ANALYSIS, ASSESSMENT, AND MANAGEMENT OF ENVIRONMENTAL AIR POLLUTION USING ENVIRONMENTAL ENGINEERING IN DEVELOPING COUNTRIES

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Highlights

In this study, environmental engineering methods are used to analyze, evaluate, and regulate environmental air pollution in emerging nations. It focuses on long-term ways to reduce pollution and enhance local populations' health.

Abstract

Recent studies underscore the value of contemporary technology and gas emissions mitigation while overlooking the necessity of optimal fuel in Developing Countries (DC). DC's historical economic expansion has significantly depended on fossil fuels, resulting in severe environmental air pollution (EAP) challenges. The separation of economic progress from pollution has been the central emphasis in advancing environmental civilization in emerging countries. This study presents an analysis, assessment, and management of EAP using environmental engineering (EE) in DC. This work has examined the evolution of EAP regulations in DC, emphasizing a strategic shift from emission regulation to Air Quality Management (AQM). The regulation of Sulfur dioxide (SO2) emissions addressed the worsening of acid rain in DC. Since 2015, regulatory measures across several sources and industries have aimed to decrease the total amount of Fine Particulate Matter (FPM2.5), signifying a shift towards an AQM-focused policy. Escalating ozone (O3) pollution necessitates integrated management measures for O3 and FPM2.5, focusing on their intricate photochemical reactions. Significant enhancement of AQM in DC, as a crucial metric for the efficacy of sustainable economic development, necessitates the profound carbon reduction of the DC's energy infrastructure and the establishment of more integrated strategies to tackle EAP and climate change in DC concurrently.

Keywords

developing countries; air quality management; air pollution; environmental engineering; analysis.

Introduction

EAP, arising from both human and natural causes, poses considerable problems and several potential threats to economic growth and the wellness of humans. According to the Worldwide Burden of Disease (WBD) study, 6.8 million fatalities were linked to both inside and outside pollution globally in 2020, with 4.4 million individuals experiencing premature mortality due to ambient EAP. Previous research has shown that, if inadequately managed, air pollution would persist and endanger human health.

Renewable technologies may improve the efficiency of fossil fuels, decreasing energy use in production [3]. The main Renewable Energy Sources (RES) are bioenergy from flora, geothermal electricity, hydroelectricity, solar power, and wind turbines. In [21], it was determined that breakthroughs may enhance the technical advancement of RES, hence increasing production capacity [2]. Advancements in RES may facilitate the provision of green power to the market and positively influence energy inventories [5]. Nevertheless, less emphasis has been directed to the causal link between RES and non-RES and airborne pollutants.

Furthermore, China is a pivotal example in the global setting for elucidating the causal link between RES and non-RES and air pollution. China, the planet's second-biggest economy, has significantly depended on extensive fossil fuel use for its fast economic expansion. Analyzing the effects of RES and non-RES on pollutants in the air in China might provide significant insights into the efficacy of various energy policies in alleviating environmental hazards and fostering environmentally friendly growth [20].

In 2021, China's greenhouse gas emissions (GHG) were around 30% of world emissions, as reported in [7]. This represents one of the methods by which China has generated disparate degrees of EAP nationwide [10]. There is growing proof that air contaminants, such as PM2.5, are disseminated above China's most populous regions (e.g., Beijing and Shanghai). Furthermore, the increase in EAP in China surpasses that of nations with developed economies (e.g., the USA and Europe) and DC (e.g., India and Pakistan), particularly during the colder seasons. Acknowledging that air contaminants may cross national borders via circulation is important. The EAP issue in China is thus intricately linked to the worldwide EAP problem [30].

DC has implemented many top-down governmental initiatives to address pollution and safeguard the ecosystem. Additionally, there was a commitment to enhance expenditure on developing RES technologies [33]. The National Implementation Plan designates six major DCs, including China, Bangladesh, India, and Pakistan, as priority regions for EAP reduction. An essential component of the action strategy to promote a healthier air supply is the implementation of innovations in RES technology [1]. EAP and GHG emissions in DC exacerbate global warming by releasing GHG from non-RES, such as coal. This exacerbates the GHG impact, resulting in elevated temperatures, altered rainfall patterns, and increased frequency of severe weather events [24]. Advocating for RES and environmentally friendly behaviors is essential for alleviating environmental difficulties and diminishing the detrimental impacts of EAP on the ecosystem and public health. Several facets of RES have garnered heightened attention after COP26 and COP27.

Nonetheless, only a handful of studies have examined the role of RES in mitigating EAP in DC. In recent research, the authors in [11] qualitatively investigated the geographical distribution of air pollution across regions in DC, focusing on advancements in RES technology. Improvements in RES technology were seen to decrease the levels of breathable PM10 and nitrogen oxides (NOx). This study builds upon previous studies by empirically investigating the effects of RES and non-RES on GHG emissions in DC. Investigating the direct link between various RES and EAP would be beneficial in ascertaining the significance of longitudinal data on energy utilization for long-term EAP prediction. To our knowledge, no empirical investigation has examined the effects of RES and non-RES on ambient pollution levels in DC, specifically using Granger-causation studies.

The spread of creativity in supplying electricity and GHG emissions in DC has been analyzed using monthly power and socioeconomic time series information from 2000 to 2024 to fill this void. Researchers utilized the regression technique and determined that EAP and GDP in DC have escalated with time. Secondly, RES decreases GHG emissions when accounting for economic development, population expansion, and coal costs, which is the primary RES in DC. Third, petroleum-based energy exacerbates CO2 and GHG emissions when considering population expansion, economic development, and coal prices (the predominant power source in DC). Fourth, further studies reveal that the influence of RES's decision on AQM is unilateral, indicating that EAP does not catalyze the DC's government to implement remedial actions to enhance RES use. It has been seen that RES considerably and adversely affects GHG and emission levels. Non-RES contribute favorably to the emission of carbon dioxide and the release of GHG. Finally, there has been insufficient proof for the inverse association. In summary, DC's economy depends significantly on conventional energy sources, such as fossil fuels, despite its commitment to fund RES alternatives. Consequently, the amount of EAP does not influence the government's choice to augment or diminish the utilization of RES.

Related Works

Individuals in both DC and developed nations often allocate 82–92% of their time inside, mostly within their residences [14][15]. The constructed environment significantly influences health, well-being, and overall quality of life, necessitating considerable energy expenditure to meet human needs inside structures. Global risks, including pandemics and international conflicts, have significantly escalated energy costs [31]. In 2021, the International Energy Agency, or IEA, reported that building operations constituted 35% of all global usage of energy and 30% of the overall energy sector emission levels, with 8.8% attributed to primary emissions from constructions and 21% to supplementary emissions from the generation of electricity and heat utilized in properties [25]. The sixth Review of the International Panel on Climatic Change [13] forecasts that climatic changes will intensify in all global areas in the next decades.

The analysis suggests that even though global warming is confined to 1.3 ◦C, extreme temperatures would increase, accompanied by extended warm seasons and abbreviated cold seasons [12]. Moreover, these climatic phenomena are anticipated to escalate markedly with a temperature increase of 1.8°C. After COP26 - The Glasgow Climate Pact (2021) and following the Paris Agreement temperature objective to restrict global warming to far below 1.5 ◦C while striving for 1 ◦C, some nations established aggressive goals to achieve net-zero GHG emissions. The attainment of this objective requires the near-total eradication of GHG emissions from the construction industry. Energy-efficient techniques are implemented to reassess climate control, heating, and airflow requirements to address these difficulties promptly [26]. Fundamentally, needs arise from human demands for health, productivity, and comfort. Moreover, specifically regarding humidity, they are also connected to the structures' endurance.

The updated Energy Performance of Buildings Directive (EPBD) in Europe outlines the pathway to attain a zero-emission and entirely decarbonized construction sector by 2045. The amended law enables more focused funding for projects in the construction industry, augmenting existing European Union (EU) mechanisms and assisting at-risk customers. Modernizing the building stock, enhancing indoor air quality (IAQ), and combatting energy poverty are all under consideration. Sociodemographic attributes such as educational level, age, sex, place of origin, and citizenship significantly influence in modifying a person's living circumstances. Higher social developments, along with several unforeseen incidents (such as the pandemic, international conflicts, and the ensuing international financial and economic crisis), are estimated to influence and potentially intensify patterns of disparities and exclusions significantly.

Although poverty criteria differ between regions, the global poverty crisis may lead to significant fluctuations, particularly in energy and fuel hardship. At-risk groups encounter heightened risks of related disease obstacles, including non-communicable illnesses (e.g., pulmonary and cardiovascular) and the transmission of viruses and bacteria [27]. Moreover, increasing research indicates that adaptation and mitigation techniques suggested for the housing and construction sector to combat climate change might impact public wellness and health by exacerbating health risks and disparities associated with the IAQ [17].

The World Health Organization (WHO) recommended mitigation strategies to address disparities in human wellness and pollution exposure [16]. These include enhancing spatial and land-use strategies to diminish emissions and protect marginalized populations; prohibiting specific household heating fuels, such as coal, while transitioning low-income families to healthier heating alternatives; and implementing immediate actions to lessen exposure for disadvantaged individuals in their residential, educational, recreational, and occupational environments. In the next decades, we must construct and refurbish structures to mitigate their environmental effect while promoting health and welfare. It may swiftly alter building operations to decrease energy usage while promptly preserving or improving IAQ. IAQ refers to the comprehensive indoor environmental elements (such as IAQ, airflow, temperature control, noise, and lighting) in a building. At the same time, IAQ particularly addresses the state of the air flowing inside the structure.

Research and current studies indicate that exposure to indoor air pollution correlates with detrimental health consequences, affecting the pulmonary, neurological, and cardiovascular systems and contributing to cancer risk and hormonal imbalances [32]. Moreover, exposure to extreme cold and excessive heat inside is linked to heightened morbidity and death rates. Indoor temperatures below 18 ◦C may result in adverse health consequences, including elevated blood pressure and an increased risk of blood clots, potentially leading to cerebrovascular accidents and heart attacks [19]. Elevated or rising temperatures will strain the cardiovascular and pulmonary systems more [6]. This may result in heat exhaustion, burnout, heatstroke, and cardiovascular incidents, including ischemic stroke, particularly in at-risk groups [28][29]. Vulnerable populations include infants, older people, those with obesity, and those with pre-existing medical conditions [18]. IAQ may be influenced by contemporary developments that significantly reduce energy usage in the residential and commercial building sectors. Guidelines are essential to sustain health, efficiency, and comfort derived from indoor environmental quality conditions.

Materials and Methods

Air pollution is a substantial challenge for several emerging nations, as rapid industrialization, urban expansion, and an increasing population exacerbate air quality issues. Environmental engineering is essential in tackling air pollution concerns by offering investigation, evaluation, and AQM methods [4]. The intricacy of air pollution in emerging countries, marked by industrial emissions, vehicle pollution, and biomass combustion, necessitates customized engineering interventions to alleviate detrimental environmental and health impacts [22].

From GHG Emission Control to AQM

Over the last three decades, DC's rapid social advancement has led to air quality management always pursuing evolving objectives, first addressing acid rain and NOx emissions and now concentrating on PM2.5 pollution (Figure 1). Regulatory measures addressing acid rain targeted SO2 emissions resulting from coal burning throughout the 2000s. The upward trend of SO2 emissions was not mitigated until 2008, when various technical and legislative measures were extensively implemented.

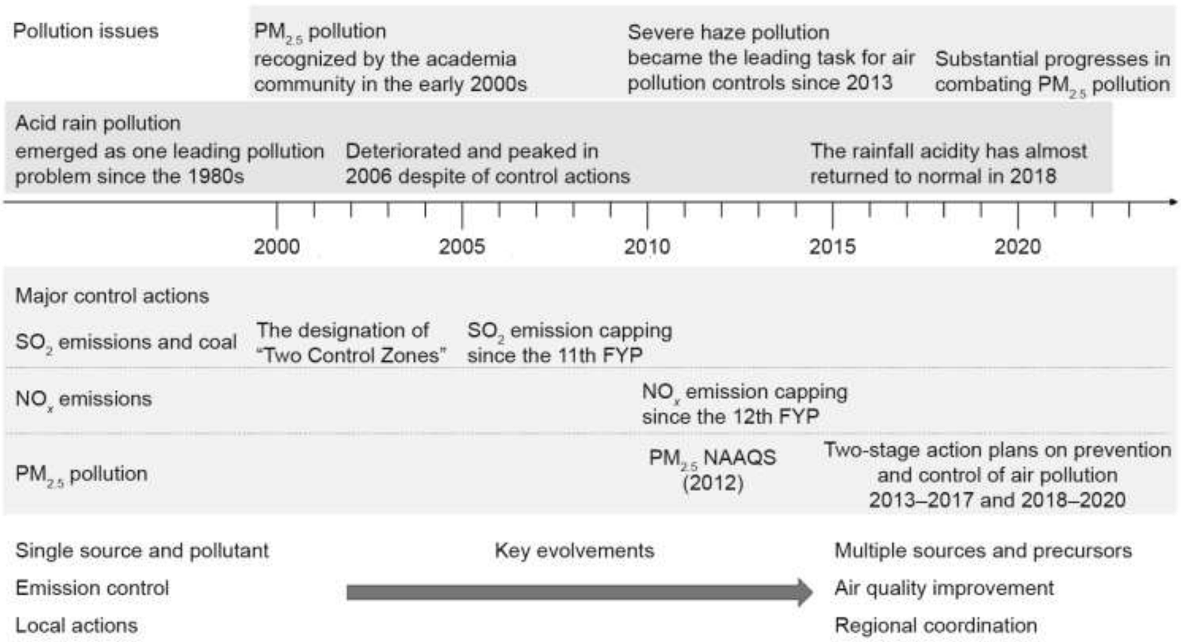

Figure 1. Significant events and the progression of policies on AQM in DC, including measures targeting the emissions of SO2 and NOx and the ambient levels of FPM2.5

This achievement was contingent upon advancements in political responsibility, monitoring of SO2 emissions, and monetary rewards for power stations to implement and maintain flue gas desulfurization (FGD) systems. NOx has a broader range of sources than SO2, like burning coal, transportation, and other petroleum-based combustion sectors. Consequently, regulatory measures on NOx emissions must be more comprehensive and intricate, necessitating collaboration across several industries. Regulating PM2.5 levels necessitates the continuous reduction of many precursors across several sectors and an understanding of the intricate effects of climatic and atmospheric chemical conditions. Effective control measures have been enacted in China, including multi-party cooperation at regional and state levels, to mitigate the detrimental ecological and socioeconomic effects of PM2.5 pollution. Since 2013, the fight against PM2.5 pollution in DC has shifted strategically from pollution control to AQM to enhance public well-being and social prosperity. The significant reduction in PM2.5 concentrations has emerged as a crucial metric for evaluating the effectiveness of sustainable civilization development in DC.

Dissociating SO2 Discharges

Despite the need for FGD systems deployment mandated by the 2000 modification of the Air Pollution legislation, enforcement of this mandate was inadequate. As a result, overall SO2 emissions rose by around 51% from 2003 to 2007, propelled by a significant rise in coal usage, exacerbating acid rain pollution throughout the country. The eleventh Five-Year Plan (FYP) (2007–2011) enhanced this position by establishing a definitive objective to reduce overall SO2 emissions by 12%. The eleventh FYP was an important achievement as it established mandated AQM targets for the province and municipal authorities for the initial duration, with local officials facing sanctions in cadre evaluations for non-compliance.

Alongside political responsibility, the confirmation of SO2 emissions and monetary incentives were employed to meet decreased targets; for instance, constant emission tracking systems have been mandated at power plants using coal since 2008 to disclose the current state of FGD and observe real-time SO2 levels in the exhaust gas. Power stations with adequately functioning FGD, used for at least 92% of power generation, have seen a price penalty of 0.015 CNY per kilowatt-hour. Otherwise, they incur a penalty of no less than the price penalty. The deployment rate of FGD in thermal power stations rose from 15% in 2006 to 88% in 2012. Emissions of SO2 from power production, the predominant manmade source in DC, fell by 22% from 2006 to 2011, despite an estimated 82% rise in electricity output during that timeframe. Based on official figures, the total release of SO2 in DC declined by 13% from 2006 to 2011, signifying the substantial achievement in regulating SO2 emissions. Also, the problems associated with acid rain were significantly alleviated.

Dissociating NOx Discharges

Building on the accomplishments of SO2 emission management in the eleventh FYP, the DC government established a comparable required objective of decreasing NOx emissions by 12% during the twelfth FYP [30]. Thermal power stations, which are accountable for a minimum of 32% of national NOx emissions, were the primary sector addressed by regulators. Numerous regulatory instruments and administration strategies used to regulate SO2 emissions were designed to reduce NOx emissions. In 2011, power stations powered by coal mostly used low-NOx heaters, an average technology aimed at regulating NOx emissions, while implementing more sophisticated technology, such as selective catalyst reduction (SCR), constituted just 13%. In the twelfth FYP, DC enforced stricter emission rules for power plants burning coal, establishing a NOx threshold of 110 mg/m^3, the most rigorous norm globally at that time. The NOx threshold was amended to 45 mg/m^3 per the new release standard. Consequently, about 82% of thermal power stations have used SCR technology to regulate the release of NOx by 2016; in the 12th FYP, overall releases of NOx declined by 11.2%, reversing the steep upward trend seen in the preceding decade.

Dissociating FPM2.5 Discharges

Atmospheric levels of FPM2.5 have emerged as a more precise signal for urban dwellers in DC than other airborne contaminants as the public increasingly comprehends the connection between FPM2.5 pollution, environmental transparency, and health effects. The elevated competence of the Implementation Plan (IP) indicated that addressing FPM2.5 pollution needed unprecedented coordination at both state and regional levels.

Numerous control measures have been executed countrywide, with supplementary initiatives in some critical districts. Enhancing AQM and alleviating FPM2.5 pollution in major megacities, such as Beijing, Delhi, and Shanghai, have been achieved owing to heightened focus from the national government and public awareness [23]. Beijing exemplifies success in addressing FPM2.5 pollution following two decades of work. The installation of extensive air pollution measures in Beijing began in the 1995s. In 2009, comprehensive pollution control initiatives were enacted in Beijing and Delhi regions to ensure optimal air quality [21]. Ambient CO, SO2, PM10, and NO2 levels consistently decreased despite substantial increases in urban GDP, local population, car inventory, and energy use from 1999 to 2014. Due to the efficacy of AQM in 2009, local authorities acknowledged that ambient FPM2.5 levels stemmed from a confluence of pollutants, meteorological factors, and atmospheric composition.

Moreover, effectively reducing FPM2.5 pollution required collaborative efforts from neighboring provinces. Consequently, the government gained significant insights into the source attribution of FPM2.5 pollution [8][9]. Evaluation of twelve months of ongoing surveillance data revealed that regional sources accounted for roughly two-thirds of FPM2.5 total concentrations in Beijing and Delhi during 2014. Road transportation, mostly on-road cars, was predicted to be most prevalent among regional sources at 32%, next to the burning of coal at 23%, manufacturing activity at 19.5%, and dust at 16%.

Before 2012, regulatory actions concentrated on high-capacity carbon-fired power facilities and coal combustion in metropolitan areas. Since 2014, urban and countryside families in DC have received increased subsidies to accelerate the transition from coal to power or gasoline. Families opting for coal-to-electricity heating renovations may obtain incentives covering the majority of the equipment purchase costs and qualify for a reduction of up to 79.5% on the heating energy bill. As of 2017, most families in major cities in DC have eliminated coal use, except for a few outlying rural regions. The removal of coal has led to the present annual SO2 level in Beijing being below ten micrograms per cubic meter, reflecting a decrease exceeding 92% over the previous twenty years. Additional initiatives are underway to convert Beijing and Delhi into a coal-free metropolis.

Beijing and Delhi also led the way in regulating automobile emissions in DC. Establishing and implementing local rules for car exhaust and fuel purity in major cities surpass national norms. Sophisticated driving monitoring methods—specifically satellite imagery and mobile emission measuring equipment—have enhanced in-use regulation. At the same time, ecological transportation systems have been advocated via significant incentives and traffic control strategies. Urban inhabitants are increasingly adopting sustainable transportation methods, with bicycles, subways, and buses currently accounting for almost 65% of all journeys in DC. By 2021, renewable energy vehicles, mostly battery electric cars and two-wheelers, were about 15% of the overall automotive market.

Major O3 Problems in the Creation of a Sustainable Society

The primary issue in controlling O3 pollution lies in the intricacies of atmospheric photochemical production, contingent upon O3–NOx sensitivity analysis and climatic variables. A control method aimed at diminishing NOx releases for FPM2.5 management may inadvertently hinder O3 reduction efforts. Robust Volatile Organic Compounds (VOC) limiting schemes are prevalent in several metropolitan regions of DC, and ozone levels in these locations may increase if VOCs are inadequately regulated alongside NOx. Following the plan of action (PoA) from 2014 to 2018, manmade NOx emissions decreased by 20%, but VOCs rose by 2.5% countrywide. The alterations in NOx–VOC releases may be advantageous for diminishing FPM2.5 levels, although detrimental for O3, as shown by the reduced levels of FPM2.5 and elevated O3 levels throughout the corresponding timeframe. The rise in levels of O3 over the PoA's time is significantly influenced by fluctuations in climatic conditions, particularly changes in heat and short-wave exposure. Consequently, a comprehensive evaluation of climatology and optimum reduction of precursor releases are essential in formulating an efficient O3 control plan.

Furthermore, O3 pollution may be exacerbated by FPM2.5 reduction via a response pathway that influences the cessation of O3 production chemistry. Decreased particle substrates, where mixed interactions with ambient oxidants transpire, may result in terminal responses of some O3-depleting radicals. The decreased FPM2.5 inhibits the end of processes for radicals, augmenting the photochemical processes and O3 levels.

The aerosol dissipation effect (ADE) further complicates O3 production. The ADE is recognized for diminishing sun radiation, resulting in decreased photolysis kinetics and reduced O3 generation. Consequently, significant decreases in FPM2.5 may provide a possible danger of increased O3 levels. Moreover, the ADE may alter vertical temperature gradients and associated air equilibrium, airflow, visibility of clouds, and precipitation, which may subsequently affect O3 levels. The method by which climatic factors affect O3 demonstrates significant volatility, which is more complex than the immediate impact of ADE on radiation. Prior research indicated that O3 levels in eastern DC might rise by 3%–4% owing to an ADE-induced spike in antecedent levels, resulting from atmospheric stability linked to decreased global border layer elevation and circulation.

Results and Discussion

In this section, the air pollutants results for two major cities in DC, Beijing (DC-1) and Delhi (DC-2), have been considered for analysis. The time frame for analysis is from August 15, 2022, to September 15, 2022.

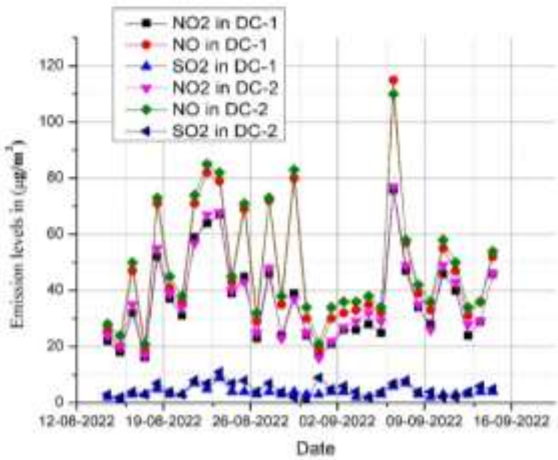

Figure 2. SO_2 and NO_x emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC

Figure 2 depicts the SO_2 and NO_x emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC. The levels of NO_2 and NO in both cities exhibited considerable variability during the period, with notable maxima on certain days, including September 7, when NO_2 reached 76 $\mu g/m^3$ in DC-1 and 77 $\mu g/m^3$ in DC-2, while NO levels were 115 $\mu g/m^3$ and 110 $\mu g/m^3$, respectively. SO_2 concentrations were relatively low, fluctuating from 1 to 11 $\mu g/m^3$, with peak values in late August and early September. This data illustrates daily fluctuations in air quality, possibly affected by variables such as industrial operations, vehicular traffic, and climatic conditions in metropolitan settings. The prevailing trend indicates a correlation in pollutant levels between the two cities, suggesting either common origins or similar patterns of pollution dispersion.

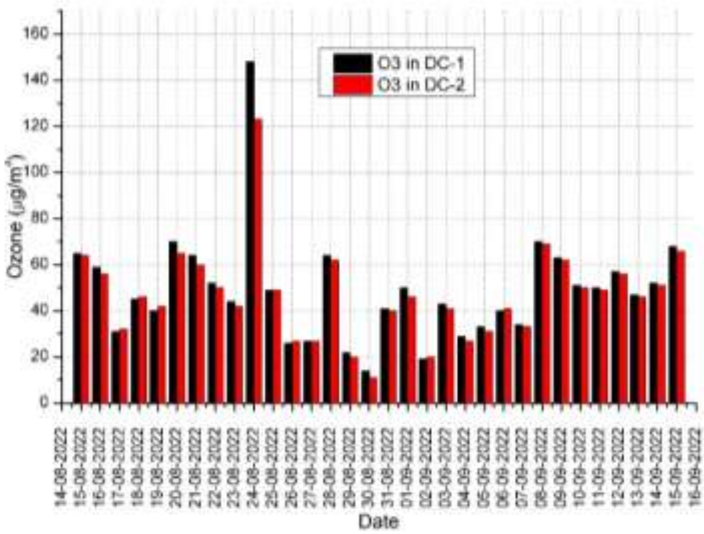

Figure 3. Ozone emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC

Figure 3 illustrates the Ozone emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC. The O_3 levels in both cities exhibit mild variations, with a notable peak on August 24, when DC-1 had an unusually high O_3 concentration of 148 $\mu g/m^3$ and DC-2 recorded 123 $\mu g/m^3$. This peak may signify an atypical pollution incident or certain environmental circumstances that momentarily increase ozone levels. After this increase, O_3 levels typically stabilized, averaging between 20-70 µg/m³ in both cities. The tight correlation of O_3 levels between DC-1 and DC-2 on most days indicates that both cities may be affected by analogous atmospheric or regional variables influencing ozone concentration.

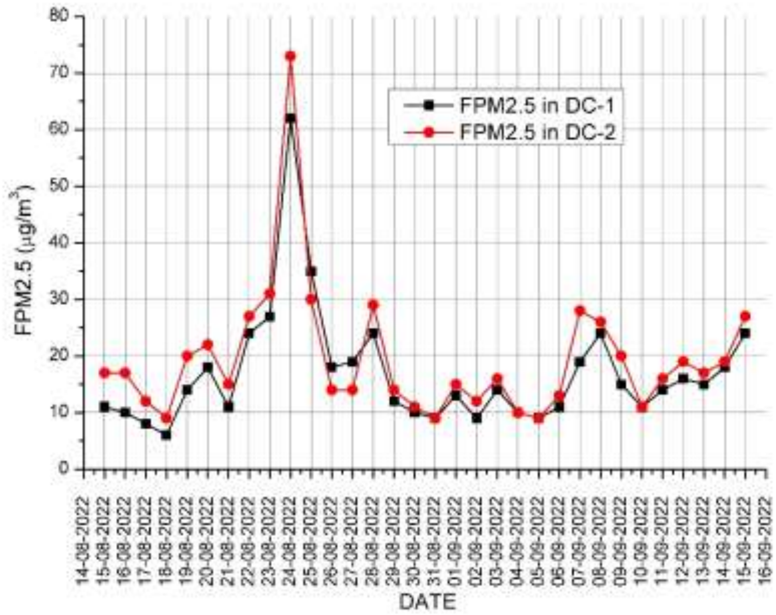

Figure. 4 FPM2.5 emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC

Figure 4 shows the FPM2.5 emission levels ($\mu g/m^3$) from August 15, 2022, to September 15, 2022, in two major cities in DC. The daily PM2.5 values typically range from 6 to 35 µg/m³, with a significant high on August 24, when DC-1 and DC-2 recorded 62 µg/m³ and 73 µg/m³, respectively. This surge may be ascribed to certain local or environmental variables, resulting in heightened particle pollution on that day. After this peak, FPM2.5 levels mostly stabilized, fluctuating daily values between 10-30 µg/m³. DC-2 regularly exhibits marginally elevated values of FPM2.5 compared to DC-1, indicating either worse air quality or supplementary emission sources in DC-2 throughout this timeframe.

Conclusion

This study has analyzed the progression of EAP legislation in DC, highlighting a deliberate transition from emission control to AQM. The control of SO2 emissions targeted the escalating acid rain issue in DC. Since 2015, regulatory initiatives across several sectors have sought to reduce the overall concentration of FPM2.5, indicating a transition towards an Air Quality Management-focused strategy. The increasing pollution of O3 requires comprehensive control strategies for both O3 and FPM2.5, emphasizing their complex photochemical interactions. The levels of NO_2 and NO in both cities exhibited considerable variability during the period, with notable maxima on certain days, including September 7, when NO_2 reached 76 µg/m³ in DC-1 and 77 µg/m³ in DC-2, while NO levels were 115 µg/m³ and 110 µg/m³, respectively. SO_2 concentrations were relatively low, fluctuating from 1 to 11 µg/m³, with peak values in late August and early September. This data illustrates daily fluctuations in air quality, possibly affected by variables such as industrial operations, vehicular traffic, and climatic conditions in metropolitan settings. FPM2.5 levels mostly stabilized, fluctuating daily values between 10-30 µg/m³. DC-2 regularly exhibits marginally elevated values of FPM2.5 compared to DC-1, indicating either worse air quality or supplementary emission sources in DC-2 throughout this timeframe. Substantial improvement of AQM in DC, as a vital indicator of the effectiveness of sustainable economic growth, requires a significant decrease in carbon emissions from DC's energy infrastructure and the implementation of more cohesive measures to address EAP and climate change in DC simultaneously.

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