# STUDYING THE CONTRIBUTION OF PUNJAB TO THE CAPITAL OF INDIA, MEGACITY DELHI USING WRF-CHEM WITH THE IMPROVED EDGAR EMISSION INVENTORY PREPARED FROM THE GROUND-BASED DATA

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by

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**Submitted**

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**to the**


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Dedicated to

Mummy, Papa, Rajeshwari and Shailaja

# CERTIFICATE

This is to certify that the thesis entitled "**Studying the Contribution of Punjab on Capital of India, Megacity Delhi using WRF-Chem with the improved EDGAR Emission Inventory prepared from the Ground-Based Data**", being submitted by **Mr. Arpit Katiyar**, to the **Indian Institute of Technology Delhi** for the award of the degree of '**Doctor of Philosophy**' in Department of Civil Engineering is a record of the bonafide research work carried out by her under my supervision and guidance. He has fulfilled the requirements for the submission of this thesis, which to the best of my knowledge has reached the requisite standard.

The material contained in the thesis has not been submitted in part or full to any other University or Institute for the award of any other degree or diploma.

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**(Arpit Katiyar)**

# ABSTRACT

Air pollution is a critical global environmental issue with profound implications for human health, ecosystems, and climate. This challenge is particularly acute in urban areas of developing countries like India, where cities such as Delhi consistently rank among the most polluted in the world. Delhi's air quality has been severely compromised due to a combination of rapid urbanization, unchecked industrial growth, and an expanding number of vehicles, all contributing to high levels of harmful pollutants. This comprehensive analysis investigates the complex relationship between regional emissions from Punjab and air quality in Delhi, employing advanced air quality modeling tools such as the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) and an improved Emissions Database for Global Atmospheric Research (EDGAR) emission inventory. Developed using meticulous ground-based data from various sources in Punjab, this study aims to elucidate how emissions from Punjab, particularly those from crop residue burning, industrial activities, vehicular emissions, and road dust, contribute to the severe air pollution in Delhi.

Delhi's air pollution crisis is not only a result of local emissions. While the city's rapid urbanization, industrialization, and increasing vehicle numbers are significant contributors, these are exacerbated by its geographical and meteorological conditions. Delhi is located in the Indo-Gangetic Plain, where pollutants are easily trapped, creating conditions that are conducive to smog formation, especially in winter. This smog is further intensified by transboundary pollution, with significant contributions from neighboring states like Punjab. The anthropogenic activities in Punjab, emits pollutants into the atmosphere. These pollutants are then carried by prevailing winds into the Delhi-NCR (National Capital Region), significantly worsening air quality and posing severe health risks and environmental degradation.

Effective management and mitigation of air pollution in Delhi require accurate and detailed emission inventories. These inventories are crucial tools in air quality management, providing a comprehensive database of the pollutants released into the atmosphere from various sources. They are indispensable for policymakers, environmental planners, and researchers as they quantify pollutant emissions over a specific period. This analysis discusses several methodologies for developing emission inventories, including bottom-up, top-down, and hybrid approaches. Bottom-up approaches involve collecting detailed data from individual sources, offering high accuracy but requiring extensive resources. Top-down approaches, in contrast, use aggregated data to estimate emissions on a larger scale, providing broader

coverage with less precision. Hybrid approaches combine both methods to offer a comprehensive and balanced view of emissions. Despite methodological advancements, creating accurate emission inventories in developing countries like India remains challenging due to constraints in data availability and quality.

Punjab's significant contribution to Delhi's air pollution, particularly during the post-monsoon season when crop residue burning is widespread, underscores the importance of focusing on this region. Although local emissions in Delhi are a major source of pollution, the transboundary nature of air pollution means that emissions from neighboring states like Punjab cannot be ignored. These fine particles are particularly harmful to human health, capable of penetrating deep into the lungs and entering the bloodstream, leading to a range of respiratory and cardiovascular diseases. Additionally, the industrial sector in Punjab, along with vehicular emissions and road dust, further contributes to the region's air pollution, which can be transported across state borders, affecting air quality far beyond Punjab.

The study employs a phased approach, beginning with the development of a high-resolution emission inventory for Punjab. This inventory is based on ground-based data collected from various sources, including domestic emissions, vehicular traffic, industrial activities, and road dust. By developing the emission inventory at a fine spatial resolution of 1000 m x 1000 m, the study allows for a detailed analysis of emissions across different regions of Punjab, enabling the identification of pollution hotspots and assessing their impact on regional air quality. The inventory includes data on key pollutants such as $PM_{10}$, $PM_{2.5}$, sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$), and carbon monoxide (CO), all of which play significant roles in the region's air quality dynamics.

To further enhance the accuracy and relevance of the emission inventory, the study identifies pollution episodes in Delhi-NCR using data from Continuous Ambient Air Quality Monitoring Stations (CAAQMS). Statistical techniques like Interquartile Range (IQR) and Mean Absolute Deviation (MAD) are employed to establish criteria for these episodes, which are characterized by sudden spikes in pollutant concentrations due to a combination of local emissions and transboundary pollution. Understanding these episodes is crucial for analyzing the temporal dynamics of air pollution in Delhi and identifying periods when regional contributions, particularly from Punjab, are most significant.

Building on the emission inventory, the study updates the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory for North India using the newly developed Punjab inventory. This updated inventory is then utilized in the WRF-Chem model to simulate the impact of Punjab's emissions on Delhi's air quality. The WRF-Chem model is

a state-of-the-art tool that integrates meteorological data with chemical transport models, simulating the dispersion, transformation, and deposition of pollutants in the atmosphere. This modeling phase provides valuable insights into the regional transport of pollutants and their contribution to air quality in Delhi during specific pollution episodes. The simulations reveal that a significant portion of Delhi's air pollution can be traced back to emissions from Punjab, particularly during winter months when meteorological conditions favor the transport of pollutants from the northwest to the capital region.

The results of this analysis underscore the significant contribution of Punjab's emissions to the pollution levels in Delhi. Several pollution hotspots are identified in Punjab, particularly in regions with high agricultural activity, industrial emissions, and dense vehicular traffic. During the winter months, when crop residue burning is most prevalent, emissions from Punjab significantly contribute to the elevated levels of $PM_{2.5}$ and $PM_{10}$ observed in Delhi. These fine particles are particularly concerning due to their ability to remain suspended in the air for extended periods and their potential to cause serious health issues, including respiratory infections, heart disease, and lung cancer. The WRF-Chem simulations confirm that during episodic pollution events, when air quality in Delhi deteriorates sharply, a substantial portion of the pollutants can be attributed to transboundary contributions from Punjab.

Addressing these challenges requires regional cooperation in air quality management. Pollution control efforts in Delhi alone may not be sufficient to achieve significant improvements in air quality, given the transboundary nature of air pollution. Coordinated efforts between Punjab and Delhi, as well as with other neighbouring states, are essential for effectively managing and reducing air pollution. The analysis suggests several pollution control strategies that could mitigate the impact of Punjab's emissions on Delhi's air quality. These include promoting alternative uses of crop residues to reduce the need for burning, improving industrial emission standards, enhancing vehicular emission controls, and implementing road dust management practices. Each of these measures could significantly reduce Punjab's contribution to Delhi's air pollution if implemented in a coordinated and sustained manner.

The findings of this analysis highlight the critical role of accurate emission inventories and advanced air quality models in understanding and managing air pollution. The WRF-Chem model, combined with the improved EDGAR emission inventory, proves to be a powerful tool for assessing the impact of regional emissions on air quality and provides valuable insights for policymakers and environmental planners. The analysis also emphasizes the need for continuous air quality monitoring, further refinement of emission inventories, and the

development of more sophisticated models to improve the understanding of air pollution dynamics and its impacts.

Future research and policy development should focus on enhancing the accuracy and resolution of emission inventories, integrating real-time data collection, and employing more advanced modeling techniques. Additionally, greater public awareness and engagement in air quality management efforts are necessary, along with stricter pollution control measures at both state and national levels. Despite challenges in data availability and the complexities of modeling atmospheric processes, this analysis significantly contributes to the field of air quality research and offers a robust framework for future studies on the impact of regional emissions on urban air quality.

In summary, this analysis serves as a critical resource for understanding the complex dynamics of air pollution in North India and offers practical insights for mitigating the impact of regional emissions on Delhi's air quality. The findings underscore the need for a comprehensive approach to air quality management that considers both local and regional pollution sources and highlights the importance of advanced modeling tools in informing policy decisions. By providing a detailed understanding of the sources and impacts of air pollution in Delhi, this analysis contributes to ongoing efforts to improve air quality, protect public health, and ensure a sustainable environment in one of the world's most polluted urban regions.

**Keywords:** Emission Inventory, Bottom Up Approach, Domestic emissions, Vehicular, Road Dust, Silt loading, Relative risk, Lower middle-income countries, Mortality, Morbidity, $PM_{2.5}$, $PM_{10}$, $SO_2$, $NO_x$, CO, India, AQI, WRF-Chem

# सार

वायु प्रदूषण एक गंभीर वैश्विक पर्यावरणीय समस्या है, जिसका मानव स्वास्थ्य, पारिस्थितिकी तंत्र, और जलवायु पर गहरा प्रभाव पड़ता है। यह चुनौती विशेष रूप से विकासशील देशों के शहरी क्षेत्रों में तीव्र है, जैसे भारत में, जहां दिल्ली जैसे शहर विश्व के सबसे प्रदूषित शहरों में लगातार शुमार होते हैं। दिल्ली की वायु गुणवत्ता तेजी से शहरीकरण, अनियंत्रित औद्योगिक विकास, और वाहनों की बढ़ती संख्या के कारण गंभीर रूप से प्रभावित हुई है, जो हानिकारक प्रदूषकों के उच्च स्तर का योगदान करते हैं। यह व्यापक विश्लेषण पंजाब से होने वाले क्षेत्रीय उत्सर्जन और दिल्ली की वायु गुणवत्ता के बीच जटिल संबंधों की जांच करता है, जिसमें वायुमंडलीय अनुसंधान के लिए मौसम अनुसंधान और पूर्वानुमान मॉडल को रसायन विज्ञान (WRF-Chem) और वैश्विक वायुमंडलीय अनुसंधान (EDGAR) उत्सर्जन इन्वेंटरी के साथ जोड़ा गया है। पंजाब के विभिन्न स्रोतों से प्राप्त सावधानीपूर्वक ग्राउंड-आधारित डेटा का उपयोग करके विकसित यह अध्ययन यह स्पष्ट करने का प्रयास करता है कि पंजाब से उत्सर्जन, विशेष रूप से फसल अवशेष जलाने, औद्योगिक गतिविधियों, वाहन उत्सर्जन, और सड़क धूल से, दिल्ली में गंभीर वायु प्रदूषण में कैसे योगदान करते हैं।

दिल्ली का वायु प्रदूषण संकट केवल स्थानीय उत्सर्जनों का परिणाम नहीं है। जबकि शहर का तेजी से शहरीकरण, औद्योगिकीकरण, और बढ़ती वाहन संख्या महत्वपूर्ण योगदानकर्ता हैं, इन्हें इसके भूगोल और मौसम विज्ञान की स्थिति और बढ़ा देती हैं। दिल्ली इंडो-गैंगेटिक मैदान में स्थित है, जहां प्रदूषक आसानी से फंस जाते हैं, जिससे विशेष रूप से सर्दियों में स्मॉग बनने की स्थिति पैदा होती है। इस स्मॉग को और भी बढ़ा देता है सीमापार प्रदूषण, जिसमें पंजाब जैसे पड़ोसी राज्यों से महत्वपूर्ण योगदान मिलता है। पंजाब के कृषि अभ्यास, विशेष रूप से कटाई के बाद धान की पराली जलाना, वायुमंडल में भारी मात्रा में कण पदार्थ और अन्य प्रदूषकों को छोड़ता है। ये प्रदूषक फिर प्रचलित हवाओं द्वारा दिल्ली-एनसीआर क्षेत्र में ले जाए जाते हैं, जिससे वायु गुणवत्ता बहुत खराब हो जाती है और गंभीर स्वास्थ्य जोखिम और पर्यावरणीय क्षरण होता है।

दिल्ली में वायु प्रदूषण के प्रबंधन और न्यूनीकरण के लिए सटीक और विस्तृत उत्सर्जन इन्वेंटरी की आवश्यकता होती है। ये इन्वेंटरी वायु गुणवत्ता प्रबंधन में महत्वपूर्ण उपकरण हैं, जो वायुमंडल में विभिन्न स्रोतों से छोड़े गए प्रदूषकों का एक व्यापक डेटाबेस प्रदान करती हैं। वे नीति-निर्माताओं, पर्यावरण योजनाकारों और शोधकर्ताओं के लिए अनिवार्य हैं क्योंकि वे एक विशिष्ट अवधि में प्रदूषक उत्सर्जन को मापते हैं। यह विश्लेषण उत्सर्जन

इन्वेंटरी विकसित करने के लिए कई पद्धतियों पर चर्चा करता है, जिसमें बॉटम-अप, टॉप-डाउन, और हाइब्रिड दृष्टिकोण शामिल हैं। बॉटम-अप दृष्टिकोणों में व्यक्तिगत स्रोतों से विस्तृत डेटा एकत्र करना शामिल होता है, जो उच्च सटीकता प्रदान करता है लेकिन व्यापक संसाधनों की आवश्यकता होती है। इसके विपरीत, टॉप-डाउन दृष्टिकोण संयुक्त डेटा का उपयोग करके बड़े पैमाने पर उत्सर्जन का अनुमान लगाते हैं, जो कम सटीकता के साथ व्यापक कवरेज प्रदान करते हैं। हाइब्रिड दृष्टिकोण दोनों तरीकों को मिलाते हैं, जो उत्सर्जन का व्यापक और संतुलित दृष्टिकोण प्रदान करते हैं। हालांकि, डेटा उपलब्धता और गुणवत्ता में बाधाओं के कारण विकासशील देशों जैसे भारत में सटीक उत्सर्जन इन्वेंटरी बनाना चुनौतीपूर्ण बना रहता है।

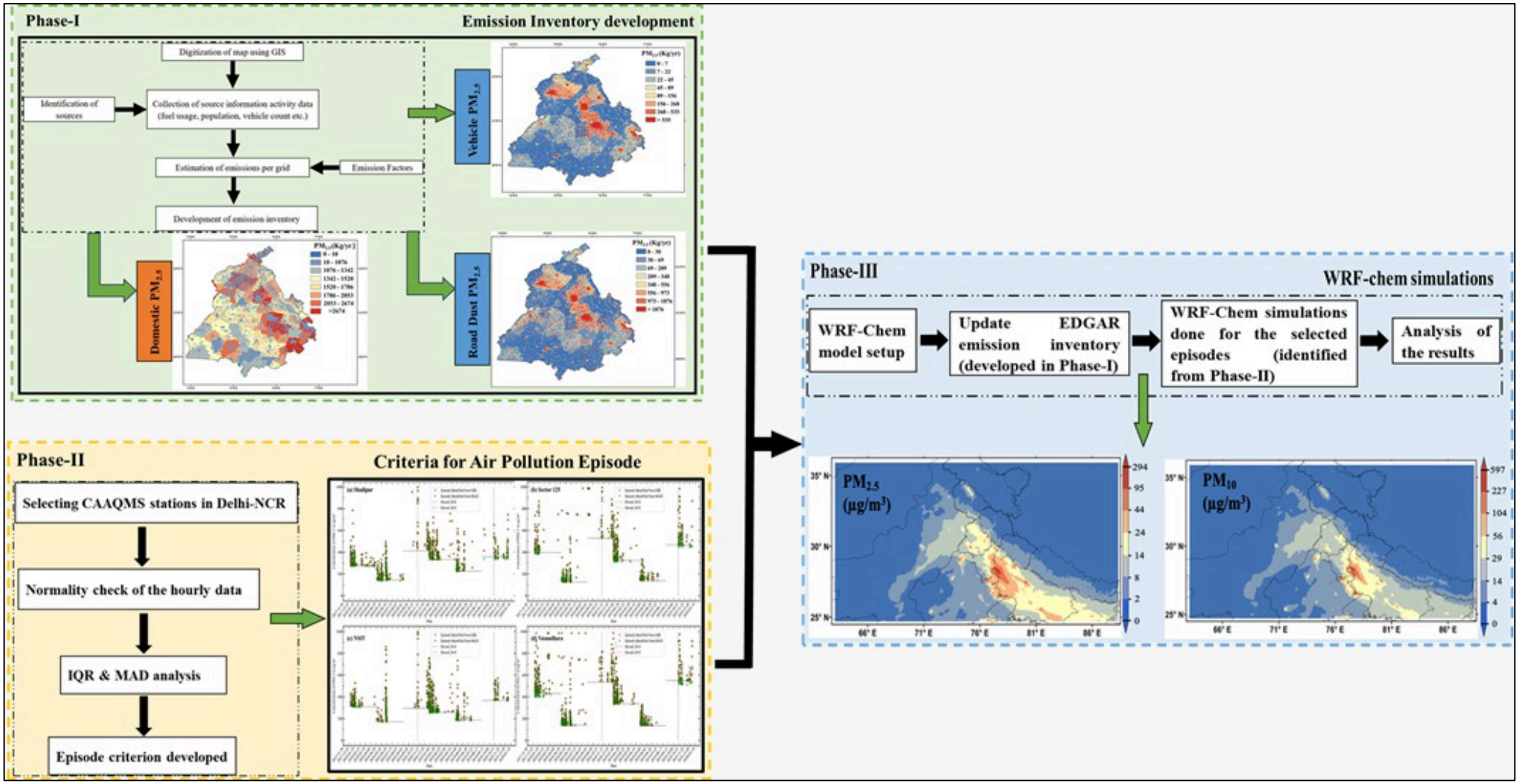
पंजाब का दिल्ली के वायु प्रदूषण में महत्वपूर्ण योगदान, विशेष रूप से मानसून के बाद के मौसम में जब फसल अवशेष जलाना व्यापक होता है, इस क्षेत्र पर ध्यान केंद्रित करने की आवश्यकता को रेखांकित करता है। जबकि दिल्ली में स्थानीय उत्सर्जन प्रदूषण का एक प्रमुख स्रोत है, वायु प्रदूषण की सीमापार प्रकृति का मतलब है कि पंजाब जैसे पड़ोसी राज्यों से होने वाले उत्सर्जनों को नजरअंदाज नहीं किया जा सकता। ये सूक्ष्म कण विशेष रूप से मानव स्वास्थ्य के लिए हानिकारक होते हैं, जो फेफड़ों में गहराई तक प्रवेश करने और रक्तप्रवाह में प्रवेश करने में सक्षम होते हैं, जिससे विभिन्न श्वसन और हृदय रोग हो सकते हैं। इसके अलावा, पंजाब में औद्योगिक क्षेत्र, साथ ही वाहन उत्सर्जन और सड़क धूल, क्षेत्र के वायु प्रदूषण में और योगदान करते हैं, जो राज्य की सीमाओं से पार होकर पंजाब से परे वायु गुणवत्ता को प्रभावित कर सकते हैं।

यह अध्ययन चरणबद्ध दृष्टिकोण का उपयोग करता है, जो पंजाब के लिए एक उच्च-रिज़ॉल्यूशन उत्सर्जन इन्वेंटरी के विकास के साथ शुरू होता है। यह इन्वेंटरी घरेलू उत्सर्जन, वाहनों की ट्रैफिक, औद्योगिक गतिविधियों, और सड़क धूल सहित विभिन्न स्रोतों से एकत्र किए गए ग्राउंड-आधारित डेटा पर आधारित है। पंजाब के विभिन्न क्षेत्रों में उत्सर्जन का विस्तृत विश्लेषण करने और प्रदूषण के हॉटस्पॉट की पहचान करने और उनके क्षेत्रीय वायु गुणवत्ता पर प्रभाव का आकलन करने के लिए, इन्वेंटरी को 1000 मीटर x 1000 मीटर के फाइन स्पेशल रिज़ॉल्यूशन पर विकसित किया गया है। इन्वेंटरी में प्रमुख प्रदूषकों जैसे $PM_{10}$, $PM_{2.5}$, सल्फर ऑक्साइड्स ($SO_2$), नाइट्रोजन ऑक्साइड्स ($NO_x$), और कार्बन मोनोऑक्साइड (CO) के डेटा शामिल हैं, जो क्षेत्र की वायु गुणवत्ता गतिशीलता में महत्वपूर्ण भूमिका निभाते हैं।

उत्सर्जन इन्वेंटरी की सटीकता और प्रासंगिकता को और बढ़ाने के लिए, अध्ययन दिल्ली-एनसीआर में निरंतर परिवेशी वायु गुणवत्ता निगरानी स्टेशनों (CAAQMS) से डेटा का उपयोग करके प्रदूषण के प्रकरणों की पहचान करता है। स्थानीय उत्सर्जन और सीमापार प्रदूषण के संयोजन के कारण अचानक प्रदूषक सांद्रता में बढ़ोतरी से इन प्रकरणों की विशेषता होती है, जिसके लिए इंटरक्वार्टाइल रेंज (IQR) और मीन एब्सोल्यूट डेविएशन (MAD) जैसी सांख्यिकीय तकनीकों का उपयोग किया जाता है। इन प्रकरणों को समझना दिल्ली में वायु प्रदूषण की समयगतिशीलता का विश्लेषण करने और उन अवधियों की पहचान करने के लिए महत्वपूर्ण है जब क्षेत्रीय योगदान, विशेष रूप से पंजाब से, सबसे महत्वपूर्ण होते हैं। उत्सर्जन इन्वेंटरी के आधार पर, अध्ययन उत्तर भारत के लिए EDGAR उत्सर्जन इन्वेंटरी को पंजाब की नई विकसित इन्वेंटरी का उपयोग करके अपडेट करता है। यह अपडेटेड इन्वेंटरी फिर WRF-Chem मॉडल में उपयोग की जाती है ताकि पंजाब के उत्सर्जनों का दिल्ली की वायु गुणवत्ता पर प्रभाव का अनुकरण किया जा सके। WRF-Chem मॉडल एक अत्याधुनिक उपकरण है जो मौसम संबंधी डेटा को रासायनिक परिवहन मॉडल्स के साथ एकीकृत करता है, वायुमंडल में प्रदूषकों के फैलाव, परिवर्तन और जमाव का अनुकरण करता है। यह मॉडलिंग चरण क्षेत्रीय प्रदूषकों के परिवहन और उनके दिल्ली की वायु गुणवत्ता में योगदान के बार

**मुख्य शब्द:** उत्सर्जन इन्वेंटरी, बॉटम अप दृष्टिकोण, घरेलू उत्सर्जन, वाहन संबंधित, सड़क धूल, सिल्ट लोडिंग, सापेक्ष जोखिम, निम्न-मध्यम आय वाले देश, मृत्यु दर, रोगात्मकता, $PM_{2.5}$, $PM_{10}$, $SO_2$, $NO_x$, CO, भारत, AQI, WRF-Chem

# GRAPHICAL ABSTRACT



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| | |
|---|---|
| 2W | Two Wheelers |
| 3W | Three Wheelers |
| 4W | Four Wheelers |
| AADT | Annual Average Daily Traffic |
| AERMOD | American Meteorological Society/Environmental Protection Agency Regulatory Model |
| AOD | Aerosol optical depth |
| BAU | Business As Usual |
| BB | Biomass burning |
| BC | Black Carbon |
| BS | Bharat Standards |
| CA | Carboncaeous aerosol |
| CAAQMS | Continuous ambient air quality monitoring stations |
| CAGR | Compound Annual Growth Rate |
| CD | Cow Dung |
| C&D | Construction and Demolition |
| CI | Confidence Interval |
| CMAQ | Community Multiscale Air Quality |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COPD | Chronic obstructive pulmonary disease |
| CPCB | Central Pollution Control Board |
| CR | Crop Residue |
| DALY | Disability Adjusted Life Years |
| DG | Diesel Generator |
| DPCC | Delhi Pollution Control Committee |
| EDGAR | Emissions Database for Global Atmospheric Research |
| EF | Emission Factor |
| EPA | Environmental Protection Agency |
| ER | Emission Rate |

| | |
|---|---|
| FW | Fire Wood |
| FJ | Food Joint |
| GBD | Global Burden of Disease |
| GIS | Geographical Information System |
| GLM | Gnerlaized linear model |
| GNI | Gross National Income |
| HCV | Heavy Commercial Vehicle |
| HIC | High income countries |
| IGP | Indo Gangetic Plain |
| IHD | Ischemic Heart Disease |
| IMD | India Meteorological Department |
| IND | Industry sector |
| IQR | Inter quartile range |
| LCV | Light Commercial Vehicle |
| LIC | Low income countries |
| LMIC | Lower middle income countries |
| LPG | Liquified Petroleum Gas |
| MATLAB | Matrix Laboratory |
| MEGAN | Model of Emissions of Gases and Aerosols from Nature |
| MFB | Mean fractional bias |
| MFE | Mean fractional error |
| MSE | Mean Squared error |
| NAAQS | National Ambient Air Quality Standards |
| NCAP | National Clean Air Programme |
| NCAR | National Centre for Atmospheric Research |
| NCEP | National Centre for Environmental Prediction |
| NCR | National Capital Region |
| NEERI | National Environmental Engineering Research Institute |
| NGT | National Green Tribunal |
| NMB | Normalised mean bias |
| NMSE | Normalized mean square error |
| NO | Nitrogen monoxide |
| $NO_2$ | Nitrogen dioxide |

| | |
|---|---|
| NSUT | Netaji Subash University of Technology |
| NWP | Numerical Weather Prediction |
| OEO | Open Eat Out |
| $O_2$ | Oxygen |
| PBL | Planetary Boundary Layer |
| $PM_{2.5}$ | Particulate Matter of aerodynamic diameter 2.5 µm or less |
| $PM_{10}$ | Particulate Matter of aerodynamic diameter 10 µm or less |
| PUC | Pollution Under Control |
| RD | Respiratory diseases |
| R&D | Research and Development |
| RES | Residential sector |
| RH | Relative humidity |
| RMSE | Root mean square error |
| RR | Relative risk |
| SAFAR | System of Air Quality and Weather Forecasting And Research |
| SIA | Secondary inorganic aerosol |
| SOx | Sulphur Dioxide |
| SOA | Secondary organic aerosol |
| SPM | Suspended particulate matter |
| TB | Tuberculosis |
| UI | Uncertainty Interval |
| UMIC | Upper middle income countries |
| USEPA | United States Environmental Protection Agency |
| VC | Ventilation coefficient |
| VKT | Vehicle Kilometer Travelled |
| VOC | Volatile Organic Compounds |
| WHO | World Health Organization |
| WPS | WRF Preprocessing System |
| WRF | Weather Research and Forecasting |
| WRF-Chem | Weather Research and Forecasting with chemistry module |
| YLD | Life lived with Disability |
| YLL | Years of Life Lost |