air pollution exposure as compared to type 2 diabetes. Until a vaccine or cure is developed, urban populations will continue, at an increasing rate, to be environmentally burdened by diabetes without intervention or lifestyle changes. The International Diabetes Federation (IDF) estimated that there were 463 million cases of diabetes in 2019 and it would rise to 700 million by 2045. Both for high-income and low-income and middle-income countries obesity and diabetes have already become a public health emergency [10-12]. The association of air pollution with diabetes risk and management is especially common among people who live in urban areas because they are more prone to the exposure of air pollutants. It is found that black carbon concentrations are substantially higher in city areas than those in the suburbs and rural areas. Also, NO_2 levels are doubled and CO_2 emissions are six times higher in the cities than in the rural or suburban areas. Therefore, it is essential to address the diabetes-related issues that have been caused by the Intake of airborne particulates for urban areas. The aim of this study is to integrate on a common platform the impact of air pollution on the diabetic subjects residing in urban areas. In this study, the authors gathered data through a comprehensive literature survey and reviewed studies conducted to date on the association of air pollution with incident type-2 out of all diabetic population as well as reported uncontrolled diabetic population. This review summarizes scientific facts and findings on the impact of air pollution in managing and controlling the progression of type-2 diabetes and discusses the possible mechanistic

pathways. Moreover, this review article will also discuss some precautionary measures to reduce the severity of diabetes-related complications due to air pollution exposure and suggest the government policies to control diabetes incident cases as well as the emission of air pollutions in urban areas. People living in some urban areas are continuously exposed to unhealthy levels of air pollutants from anthropogenic and natural sources, mainly vehicle emissions, industrial and domestic combustion, and dust [9]. Particulate matter (PM10 and PM2·5), nitrogen dioxide (NO2), sulphur dioxide (SO2), and carbon monoxide (CO) have been found to be associated with increases in cardiovascular and lung morbidity and mortality among people exposed to these pollutants [10]. Evidence from epidemiological and laboratory studies suggests that air pollution could also be associated with diabetes.

Scope and Objectives

The work critique suggests that within studies PM2.5 diagnoses and exposure should be diagnosed by cotemporal measures to allow for more adequate interrelation and scrutinizing of the T2D risk impact. However, studies often repore exposure information from urban systems while diagnosing diabetes with data from chronic disease surveillance systems that range very in their geographic coverage. Conversely, 3 commonly noted groups of disease management are menti0ned for prevention measures - lifestyle changes, insulin therapy, and other forms of disease management such as medications and other therapies, and for each of these disease management aspects one type of intervention is proposed [11-13]. The study utilised a cross-sectional research design to gather data, with the Global Burden of Disease Study providing details on recent diabetes incidence rates in urban environments. A range of articles and correlative analyses were employed to establish a causal impact on T2D risk from long-term exposure to PM2.5 air pollution and identify the mechanisms by means of which air pollution impacts the management of T2D. Although most of the studies reported China-specific findings, in studies with global samples diabetes diagnosis matched to total PM2.5 exposure. Chronic diseases (CDs) such as diabetes continue to be a heavy burden on healthcare systems worldwide, with significant regional disparities in prevalence and management, and limited system-level intersectoral collaboration and tailored interventions [11]. The existing literature suggests that incidence and the management of type 2 diabetes (T2D) can be heavily affected by exposure to environmental air pollution. With this in mind, the current paper explores the interconnected potential between air pollution and T2D, offering diverse urban-specific intreventions, insights on future risk, and regulatory measures for whom the incidence of diabetes increses best with exposure to fine particulate matter (PM2.5) [14-16].

Understanding Diabetes

In terms of diabetes onset, exposure to air pollution and related compounds including diesel emissions and tobacco smoke has been documented to heighten the risk of diabetes. Such exposures can also reduce glucose tolerance in both rat and human models. In a British study, elevated fasting blood glucose and total record annual concentrations of nitrogen dioxide showed a linear increase in risk of diabetes. Similarly, in China, 40,475 people experienced atmospheric PM_2.5 concentrations agreeing with 18% higher chances of type 2 diabetes in 2013 than with 23% of the expected rate in 2017. Obvious is that there is a varied array of pollutants that are thought or known to directly impair insulin signaling or pancreas function. Direct effects of air pollution on type 2 diabetes are a distinct public health problem. SHS was found by the Centers for Disease Control and Prevention to contain particulate matter of 2.5 μm, as well as nearly 4,000 other toxins. Fine particles are significantly established to be associated with the highest increases in bloodstream glucose levels, but there may also be a health effect for coarser PM 10. The study of urbanized populations has long been recognized as valuable in understanding diabetes mellitus [17-19]. The countries defined as being significantly urban have problematically high numbers of people with diabetes [20-21]. However, urbanization itself is not inherently a condition for lifestyle changes that lead to diabetes. Rather, specific behaviors tied to rapid urbanization, economic highs and lows, and misrepresented policy often lead to physical inactivity and poor dietary patterns. These adoptions often are side effects of urban expansion and population growth. The fact that it is women who fear the comorbidities of the metabolic syndrome in highly urbanized areas is in large part why so many links between the syndrome and air pollution in Lights of highly developed countries indicate this to be true. Traffic exposure is also a link. Women's metabolic health in urban areas may be compromised by spending time in public and commuting in urban areas.

Types of Diabetes

The term diabetes encompasses a group of metabolic diseases in which an individual has high blood sugar levels (hyperglycemia) due to either insulin production insufficient, or the body's cells do not respond properly to insulin, or both [9]. Common symptoms of diabetes include frequent urination, increased thirst, and extreme hunger. If left untreated, diabetes can cause many complications [5]. Today, four

main types of diabetes can be distinguished: type 1 diabetes, type 2 diabetes, gestational diabetes, and monogenic diabetes [9]. Type 1 diabetes (T1D) results from the autoimmune destruction of the insulin-producing β-cells of the pancreas. T1D patients, therefore, have to rely on insulin injections for the rest of their lives. Type 1 diabetes has historically been known as juvenile diabetes because it is usually first diagnosed in children, teenagers, or young adults. It is also considered an autoimmune disease, with its causes like genetics and unknown environmental factors. The most common, accounting for between 85% and 95% of all diabetes cases, is Type 2 Diabetes (T2D), which is also known as non-insulin-dependent diabetes. It develops when the body does not produce enough insulin or does not respond effectively to the insulin that it does produce. T2D does not only affect adults, since rates of childhood obesity have soared in recent years, increasing the number of young people who will be affected by the condition over time. T2D used to be considered an adult's disease, but it is now being diagnosed in children and adolescents, especially those who are overweight with a sedentary lifestyle.

Prevalence and Trends

India is one of the largest and fastest-growing economies in the world, with an increase in urbanization and industrialization since the economic liberalization of the 1990s. Consequently, air pollution has emerged as one of the most severe environmental threats to public health in India. The air pollution levels are alarmingly high in urban areas such as the National Capital Region (NCR) of Delhi, Lucknow, Patna, Kanpur, and Varanasi leading to serious health concerns. India was ranked 117th among 180 countries in environmental performance among four domains—environmental health, air quality, water and sanitation, and sustainable energy [5]. The health impacts of air pollution might undermine India's aspiration for sustainable development, the Universal Health Coverage and the health of the population because of the high incidence of respiratory illnesses, cardiovascular diseases, diabetes, etc. Air pollution has evolved as a problem with the rapid advancements in industrialization and urbanization [7]. High-income countries had witnessed worsening stages of air pollution during their early developmental stages as observed in countries like the United States of America, but have effectively managed the air quality in recent years [6]. In contrast, the problem of air pollution is more recent in low- and middle-income nations, which can still ameliorate its impacts by implementing corrective and preventative measures as observed in South Asia and Central Africa [11]. Moreover, climate change has led to meteorological factors such as temperature and humidity influencing air pollution levels in recent years.

Air Pollution and Its Sources

Things take a catastrophic turn when air pollution surpasses the critical values, leading to environmental degradation, ecological imbalance and, most importantly, the health disasters [8]. Urban areas are sprawling, and this influx, along with the increasing traffic and industrial catchments, has deteriorated the quality of air. Such pools of population and activities have given impetus to various diseases and long-term health effects. Urban population is profoundly prone to cardiovascular diseases, strokes, pulmonary diseases, and a myriad of kidney and other system diseases. Nonetheless, cities are not only struggling with airborne diseases, but they are also witnessing the soaring diabetes cases [13]. A significant share of the global burden of diabetes is being shared by the cities and urbanites amidst the burgeoning concern of air pollution in such areas. Air pollution is a pressing global issue [14]. Nearly 95% of the human population faces the menace of compromised air quality. The rising economic activities and a constantly surging energy demand are potent catalysts for air pollution. The quality of air is a function of the concentration of various constituents present in the atmosphere, including Particulate Matter (PM), gases, and heavy metals. The prime sources of such pollutants could be natural or anthropogenic. The natural sources include volcanic eruptions, landslides, and wildfires, whereas the anthropogenic sources are residential fuel combustion, power plants, automobiles, construction activities, industrial processes, and landfills.

Types of Air Pollutants

The mechanisms from which air pollution could alter the risks of a range of diabetes are less understood, particularly from larger human observational studies, although data suggests that air pollutants can potentially reduce insulin production and pancreatic beta-cell functionality, increase insulin resistance, and impair glucose homeostasis, especially if those who were exposed were situated in those high concentration sites for long periods in high metabolic activities as well as low insulation when glucose is processed. Animal toxicokinetic studies and high-throughput in-vitro toxicology transcriptomics data, as well as toxicology-oriented clinical and human exposure intervention trials did start to establish biological mechanisms although are not tailored for directly relevant to human metabolic health diseases such as diabetes [3]. Several types of air pollutants can independently of or synergistically interact with one another to increase or decrease the risks of type 2 diabetes mellitus (T2DM) and other types of

diabetes, for example, air pollutants produced by human economic activities or those from natural sources during wildfire and volcanic eruption events, to actual exposure patterns and uptake into human organisms [7]. The evidence for the changes in risks of diabetes from the pollutants so far have surfaced from epidemiology studies with various designs (e.g., ecological, cross-sectional, cohort, and natural experimental studies), where the risks of diabetes and types presumably from various types of air pollution were estimated [13]. For example, higher up- taken of production of some types of air pollution surrogates (e.g., PM2.5 and PM10 particulate matter, or specific gases like nitrogen oxides and ozone) showed biomarker signals indicating potentially negative relationships with human metabolic health [13].

Sources of Air Pollution in Urban Areas

Additionally, motorized vehicles are stamped as one among the key sources of environmental pollutants emerging in the form of fine as well as coarse particulate matters [7]. Diesel emissions include black carbon, hydrocarbons, and nitrogen oxides. The diesel powered generator sets or machineries used in the industrial sectors are also expected to release black carbon as by-products. Disconnected and defective household appliances or electrical systems in urban areas result in zapping of electrical current, in the form of electrified embers along with toxic combustion gases. These admissions not only create respiratory health problems but are also potentially responsible for deteriorating effects that encompass damage to buildings, properties, and acute impacts on human health Also, a direct correlation exists between the emission of black carbon with incomplete combustion, largely emitted from vehicles that utilise diesel fuel, kerosene fired cooking appliances, generator sets, and chulhas (indigenous cookstoves) for burning of bio-fuels and others [9]. The occurrence of diabetes is a global public health hazard with around one-tenth of the world's adult population affected and its numbers rising [8]. In cities, persistent exposure to elevated levels of air pollutants associated to the traffic emissions can have manifold effects on human health, clearly they can instigate and exacerbate health conditions, inclusive of endocrinopathies [6]. One must observe the association between air quality and public health on three levels: direct incidents of lung and heart diseases, secondly the long-term incidents associated to air pollution and most significantly the research on the impacts of air quality on metabolism disorders [10]. Some previous investigations have reported increasing prevalence of diabetes mellitus (DM) type 2 is associated with outdoor air pollution [5]. A detailed inspection for the stratifying population confirm the associations of prevalent DM with air particles, specially at high concentration areas (eg. PM10 greater than 50 μg/m3) [8]. Along with PM, traffic-derived emissions of nitrogen oxide have been proven to be linked with adverse health impacts [7]. Urban air pollution is one of the critical environmental health issues around the world. Rapid industrialization, urbanization, and population growth are the significant contributors to the worsening air quality of the urban areas [9]. The rapid expansion of urban areas has initiated the immediate modification in the micro-environment; consequently transitioning into urban air pollution [8]. The situation is further compounded with transportation being an essential facility in some cities, leading to a substantial surge in vehicle emissions, heated up by the price of private car ownership substantially reducing across the globe due to advancement of urbanization, improved income and incremental monetary benefits in globalisation [9]. The existing emission rates are boosting from vehicles and transportation, thus causing noxious pollutants, including nitrogen oxides, carbon monoxide, hydrocarbons and fine particulate matter [6].

The Link Between Air Pollution and Diabetes

Metabolic research and epidemiologic evidence have shown the interaction between exposure to ambient pollution and insulin resistance, with toxic components of air pollution, inhaled by humans, promote reactive oxidative stress, inflammation, and disturb metabolism. Visceral adipose tissue, key factor of type 2 diabetes (T2D), has a higher capacity to generate reactive oxygen species and is a key site for the inflammatory processes, developing insulin resistance with adipocytokine production and secretion changes. Some authors reported that T2D might be a risk factor for poorer COVID-19 outcomes, that pollutant might indirectly decrease the quality of life by potentiating comorbidities of severe acute respiratory syndrome-related coronoavirus 2 (SARS-CoV-2), primarily T2D, and that air quality index increase risk to be affected in COVID-19 [8]. Diabetes is an increasing health concern and has been the third priority to be address in this 21st century. While genetic background can play an important role in the development of diabetes, lifestyle modifications, insulin resistance, and obesity remain as the hallmark of this disease. Some previous studies have suggested the possible role of air pollution and temperature on the incidence of diabetes, as well as impaired diabetes control, but to our knowledge the temporal association of pollution and diabetes control (measured in terms of Glycosylated-hemoglobin A1c, (HbA1c)) is still not well studied [12]..

Epidemiological Evidence

In contrast, other studies do not seem to confirm significant associations between the risk of T2DM incidence and exposure to air pollution, depending on the exposure period and the database used for air quality. A recent cohort investigation supports a lack of association between incident T2DM and exposure to nitrogen dioxide (NO2), black carbon (BC) and soot (SC), carbon monoxide, or ozone (O3). The study focused on the elderly living in the region of the Netherlands and highlights that areas with higher exposure to PM10 also have higher traffic-related air pollution for which associations with T2DM were significant. Other results are consistent with a larger study conducted in Sweden, where prevailing levels of bad air are lower than in other European countries and North America [8]. At present, available evidence is suggestive but not completely conclusive in epide-miological investigations focusing on the relation between air pollution, especially long-term exposures to particulate matter (PM), and the development of incident Type 2 Diabetes Mellitus (T2DM) [6]. A recent systematic review of cross-sectional studies found significant associations between long-term PM exposure and the incidence of T2DM, even after considering other factors such as demographic variables or lifestyle and using a meta-analysis approach [14]. Another 2019 meta-analysis of prospective cohort research suggests that an increase in PM concentrations may increase the risk of developing T2DM and that women, especially obese women, could be at higher risk [9]. Other findings demonstrate a possible greater risk of prevalence and incident diabetes in populations exposed to higher long-term levels of nitric oxide (NO2) and nitric oxides (NOx) and to an increment of 5 g/m3 in long-term exposure to elemental carbon dysregulation of the glucose-homeostasis.

Mechanisms of Action

Multiple effects of these NPs and air pollution have been reported as linked to the onset and progression of diabetes. They can cause inflammation within the different organs and can also induce endoplasmic reticulum stress, apoptosis, and autophagy in different cell types, as well as affecting hormonal physiology. More generally, studies have indicated that long-term exposure to different forms of air pollution can lead to chronic (low-grade) systemic inflammation, which can promote insulin resistance and lead to the onset of diabetes [7]. Similarly, NPs can bind to different bioorganic molecules and produce other reactive species which lead to the overload of short-term defence mechanisms. This cumulative oxidative/nitrosative stress attacks cellular proteins, lipids, and nucleic acids, and can produce genetic mutations and consequential harm, ultimately leading to cellular dysfunction, and then tissue, and then eventually organ dysfunction. Nanoparticles (NPs) and nanomaterials are ubiquitous in the environment and come from different natural (i.e., volcanoes, storms, etc.) and anthropogenic sources (i.e., energy production, transportation, construction, etc.) [11]. The smallest dimensions of NPs (less than 0.1 μm) enable them to easily reach the alveolar region when inhaled. In the alveolar region, these NPs can traverse the epithelial air-blood barrier and exert effects both locally at the lung and then once circulating in blood in other distal organs, such as liver, heart and/or pancreas. Since almost half of the global population resides in urban areas, we also noted that NPs are predominantly concentrated in the urban centers due to their multitude sources. Diabetes and air pollution are complex, multifaceted health issues. Although they are seemingly different in terms of their characteristics, there are plausible biological and epidemiological pathways that indicate diabetes pathogenesis maybe related to air pollution [13]. To delve deeper into these issues and understand their interconnectedness, we investigated the possible mechanisms by which air pollution can drive the onset, progression, and pathogenesis of diabetes.

Impact on Diabetes Management

Type 2 diabetes is GDP's fasting-growing health crisis, often referred to as the silent killer; however, serious long-term complications such as amputations, heart disease, and vision loss may occur to almost half of the population [3]. Type 2 diabetes can be treated; however, the difficulties encountered by individuals, providers, and policy makers are complex. Concurrently, global corporations contribute approximately one-third of global carbon emissions, which also contribute to long-term exposures to toxic conditions that affect health; in particular, motor traffic and industrial activity. About 80% of climate change-mitigation-credit medication suggests alleviation of oxidative factors such as air pollution. Though health care providers recognise environmental exposures as a risk own for providing their patients and advise them to avoid traffic crashes and spend as much time indoors as possible, few advise and manage environmental exposures [8]. Air pollution, as an environmental determinant of health, is linked with diabetes and is associated with suboptimal glycaemic management among individuals with diabetes [11]. Yet, few studies have investigated the perceptions of stakeholders responsible for diabetes management within urban communities that experience toxic exposures from air contaminants, and how they contend with those exposures [9]. This analysis aims to address this gap and aims to 1) determine if

urban areas with hazardous air quality have adapted their services for those individuals living with type 2 diabetes and 2) to explore the factors that support or impede policy makers and health care providers in reducing long-term exposures to these toxic conditions. As part of the study protocol to assess the stakeholders' understanding of the co-evolution of diabetes and air pollution in an urban environment, we use a purpose-built qualitative analysis instrument that leverages the concept of a Health Urban through a compact and naturally occurring promotional disease model, to deliver a holistic perspective.

Challenges in Urban Settings

As one of the most under-recognized micro-level risk factors, air pollution appears to be a salient and prevalent driver of inequitable mortality risks – particularly for socially marginalized populations. Yet, to promote understanding and raise awareness of these pervasive, overlapping urban health risks that are not properly perceived by the public yet left at the hands of individual agency, reliable city-level data and communication tools are necessary – a premise aligning with certain [9], 'optimistic' (harm reduction) and anti-fatalistic strategies to combat air pollution amidst the consequences of private companies' deliberate inefforts to commit to environmental measures, and/or autocratic rulers. We point to the increasing use of air quality maps and shows in the article the ways in which they can become tools for public-confrontation prowess [7]. Urban settings provide abundant possibilities for change and novel ideas in combatting air pollution, as their populations are high consumers of resources and services, venues for innovation, and current hotspots in air pollution [6]. Cities are also places of contrasts with high inequity and poverty rates, complex policy infrastructures, and distinct challenges accessible information could help negotiate. It is here, also, where diabetes is a lurking public health issue worldwide, with several studies demonstrating increased incidences of Type 2 Diabetes (T2D) amidst city dwellers being repeatedly scored to adverse air qualities [11]. T2D is a chronic disease that, during its progression may degenerate into several corrosive complications denunciating heavily on public and private health sectors, in which medication and doctor-visit costs demand the public health sector to re-configure itself amidst a possible option of replacing it altogether, through a universal health insurance.

Strategies for Mitigation

Whilst attention is focused on the benefits of parks and green spaces, relatively little is known about how best to design them to maximise public health. To address this gap, a research team undertook the Blue Health Global Assessment, which analysed evidence from over 300 studies and articles published over the past 30 years [5]. The team focused on physical activity, heat exposure, air quality, mental health and several other health outcomes known to be affected by spending time in green spaces. The research is based on the idea that dwelling in more populated areas can strain mental health and is linked with a range of mental disorders. These can result, for example, from elevated stress levels because of noise, diminished spatial liberty, or inevitable exposure to exhaust fumes, which have a negative impact on the nervous system. The paper does not, however, consider the possibility that energy efficiency measures in new dense urban areas could significantly contribute to the reduction of air pollution, including on a ground level. It does not mention the use of clean renewable energy sources and the vendor-neutral vehicle concept. As the quality of urban air worsens in the face of climate change and rapidly growing cities, efforts to mitigate its effects on health have received increasing attention [8]. A promising strategy is to increase the amount of green space in urban areas in the form of parks and gardens. Such "green-blue spaces" are known to provide numerous benefits, including improved mental health and better respiratory function [17]. Green urban areas can also help with management of extreme heat events by lowering the temperature and increasing air circulation. Activities that occur in green spaces, including physical exercise and contact with nature, bring additional health benefits. Overall, greater access to natural spaces enhances the health-related quality of life of residents [6].

CONCLUSION

The syndemic relationship between diabetes, environmental pollution, and climate change presents a significant public health challenge, particularly for urban populations. The evidence underscores the need for integrated public health strategies that address both metabolic health and environmental exposures. Implementing policies to reduce air pollution, improve urban living conditions, and provide better healthcare resources for diabetes management can mitigate the compounded risks faced by vulnerable populations. Future research should focus on elucidating the mechanistic pathways of this syndemic and developing targeted interventions to improve health outcomes in polluted urban environments.

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