

# **ASSESSING AIR QUALITY IMPACTS FROM INDIAN AGRICULTURE SECTOR**

**THIRUNAGARI BABY KEERTHI**



**DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI  
MARCH 2026**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2026

# **ASSESSING AIR QUALITY IMPACTS FROM INDIAN AGRICULTURE SECTOR**

**By**

**THIRUNAGARI BABY KEERTHI**

Department of Civil and Environmental Engineering

**Submitted**

In the fulfilment of the requirements of the degree of Doctor of Philosophy

**to the**



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**March 2026**

*Dedicated to my parents,  
my brother,  
and my special friend Sai Teja*

*कर्मण्येवाधिकारस्ते मा फलेषु कदाचन।  
मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि ॥  
(Bhagavad Gita, Chapter 2, Verse: 47)*

## CERTIFICATE

This is to certify that the thesis entitled “**Assessing Air Quality Impacts from Indian Agriculture Sector**” is being submitted by **Ms. Thirunagari Baby Keerthi** to the **Indian Institute of Technology Delhi** for the award of the degree of ‘**Doctor of Philosophy**’ in the Department of Civil and Environmental Engineering and is a record of the bonafide research work carried out by her under my supervision. She has fulfilled the requirements of the Indian Institute of Technology Delhi for the submission of this thesis, which, to the best of my knowledge, has reached the requisite standard.

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



**(Prof. Sri Harsha Kota)**

Professor

Department of Civil and Environmental  
Engineering,

Indian Institute of Technology Delhi,

New Delhi-110016, India

**(Dr. Rajesh Kumar)**

Deputy Lab Director,

Research Applications Laboratory,

National Center for Atmospheric Research,

Boulder, CO 80301, USA

## ACKNOWLEDGEMENTS

The path to completing this thesis has been demanding yet deeply enriching, a journey marked by perseverance and numerous learnings. Along the way, I have been fortunate to receive unwavering support, guidance, and encouragement from many remarkable individuals. I express heartfelt gratitude to all who stood by me, making this challenging yet rewarding journey possible.

First and foremost, I would like to express my profound gratitude to my respected supervisors, Prof. Sri Harsha Kota (IIT Delhi, India) and Dr. Rajesh Kumar (NCAR, USA). Their continuous support, scholarly guidance, intellectual insight, and critical feedback have been instrumental throughout the journey of this thesis. Their mentorship has not only shaped the direction of this research but also significantly contributed to my personal and professional growth as a researcher.

I am deeply indebted to them for their patience, encouragement, and for always being available to discuss ideas, resolve doubts, and motivate me during challenging times. They provided me with invaluable opportunities to learn, collaborate, and present my work, which has greatly enriched my academic experience and broadened my horizons. I feel truly fortunate to have worked under their guidance and will always remain grateful for their mentorship and the immense impact they have had on both my career and character.

My genuine thanks and sincere admiration to the members of my student research committee, Prof. Shashank Bishnoi (Chairman), Prof. Arvind Kumar Nema (Expert from the Department), and Prof. Sagnik Dey (Expert from outside the Department) for their best reviews, constructive comments, and helpful suggestions. Their thoughtful comments have significantly influenced the development and academic strength of this work. I extend my sincere thanks to the professors and staff of the Department of Civil and Environmental Engineering, IITD, for their invaluable help and assistance throughout my academic journey here. Additionally, my sincere appreciation lies with Mr. Rajiv Sharma (Geomatics Lab, IITD), and Dr. Sanjay Kumar Gupta and Ms. Debasmita Mallik (Environmental Engineering Lab, IITD).

I would like to acknowledge the financial support provided by the *Prime Minister's Research Fellows (PMRF) Scheme*, as well as IIT Delhi's *Full-Time Institute Assistantship (FTIA)*.

Personal thanks go to my colleagues and friends of the *Environmental Computational Lab* (Room: 333) Mr. Vishwanath Velamuri, Mr. Gandham Phani Kumar, Ms. Shipra Lakshmi, Dr. Aparna Sharma, Dr. Sasi Kumar N, Mr. Parmar Pareshbhai Dineshbhai. I am glad for all the support from the members of Urban Regional Air Quality Modeling (URAM) Group and the various research scholars working with Prof. Sri Harsha Kota (Dr. Shubham Sharma, Dr. Arpit Katiyar, Mr. Diljit Kumar Nayak, Mrs. Pratibha Anand, Ms. Medhavi Gupta). I use this chance to thank my friend group at IIT Delhi (Dr. Durga Prasad Tripathi, Mr. Vannum Siva Prasad, Mr. Poralla Venkat Sateesh, Dr. Chappidi Srinivas, and Mr. Venu) for all the comradeship, discussions, and moral support. I extend my thanks to all my teachers and mentors (Prof. Rajyalakshmi Garaga (IIT Jodhpur), and Prof. Sumanth Chinthala (NIT Warangal)) for their professional support and best wishes. I take this opportunity to thank all the research scholars of Environmental Engineering for their companionship.

Special and profound recognition goes to my brother, Mr. Thirunagari Sai Aravindh, for his constant support. I wish to express immense gratitude to my close friend, Mr. Thota Sai Teja, for his continual encouragement, particularly during the most demanding phases of this endeavor. I owe my deepest gratitude to my colleague and friend Dr. Gummadivalli Shiva Kumar, who has been nothing less than a brother to me. His unwavering support, sincere guidance, and constant encouragement have been a pillar of strength throughout this journey, and I could not have accomplished this without him. Their invaluable love and backing have been pivotal to both my personal and professional journey.

Finally, I extend my deepest and most heartfelt acknowledgment to my beloved parents, Mr. Thirunagari VenkataNarasaiah and Mrs. Thirunagari Sridevi, for their unconditional love and steadfast support, which have been the foundation of my journey. Their sacrifices, values, and constant encouragement have been a source of strength and inspiration throughout my life. They have instilled in me the discipline to work hard, the courage to face challenges, and the humility to stay grounded. This achievement is as much theirs as it is mine.



**(THIRUNAGARI BABY KEERTHI)**

## ABSTRACT

Agriculture constitutes a fundamental pillar of human civilization, sustaining food production through crop cultivation and livestock husbandry. However, the environmental consequences of agricultural practices are not confined to farmland boundaries; they extend to surrounding ecosystems and the atmosphere. Agricultural activities contribute substantially to air pollutant emissions, leading to atmospheric degradation. Further, different sectors of agriculture emit various greenhouse gas emissions. In India, the agricultural sector represents a significant source of such emissions, with pronounced implications for regional air quality, climate variability, and public health. However, previous research on agricultural emission sources in India has primarily been limited to specific activities, including crop residue burning (CRB) and fertilizer application (FA). Consequently, a nationally consistent and comprehensive emission inventory (EI) for India that incorporates the full spectrum of major agricultural operations remains underdeveloped. This gap constrains the accurate quantification of agricultural emissions and limits the ability to robustly assess, predict, and mitigate their impacts on air quality and human health. Also, existing global EIs often omit important agricultural processes and fail to capture the spatial and seasonal variability critical for accurate modelling and mitigation planning.

Existing EIs rely on fixed emission factors (EFs) and lack temporal resolution, leading to substantial uncertainties, especially in a country like India, which is the second-largest global consumer of synthetic fertilizers and home to extensive CRB and livestock activity. Therefore, there is a pressing need for updated, localized EIs that can support robust air quality modelling and health risk assessments. In addition, there is a need for the development and implementation of effective mitigation strategies for this sector, alongside the systematic identification and quantitative characterization of emission sources, to enable informed decision-making and facilitate the evaluation of mitigation progress within the agricultural

system. To address these gaps, this study aims to develop a high-resolution, regionally specific agricultural EI for India, encompassing key operations including FA, tillage, CRB, and livestock activities. In addition, the study evaluates the effectiveness of various mitigation strategies associated with each of these agricultural practices to inform policy and management decisions. The developed EI is subsequently applied within the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) modeling framework to assess its utility in accurately predicting air pollutant concentrations. Finally, the study examines the potential health impacts attributable to agricultural emissions, providing a comprehensive assessment of the sector's influence on the air quality and public health.

A district-level EI was developed for the year 2018–19 at  $0.1^\circ \times 0.1^\circ$  spatial and monthly temporal resolution, incorporating crop-specific fertilizer use (covering 52 crops), CRB estimates based on fire radiative energy (FRE) correlations, monthly tillage emissions based on field surveys, and livestock emissions using updated India-specific EFs. Activity data was obtained from various sources, with field surveys across 102 districts in 14 states. The inventory was then used to evaluate the impact of various mitigation strategies and to drive simulations with the WRF-Chem for the year 2022. Two scenarios were analyzed, one using the Emission Database for Global Atmospheric Research (EDGAR) inventory (EEI) and another with a Modified EDGAR EI (MEEI). MEEI is equivalent to EEI, with EDGAR's agricultural emissions replaced with the developed agricultural EI. An additional one-month WRF-Chem simulation using 'EEI without agricultural emissions' isolated their health burden.

The resulting EI estimates show annual emissions of 3.15 Tg  $\text{NH}_3$  and 138.53 Gg  $\text{N}_2\text{O}$  from FA, 583 Gg  $\text{PM}_{10}$  and 278 Gg  $\text{PM}_{2.5}$  from tillage, 3.4 Tg  $\text{NH}_3$  and 14 Tg  $\text{CH}_4$  from livestock, and CRB emissions were dominant from rice and wheat residues, particularly in the Indo-Gangetic Plain. Urea accounted for over 93% of FA-related emissions, and cattle and buffalo contributed 91% of  $\text{CH}_4$  emissions from livestock. Temporal analysis revealed distinct seasonal

peaks, such as NH<sub>3</sub> and N<sub>2</sub>O in July–August for FA activity and CRB in October–November for PM. Mitigation assessments indicate that strategies like NBPT-coated urea, zero tillage, sustainable crop residue management, and livestock dietary improvements could reduce emissions by up to 44%. Zero tillage adoption (25% conversion of conventional tillage land to zero tillage) reduced PM emissions by 17%, and dietary changes in livestock decreased CH<sub>4</sub> by 12%.

WRF-Chem simulations with MEEI improved model accuracy substantially, reducing bias in PM<sub>2.5</sub> by 24%, NH<sub>3</sub> by 50% in agriculturally intensive regions, and aligning better with observed seasonality. Further, WRF-Chem simulated annual average aerosol optical depth (AOD) correlations improved when compared to MODIS AOD with coefficient of determination ( $R^2$ ) increasing from 0.67 with EEI to 0.74 with MEEI. These enhancements were particularly more evident during peak emission periods, such as tilling and FA months. Critically, health impact assessment revealed that agriculture alone contributes 16.4% of PM<sub>2.5</sub>-related premature mortality, compared to 11% under EEI, translating to an additional 0.53 lakh deaths, with the Indo-Gangetic Plain being the most affected region. Furthermore, agricultural emissions not only drive air pollution but also alters near-surface temperature through aerosol–radiation feedback. Excluding agricultural emissions from simulations led to systematic overestimation of near-surface temperatures, exceeding 1.5 °C in BR and AS and 1.38-1.2 °C in WB, UP, and MP. With MEEI, temperature biases decreased by ~1.25 °C on average across agriculturally intensive states, underscoring the pivotal role of agricultural aerosols in shaping regional temperatures

In conclusion, this study underscores the necessity of localized, temporally resolved agricultural EIs for India. The demonstrated improvements in model fidelity and health impact estimation reinforce the value of such EIs in guiding air quality regulation, climate policy, and sustainable agricultural practices. This work lays the foundation for science-driven

policymaking aimed at reducing agricultural emissions while safeguarding environmental and public health outcomes.

**Keywords:** Emission Inventory, Particulate Matter, Ammonia, WRF-Chem, Aerosol Optical Depth, MODIS AOD, IASI NH<sub>3</sub>, Fertilizer Application, Tillage Activity, Crop Residue Burning, Livestock, Health Analysis, Temperature, Agriculture Sector, India

## सार

कृषि मानव सभ्यता का एक मूलभूत स्तंभ है, जो फसल उत्पादन और पशुपालन के माध्यम से खाद्य उत्पादन को बनाए रखती है। हालांकि, कृषि पद्धतियों के पर्यावरणीय परिणाम केवल खेतों तक ही सीमित नहीं हैं; वे आसपास के पारिस्थितिकी तंत्र और वायुमंडल तक भी फैलते हैं। कृषि गतिविधियां वायु प्रदूषकों के उत्सर्जन में महत्वपूर्ण योगदान देती हैं, जिससे वायुमंडल का क्षरण होता है। इसके अलावा, कृषि के विभिन्न क्षेत्र विभिन्न ग्रीनहाउस गैसों का उत्सर्जन करते हैं। भारत में, कृषि क्षेत्र ऐसे उत्सर्जनों का एक महत्वपूर्ण स्रोत है, जिसका क्षेत्रीय वायु गुणवत्ता, जलवायु परिवर्तनशीलता और सार्वजनिक स्वास्थ्य पर गंभीर प्रभाव पड़ता है। हालांकि, भारत में कृषि उत्सर्जन स्रोतों पर पूर्व में किए गए शोध मुख्य रूप से फसल अवशेष जलाने (CRB) और उर्वरक प्रयोग (FA) जैसी विशिष्ट गतिविधियों तक ही सीमित रहे हैं। परिणामस्वरूप, भारत के लिए एक राष्ट्रीय स्तर पर सुसंगत और व्यापक उत्सर्जन सूची (EI) का विकास अभी तक नहीं हो पाया है, जिसमें प्रमुख कृषि कार्यों की पूरी श्रृंखला शामिल हो। यह कमी कृषि उत्सर्जन के सटीक मात्रात्मक निर्धारण में बाधा डालती है और वायु गुणवत्ता और मानव स्वास्थ्य पर उनके प्रभावों का प्रभावी आकलन, पूर्वानुमान और शमन करने की क्षमता को सीमित करती है। इसके अलावा, मौजूदा वैश्विक EI अक्सर महत्वपूर्ण कृषि प्रक्रियाओं को छोड़ देते हैं और सटीक मॉडलिंग और शमन योजना के लिए महत्वपूर्ण स्थानिक और मौसमी भिन्नता को समझने में विफल रहते हैं।

मौजूदा उत्सर्जन सूचकांक (ईआई) निश्चित उत्सर्जन कारकों (ईएफ) पर आधारित हैं और इनमें समय के साथ बदलाव की कमी है, जिससे काफी अनिश्चितताएं पैदा होती हैं, खासकर भारत जैसे देश में, जो कृत्रिम उर्वरकों का दूसरा सबसे बड़ा वैश्विक उपभोक्ता है और जहां व्यापक रूप से कृषि उर्वरक और पशुपालन गतिविधियां होती हैं। इसलिए, अद्यतन, स्थानीयकृत ईआई की तत्काल आवश्यकता है जो मजबूत वायु गुणवत्ता मॉडलिंग और स्वास्थ्य जोखिम आकलन में सहायक हो सकें। इसके अलावा, इस क्षेत्र के लिए प्रभावी शमन रणनीतियों के विकास और कार्यान्वयन के साथ-साथ उत्सर्जन स्रोतों की

व्यवस्थित पहचान और मात्रात्मक विश्लेषण की भी आवश्यकता है, ताकि सूचित निर्णय लेने में मदद मिल सके और कृषि प्रणाली के भीतर शमन प्रगति के मूल्यांकन को सुगम बनाया जा सके। इन कमियों को दूर करने के लिए, इस अध्ययन का उद्देश्य भारत के लिए एक उच्च-रिज़ॉल्यूशन वाला, क्षेत्रीय विशिष्ट कृषि पर्यावरण सूचकांक (ईआई) विकसित करना है, जिसमें कृषि उत्पादन, जुताई, कृषि प्रजनन प्रणाली (सीआरबी) और पशुधन गतिविधियों सहित प्रमुख कार्यों को शामिल किया गया है। इसके अतिरिक्त, यह अध्ययन नीति और प्रबंधन संबंधी निर्णयों को सूचित करने के लिए इनमें से प्रत्येक कृषि पद्धति से जुड़ी विभिन्न शमन रणनीतियों की प्रभावशीलता का मूल्यांकन करता है। विकसित ईआई को बाद में मौसम अनुसंधान और पूर्वानुमान मॉडल (डब्ल्यूआरएफ-केम) मॉडलिंग ढांचे के भीतर लागू किया जाता है ताकि वायु प्रदूषक सांद्रता का सटीक पूर्वानुमान लगाने में इसकी उपयोगिता का आकलन किया जा सके। अंत में, यह अध्ययन कृषि उत्सर्जन से होने वाले संभावित स्वास्थ्य प्रभावों की जांच करता है, जिससे वायु गुणवत्ता और सार्वजनिक स्वास्थ्य पर इस क्षेत्र के प्रभाव का व्यापक मूल्यांकन प्राप्त होता है।

वर्ष 2018-19 के लिए  $0.1^\circ \times 0.1^\circ$  स्थानिक और मासिक लौकिक रिज़ॉल्यूशन पर एक जिला-स्तरीय उत्सर्जन सूचकांक (ईआई) विकसित किया गया, जिसमें फसल-विशिष्ट उर्वरक उपयोग (52 फसलों को कवर करते हुए), अग्नि विकिरण ऊर्जा (एफआरई) सहसंबंधों पर आधारित कृषि उत्सर्जन नियंत्रण (सीआरबी) अनुमान, क्षेत्र सर्वेक्षणों पर आधारित मासिक जुताई उत्सर्जन और अद्यतन भारत-विशिष्ट ईएफ का उपयोग करके पशुधन उत्सर्जन शामिल थे। गतिविधि डेटा विभिन्न स्रोतों से प्राप्त किया गया था, जिसमें 14 राज्यों के 102 जिलों में क्षेत्र सर्वेक्षण शामिल थे। इसके बाद इस सूची का उपयोग विभिन्न शमन रणनीतियों के प्रभाव का मूल्यांकन करने और वर्ष 2022 के लिए डब्ल्यूआरएफ-केम के साथ सिमुलेशन संचालित करने के लिए किया गया। दो परिदृश्यों का विश्लेषण किया गया, एक में वैश्विक वायुमंडलीय अनुसंधान के लिए उत्सर्जन डेटाबेस (ईडीजीएआर) सूची (ईईआई) का उपयोग किया गया और दूसरे में संशोधित ईडीजीएआर ईआई (एमईईआई) का। एमईईआई, ईईआई के समतुल्य है, जिसमें ईडीजीएआर के कृषि उत्सर्जन को विकसित कृषि ईआई से प्रतिस्थापित किया गया है। कृषि उत्सर्जन के

बिना 'ईईआई' का उपयोग करते हुए एक अतिरिक्त एक महीने के डब्ल्यूआरएफ-केम सिमुलेशन ने उनके स्वास्थ्य संबंधी बोझ को अलग कर दिया।

परिणामी EI अनुमानों से पता चलता है कि FA से 3.15 Tg NH<sub>3</sub> और 138.53 Gg N<sub>2</sub>O, जुलाई से 583 Gg PM<sub>10</sub> और 278 Gg PM<sub>2.5</sub>, पशुधन से 3.4 Tg NH<sub>3</sub> और 14 Tg CH<sub>4</sub> वार्षिक उत्सर्जन है, और CRB उत्सर्जन मुख्य रूप से चावल और गेहूं के अवशेषों से होता है, विशेष रूप से इंडो-गंगा के मैदान में। FA से संबंधित उत्सर्जन में यूरिया का योगदान 93% से अधिक था, और पशुधन से CH<sub>4</sub> उत्सर्जन में गाय और भैंस का योगदान 91% था। सामयिक विश्लेषण से अलग-अलग मौसमी चरम सीमाएँ सामने आईं, जैसे कि FA गतिविधि के लिए जुलाई-अगस्त में NH<sub>3</sub> और N<sub>2</sub>O और PM के लिए अक्टूबर-नवंबर में CRB। शमन आकलन से संकेत मिलता है कि NBPT-लेपित यूरिया, शून्य जुलाई, टिकाऊ फसल अवशेष प्रबंधन और पशुधन आहार सुधार जैसी रणनीतियों से उत्सर्जन में 44% तक की कमी आ सकती है। शून्य जुलाई को अपनाने (पारंपरिक जुलाई वाली भूमि के 25% हिस्से को शून्य जुलाई में परिवर्तित करने) से पीएम उत्सर्जन में 17% की कमी आई, और पशुधन के आहार में बदलाव से CH<sub>4</sub> में 12% की कमी आई।

MEEI के साथ WRF-Chem सिमुलेशन ने मॉडल की सटीकता में काफी सुधार किया, जिससे कृषि प्रधान क्षेत्रों में PM<sub>2.5</sub> में 24% और NH<sub>3</sub> में 50% तक पूर्वाग्रह कम हुआ और यह देखे गए मौसमी बदलावों के साथ बेहतर ढंग से मेल खाने लगा। इसके अलावा, WRF-Chem द्वारा सिमुलेटेड वार्षिक औसत एरोसोल ऑप्टिकल डेप्थ (AOD) सहसंबंध MODIS AOD की तुलना में बेहतर हुए, जिसमें निर्धारण गुणांक (R<sup>2</sup>) EEI के साथ 0.67 से बढ़कर MEEI के साथ 0.74 हो गया। ये सुधार विशेष रूप से चरम उत्सर्जन अवधि के दौरान अधिक स्पष्ट थे, जैसे कि जुलाई और फसल कटाई के महीने। महत्वपूर्ण रूप से, स्वास्थ्य प्रभाव आकलन से पता चला कि PM<sub>2.5</sub> से संबंधित समय से पहले होने वाली मृत्यु में अकेले कृषि का योगदान 16.4% है, जबकि EEI के तहत यह 11% है, जिसका अर्थ है अतिरिक्त 0.53

लाख मौतें, जिनमें इंडो-गंगा का मैदान सबसे अधिक प्रभावित क्षेत्र है। इसके अलावा, कृषि उत्सर्जन न केवल वायु प्रदूषण को बढ़ाता है बल्कि एरोसोल-विकिरण प्रतिक्रिया के माध्यम से सतह के निकट के तापमान को भी बदलता है। सिमुलेशन से कृषि उत्सर्जन को बाहर रखने से सतह के निकट के तापमान का व्यवस्थित रूप से अधिक अनुमान लगाया गया, जो BR और AS में 1.5°C से अधिक और WB, UP और MP में 1.38-1.2°C तक था। MEEI को शामिल करने से, कृषि प्रधान राज्यों में तापमान पूर्वाग्रह औसतन ~1.25°C तक कम हो गया, जो क्षेत्रीय तापमान को निर्धारित करने में कृषि एरोसोल की महत्वपूर्ण भूमिका को रेखांकित करता है।

निष्कर्षतः, यह अध्ययन भारत के लिए स्थानीयकृत, समयबद्ध कृषि संबंधी पर्यावरणीय सूचकांकों की आवश्यकता पर बल देता है। मॉडल की सटीकता और स्वास्थ्य प्रभावों के आकलन में प्रदर्शित सुधार वायु गुणवत्ता विनियमन, जलवायु नीति और टिकाऊ कृषि पद्धतियों के मार्गदर्शन में ऐसे पर्यावरणीय सूचकांकों के महत्व को सुदृढ़ करते हैं। यह कार्य कृषि उत्सर्जन को कम करने के साथ-साथ पर्यावरणीय और सार्वजनिक स्वास्थ्य परिणामों की रक्षा करने के उद्देश्य से विज्ञान-आधारित नीति निर्माण की नींव रखता है।

# Table of Contents

|   |      |
|---|------|
| Certificate   | i    |
| Acknowledgements  | ii   |
| Abstract  | iv   |
| Table of Contents   | xii  |
| List of Figures   | xvi  |
| List of Tables  | xx   |
| List of Abbreviations and Acronyms  | xxii |
| CHAPTER 1 .....   | 1    |
| INTRODUCTION .....  | 1    |
| 1.1 General.....  | 1    |
| 1.2 Main Atmospheric Pollutants and Their Sources.....  | 4    |
| 1.3 Emissions from Agriculture .....  | 8    |
| 1.4 Air Quality Modelling.....  | 10   |
| 1.5 Thesis Organization .....   | 14   |
| 1.6 Chapter Conclusions .....   | 16   |
| CHAPTER 2 .....   | 17   |
| LITERATURE REVIEW.....  | 17   |
| 2.1. Sources of PM and its Precursors from Agriculture .....                                  | 17   |
| 2.1.1. Crop Residue Burning.....  | 18   |
| 2.1.2. Tillage Operations .....   | 19   |
| 2.1.3. Livestock Production and Nitrogen Fertilizers .....                                    | 20   |
| 2.2. Quantification of Emissions from Agriculture.....  | 21   |
| 2.3 Agricultural Emissions: Modelling Approaches and Health Implications.....                 | 26   |
| 2.4 Problems with Existing EIs for Agriculture Sector.....                                    | 30   |
| 2.4.1 Crop Residue Burning.....   | 36   |
| 2.4.2 Tillage .....   | 38   |
| 2.4.3 Fertilizer Application .....  | 39   |
| 2.4.4 Livestock Waste .....   | 40   |
| 2.5 Performance of WRF-Chem Model.....  | 41   |
| 2.6 Modelling Agricultural Sector PM <sub>2.5</sub> Emissions over India Using WRF-Chem ..... | 47   |

|  |     |
|--|-----|
| 2.7 Research Gaps and Objectives .....                                     | 50  |
| 2.7.1 Gap Analysis .....   | 50  |
| 2.7.2 Objectives .....   | 51  |
| 2.7.3 Novelty of the Study .....   | 52  |
| 2.7.4 Scope of the Study .....   | 54  |
| 2.8 Chapter Conclusions .....  | 55  |
| CHAPTER 3 .....  | 56  |
| METHODOLOGY .....  | 56  |
| 3.1 Workflow .....   | 56  |
| 3.2 Stage I: Emission Inventory Development for Agriculture Sector .....   | 58  |
| 3.2.1 Emission Inventory for FA.....                                       | 59  |
| 3.2.2 Emission Inventory for Tillage Activity .....                        | 66  |
| 3.2.3 Emission Inventory for Livestock.....                                | 69  |
| 3.2.4 Emission Inventory for CRB .....                                     | 84  |
| 3.2.5 Spatial and Temporal Distribution of Emissions .....                 | 87  |
| 3.3 Stage II: Mitigation Interventions .....                               | 90  |
| 3.3.1 Fertilizer Application .....   | 90  |
| 3.3.2 Diverting Crop Residues for Biofuel and Biopower Generation.....     | 98  |
| 3.3.3 Implementation of Zero Tillage Practices.....                        | 99  |
| 3.3.4 Ionospheres for Livestock.....                                       | 101 |
| 3.4 Stage III: WRF-Chem Simulations and Their Validation .....             | 101 |
| 3.4.1 Model Configuration and Data sources .....                           | 103 |
| 3.4.2 Emission Inventories.....  | 105 |
| 3.4.3 Model Validation Using Satellite and Ground-based Observations ..... | 107 |
| 3.5 Stage IV: Temperature and Health Impact Assessment .....               | 110 |
| 3.5.1 Temperature Evaluation .....   | 110 |
| 3.5.2 Health Analysis .....  | 111 |
| 3.6 Chapter Conclusions .....  | 112 |
| CHAPTER 4 .....  | 113 |
| STAGE I: EMISSION INVENTORY DEVELOPMENT FOR AGRICULTURE SECTOR             | 113 |
| 4.1 Fertilizer Application .....   | 113 |
| 4.1.1 Variations in FA .....   | 113 |
| 4.1.2. Variations of NH <sub>3</sub> and N <sub>2</sub> O Emissions.....   | 122 |

|  |     |
|--|-----|
| 4.1.3. Uncertainty Analysis.....   | 143 |
| 4.2 Tillage .....  | 144 |
| 4.2.1. Tillage Frequency .....   | 144 |
| 4.2.2. Spatial Distribution of PM Emissions.....                           | 149 |
| 4.2.3. Temporal Variations in Emissions.....                               | 151 |
| 4.3 Crop Residue Burning.....  | 152 |
| 4.3.1. Regression Models.....  | 152 |
| 4.3.2. Trends in OBP and Residue Generated.....                            | 153 |
| 4.3.3. Annual Emissions .....  | 159 |
| 4.3.4. Spatial Variation in Emissions .....                                | 163 |
| 4.3.5. Temporal Variations in Emissions.....                               | 168 |
| 4.4 Livestock.....   | 171 |
| 4.4.1. Annual Emissions .....  | 171 |
| 4.4.2. Spatial Analysis.....   | 174 |
| 4.4.3. Temporal Analysis .....   | 176 |
| 4.5. Comparison of TA, CRB and livestock emissions with Other Studies..... | 178 |
| 4.6 Uncertainty Analysis of TA, CRB and Livestock .....                    | 180 |
| 4.6.1 Uncertainty Calculations.....  | 180 |
| 4.6.2 Pathways for Improving the Reliability of Future EIs.....            | 181 |
| 4.7. Contribution of Total Agricultural Emissions.....                     | 183 |
| 4.8 Chapter Conclusions .....  | 185 |
| CHAPTER 5 .....  | 186 |
| STAGE II: MITIGATION INTERVENTIONS .....                                   | 186 |
| 5.1. Mitigation Measures for FA.....                                       | 186 |
| 5.2. Mitigation Measures for TA, Livestock and CRB .....                   | 188 |
| 5.3 Chapter Conclusions .....  | 191 |
| CHAPTER 6 .....  | 192 |
| STAGE III: WRF-CHEM SIMULATIONS AND THEIR VALIDATION.....                  | 192 |
| 6.1 Spatial and Temporal Accuracy .....                                    | 192 |
| 6.1.1 PM <sub>2.5</sub> Analysis.....                                      | 192 |
| 6.1.2 NH <sub>3</sub> Analysis.....  | 196 |
| 6.2 Validation with Ground-based Monitoring Stations .....                 | 200 |
| 6.2.1 PM <sub>2.5</sub> Analysis.....                                      | 200 |

|  |     |
|--|-----|
| 6.2.2 NH <sub>3</sub> Analysis.....                                | 202 |
| 6.3 Model Performance Across Agricultural Activity Gradients ..... | 202 |
| 6.3.1 AOD Validation.....  | 203 |
| 6.3.2 NH <sub>3</sub> VCDs Validation .....                        | 207 |
| 6.4 Chapter Conclusions .....                                      | 210 |
| CHAPTER 7 .....  | 211 |
| STAGE IV: TEMPERATURE AND HEALTH IMPACT ASSESSMENT .....           | 211 |
| 7.1 Impact of EIs on Temperature.....                              | 211 |
| 7.2 Health Analysis .....  | 214 |
| 7.3 Agricultural Sector Impact on Mortality and Temperature .....  | 219 |
| 7.4 Chapter Conclusions .....                                      | 221 |
| CHAPTER 8 .....  | 222 |
| OVERALL CONCLUSIONS .....  | 222 |
| 8.1 Summary .....  | 222 |
| 8.2 Environmental Implications.....                                | 226 |
| 8.3 Limitations, Future Scope and Recommendations .....            | 227 |
| REFERENCES .....   | 231 |
| ANNEXURE A .....   | 257 |
| ANNEXURE B.....  | 279 |
| LIST OF PUBLICATIONS.....  | 299 |
| CURRICULUM VITAE .....   | 300 |

## LIST OF FIGURES

|  |     |
|--|-----|
| Figure 1.1: Sources of Air pollution.....  | 6   |
| Figure 2.1: NH <sub>3</sub> Emissions from Agricultural Soils: Spatial Distribution and Comparison between EDGAR and ECLIPSE Inventories.....  | 33  |
| Figure 2.2: Spatial Patterns of NH <sub>3</sub> Emissions from MM (EDGAR Inventory).....   | 33  |
| Figure 2.3: PM <sub>2.5</sub> Emissions from Agricultural Waste Burning: Spatial Distribution Across EDGAR, ECLIPSE, and SMOG Inventories .....  | 34  |
| Figure 2.4: Spatial Distribution of NMVOCs from agriculture waste burning - Comparison of EDGAR, ECLIPSE and SMOG Inventories .....  | 34  |
| Figure 2.5: Spatial Distribution of NO <sub>x</sub> from agriculture waste burning - Comparison of EDGAR, ECLIPSE and SMOG Inventories.....  | 35  |
| Figure 2.6: Spatial Distribution of SO <sub>2</sub> from agriculture waste burning - Comparison of EDGAR, ECLIPSE and SMOG Inventories.....  | 35  |
| Figure 3.1: Flowchart depicting the methodological workflow of the study.....  | 57  |
| Figure 3.2: Detailed flow diagram for estimating NH <sub>3</sub> -FA and N <sub>2</sub> O-FA emissions.....  | 60  |
| Figure 3.3: Flow-chart of detailed methodology followed to estimate A: TA emissions; B: CRB; C: Livestock.....   | 76  |
| Figure 4.1: (A) Total Fertilizer consumption in each state, (B) Quantity of each fertilizer type consumed in various regions of India.....   | 114 |
| Figure 4.2: Basal- and Top-dressing FA months for the top 95pth crops (Part I).....  | 117 |
| Figure 4.3: Basal- and Top-dressing FA months for the top 95pth crops (part II).....   | 118 |
| Figure 4.4: Basal- and Top-dressing FA months for the top 95pth crops (Part III).....  | 119 |
| Figure 4.5: A: Urea fertilizer quantity (in tons) consumed by top 95pth crops (52 crops), B: Month-wise total N-consumption (in tons) from all fertilizer types by 95pth crops regions of India..... | 120 |
| Figure 4.6: Fertilizer quantities of DAP, AS and NPK fertilizers (in tons) consumed by top 95pth crops.....  | 121 |

|   |     |
|---|-----|
| Figure 4.7: A: Proportion of N-consumed by various crops at the national-level, B: N (in tons) from all fertilizer types consumed by Rice and Wheat at state- and regional-levels.....  | 123 |
| Figure 4.8: Month-wise NH <sub>3</sub> emissions from FA at grid-level.....   | 129 |
| Figure 4.9: Month-wise N <sub>2</sub> O emissions from FA at grid-level.....  | 130 |
| Figure 4.10: A. Top 20 states emitting NH <sub>3</sub> -FA in India, B. Top 20 states emitting N <sub>2</sub> O-FA in India.....  | 133 |
| Figure 4.11: A: N-consumption associated with FA across different states along with the corresponding NH <sub>3</sub> -FA and N <sub>2</sub> O-FA emissions per unit of N-consumed, B: The association between two NH <sub>3</sub> emissions-related ratios (NH <sub>3</sub> -FA per capita and NH <sub>3</sub> -FA per Gross State Domestic Product (GSDP))..... | 137 |
| Figure 4.12: Month-wise NH <sub>3</sub> emissions from the top three emitting states within each administrative region.....   | 139 |
| Figure 4.13: State average tillage frequencies for all crop types.....  | 145 |
| Figure 4.14: State average tillage frequency for all crop types – Part I.....   | 146 |
| Figure 4.15: State average tillage frequency for all crop types – Part II.....  | 147 |
| Figure 4.16: State average tillage frequency for all crop types – Part III.....   | 148 |
| Figure 4.17: Monthly PM <sub>2.5</sub> emissions from Tillage activity.....   | 149 |
| Figure 4.18: Monthly PM <sub>10</sub> emissions from Tillage activity.....  | 150 |
| Figure 4.19: Regression analysis between open burning proportions and Fire radiative energy for different administrative regions of India.....  | 154 |
| Figure 4.20: A. State-level total crop-wise residue generated in 2018-19 from the crops considered in this study; B. Spatial distribution of agricultural land; C. Fire counts over agricultural land during various seasons in different administrative regions of India.....  | 158 |
| Figure 4.21: A. Livestock category-wise CH <sub>4</sub> emissions from ENF and MM across all districts of India; B. Administrative region-wise CH <sub>4</sub> emissions from ENF and MM across all districts of India; C. Livestock category-wise N <sub>2</sub> O emissions from MA and MM  |     |

|  |     |
|--|-----|
| across all districts of India; D. Administrative region-wise N <sub>2</sub> O emissions from MA and MM across all districts of India; E, F, G: Administrative region-wise CH <sub>4</sub> , N <sub>2</sub> O and CO <sub>2</sub> emissions from CRB across all districts of India respectively; H: CO <sub>2</sub> equivalents from CRB across all districts of India.....   | 167 |
| Figure 4.22: Monthly pollutant emissions from CRB for different agro-climatic zones of India (1; Jan; 12: Dec).....  | 170 |
| Figure 4.23: Annual Emissions from the Livestock sector for ENF (A), MM (B, D, F), and MA (C, E).....  | 174 |
| Figure 4.24: Monthly CH <sub>4</sub> Emissions from MM.....  | 177 |
| Figure 4.25: Monthly NH <sub>3</sub> Emissions from MA.....  | 177 |
| Figure 4.26: Monthly NH <sub>3</sub> Emissions from MM.....  | 178 |
| Figure 5.1: Emission reduction potentials of various mitigation strategies. A: NH <sub>3</sub> emission reduction potential from recommended FA, B: NH <sub>3</sub> emission reduction potentials of OF alone and U+OF combined (all substitution scenarios), C: NH <sub>3</sub> emission reduction potentials of nitrification inhibitor (neem-coated urea) and urease inhibitor (NBPT), D: N <sub>2</sub> O emission reduction potential from recommended FA, E: NH <sub>3</sub> emission reduction potentials U+OF combined (all substitution scenarios), F: NH <sub>3</sub> emission reduction potentials of nitrification inhibitor (neem-coated urea) and urease inhibitor (NBPT)..... | 187 |
| Figure 5.2: Percentage reduction in emissions from all three agricultural operations after implementing mitigation measures.....   | 190 |
| Figure 6.1: Seasonal spatial distribution of PM <sub>2.5</sub> concentrations using EEI and MEEI based simulations.....  | 195 |
| Figure 6.2: Monthly spatial distribution of NH <sub>3</sub> VCDs using MEEI based simulations.....   | 197 |
| Figure 6.3: Monthly spatial distribution of NH <sub>3</sub> VCDs using EEI based simulations.....  | 197 |
| Figure 6.4: Comparison of MFB for (A) PM <sub>2.5</sub> across 23 cities and (B) NH <sub>3</sub> across 15 cities between WRF-Chem simulations using the MEEI and the EEI, evaluated against ground-based observations.....  | 201 |

|   |     |
|---|-----|
| Figure 6.5: Fractional Bias (FB) across agricultural emission bins comparing WRF-Chem simulations using EEI and MEEI.....   | 204 |
| Figure 6.6: Monthly comparison of MFB between modelled AOD using EEI and MEEI against MODIS AOD, focusing on grids within the 80th–100th emission percentiles....                                   | 206 |
| Figure 6.7: Monthly comparison of MFB between modelled NH <sub>3</sub> VCDs using EEI and MEEI against IASI NH <sub>3</sub> VCDs, focusing on grids within the 80th–100th emission percentiles..... | 209 |
| Figure 7.1: Seasonal distribution of 2 m temperature from EEI- and MEEI-based simulations: (A) EEI-based simulation, (B) MEEI-based simulation, (C) Difference in temperature (EEI – MEEI).....     | 213 |
| Figure 7.2: Spatial distribution of total PRE-M attributed to PM <sub>2.5</sub> exposure: (A) EEI-based simulation, (B) MEEI-based simulation, (C) Difference in mortality (MEEI – EEI).....        | 214 |
| Figure 7.3: Disease-specific PRE-M attributed to EEI-based simulated PM <sub>2.5</sub> exposure: (A) LC, (B) Stroke, (C) IHD, (D) COPD.....   | 218 |
| Figure 7.4: Disease-specific PRE-M attributed to MEEI-based simulated PM <sub>2.5</sub> exposure: (A) LC, (B) Stroke, (C) IHD, (D) COPD.....  | 218 |
| Figure 7.5: State-wise distribution of PRE-M (in lakh) from IHD, stroke, COPD, and LC, separated into agricultural and non-agricultural sources.....  | 220 |

## LIST OF TABLES

|  |     |
|--|-----|
| Table 2.1: Studies on agricultural emissions, modelling, and health impacts.....   | 27  |
| Table 2.2: Comparative inclusion of agricultural operations across different existing EIs for Indian context.....                            | 32  |
| Table 2.3: Comparison of air pollutant emission quantities from various EIs across India....   | 36  |
| Table 2.4: Comparative performance of WRF-Chem vs other models in regional/national PM modeling among studies worldwide.....                 | 44  |
| Table 2.5: WRF-Chem applications in Indian PM <sub>2.5</sub> and agricultural emissions studies.....   | 48  |
| Table 3.1: EF and modification factors adopted for NH <sub>3</sub> FA.....   | 63  |
| Table 3.2: EF adopted for N <sub>2</sub> O-FA.....   | 65  |
| Table 3.3: Livestock category-wise gross energy intake values.....   | 71  |
| Table 3.4: Livestock category-wise methane emission factors for ENF.....   | 73  |
| Table 3.5: N <sub>2</sub> O emissions factors adopted for calculation of emissions from MM .....   | 79  |
| Table 3.6: NH <sub>3</sub> emission factors adopted for estimating emissions from MM.....  | 81  |
| Table 3.7: N <sub>2</sub> O EFs adopted for MA.....  | 82  |
| Table 3.8: NH <sub>3</sub> EFs for MA.....   | 83  |
| Table 3.9: Parameters used for CRB emission calculation.....   | 85  |
| Table 3.10: Crop-wise emission factors (g/kg) for CRB emission estimation.....   | 86  |
| Table 3.11: Emission Factor for Organic fertilizer.....  | 92  |
| Table 3.12: Emission reductions from mitigation measures (Urease and Nitrification inhibitors) for NH <sub>3</sub> and N <sub>2</sub> O..... | 97  |
| Table 3.13: Suitability of crops for ZT.....   | 99  |
| Table 3.14: Percentage reduction in Y <sub>m</sub> due to monensin in various livestock categories.....                                      | 101 |
| Table 3.15: Selected parametrization schemes for WRF-Chem simulations.....   | 104 |
| Table 4.1: Monthly NH <sub>3</sub> emissions in tons for each State and UT.....  | 125 |

|   |     |
|---|-----|
| Table 4.2: Monthly N <sub>2</sub> O emissions in tons for each State and UT.....  | 127 |
| Table 4.3: Area in hectares (treated with urea fertilizer) under the top six crops in various administrative regions.....   | 135 |
| Table 4.4: Season and region-wise NH <sub>3</sub> emissions in kg.....  | 141 |
| Table 4.5: Season and region-wise N <sub>2</sub> O emissions in kg.....   | 141 |
| Table 4.6: State wise dry-crop residue generated for the year 2018-19 in million tons.....  | 155 |
| Table 4.7: Crop-wise emissions from CRB across all pollutant types.....   | 160 |
| Table 4.8: State wise contribution of CRB emissions across all pollutant types in Gg.....   | 165 |
| Table 4.9: Livestock category-wise annual enteric methane emissions in Gg.....  | 171 |
| Table 4.10: Comparison of CRB emissions (Gg) with existing studies for different base years.....  | 178 |
| Table 4.11: Contribution of agricultural operations to emissions of various pollutants.....   | 183 |
| Table 6.1: Agro-Climatic Zone-Wise Annual Mean PM <sub>2.5</sub> Concentrations (µg/m <sup>3</sup> ) in the Most Polluted State from WRF-Chem Simulations Using EEI and MEEI.....           | 193 |
| Table 6.2: Administrative region wise annual mean PM <sub>2.5</sub> concentrations in µg/m <sup>3</sup> from model simulations using MEEI and EEI.....                                      | 194 |
| Table 6.3: Coefficient of determination (R <sup>2</sup> ) between WRF-Chem simulated NH <sub>3</sub> VCDs using MEEI and EEI and IASI observations across agro-climatic zones in India..... | 198 |
| Table 6.4: Mean fractional bias (MFB) between annual mean NH <sub>3</sub> VCDs and IASI observations for simulations using MEEI and EEI, with corresponding percentage improvements.....    | 208 |
| Table 7.1: Mean bias (MB) and root mean square error (RMSE) of 2 m temperature simulated using MEEI and EEI compared to ERA5 reanalysis across different seasons.....                       | 212 |
| Table 7.2: State wise estimated PRE-M attributable to PM <sub>2.5</sub> exposure by disease category using EEI-based simulations.....   | 215 |
| Table 7.3: State wise estimated PRE-M attributable to PM <sub>2.5</sub> exposure by disease category using MEEI-based simulations.....  | 216 |

## LIST OF ABBREVIATIONS AND ACRONYMS

|                 |  |
|-----------------|--|
| AAP             | Ambient Air Pollution  |
| AOD             | Aerosol Optical Depth  |
| AP              | Andhra Pradesh   |
| AS              | Ammonium Sulfate   |
| BR              | Bihar  |
| CAMx            | Comprehensive Air Quality Model with Extensions                          |
| CH <sub>4</sub> | Methane  |
| CMAQ            | Community Multiscale Air Quality   |
| CO              | Carbon Monoxide  |
| CO <sub>2</sub> | Carbon Dioxide   |
| COPD            | Chronic Obstructive Pulmonary Disease                                    |
| CR              | Central Region   |
| CRB             | Crop Residue Burning   |
| CTM             | Chemical Transport Models  |
| CVs             | Coefficient of Variations  |
| DALYs           | Disability Adjusted Life Years   |
| DAP             | Di-ammonium Phosphate  |
| ECLIPSE         | Evaluating the CLimate and Air Quality ImPacts of Short-livEd Pollutants |
| EDGAR           | Emission Database for Global Atmospheric Research                        |
| EEA             | European Environmental Agency  |
| EI              | EDGAR Emission Inventory   |
| EF              | Emission Factor  |
| EIs             | Emission Inventories   |
| ENF             | Enteric Fermentation   |
| EPI             | Environmental Performance Index  |
| ER              | Eastern Region   |
| F               | Frequency  |
| FA              | Fertilizer Application   |
| FB              | Fractional Bias  |
| FINN            | Fire INventory from NCAR   |
| FQs             | Fertilizer Quantities  |
| FRE             | Fire Radiative Energy  |
| FRP             | Fire Radiative Power   |
| FS              | Field Surveys  |
| GBD             | Global Burden of Disease   |
| GE              | Gross Energy   |
| GFEDv4.1        | Global Fire Emissions Database, Version 4.1 with Small Fires             |
| GHGs            | Greenhouse Gases   |
| GR              | Government Records   |
| GSDP            | Gross State Domestic Product   |

|                              |   |
|------------------------------|---|
| Gujarat                      | GJ  |
| HAP                          | Household Air Pollution                       |
| HNO <sub>3</sub>             | Nitric Acid                                   |
| HP                           | Himachal Pradesh                              |
| HR                           | Haryana                                       |
| IASI                         | Infrared Atmospheric Sounding Interferometer  |
| IGP                          | Indo Gangetic Plain                           |
| IHD                          | Ischemic Heart Disease                        |
| IPCC                         | Intergovernmental Panel for Climate Change    |
| KA                           | Karnataka                                     |
| KVKs                         | Krishi Vigyan Kendras                         |
| LC                           | Lung Cancer                                   |
| LULC                         | Land Use and Land Cover                       |
| LGPR                         | Lower Gangetic Plain Region                   |
| LRIs                         | Lower Respiratory Infections                  |
| MA                           | Manure Application                            |
| MB                           | Mean Bias                                     |
| MEEI                         | Modified EDGAR Emission Inventory             |
| MEF                          | Methane Emission Factor                       |
| MFB                          | Mean Fractional Bias                          |
| MFE                          | Mean Fractional Error                         |
| MFs                          | Modification Factors                          |
| MH                           | Maharashtra                                   |
| MM                           | Manure Management                             |
| MODIS                        | Moderate Resolution Imaging Spectroradiometer |
| MP                           | Madhya Pradesh                                |
| N                            | Nitrogen                                      |
| N <sub>2</sub> O             | Nitrous Oxide                                 |
| NBPT                         | N-(n-butyl) thioPhosphoric Triamide           |
| NCU                          | Neem Coated Urea                              |
| NER                          | Northeastern Region                           |
| NH <sub>3</sub>              | Ammonia                                       |
| NH <sub>4</sub> <sup>+</sup> | Ammonium                                      |
| NMVOCs                       | Non-Methane Volatile Organic Compounds        |
| NO <sub>3</sub> <sup>-</sup> | Nitrate                                       |
| NO <sub>x</sub>              | Nitrogen Oxides                               |
| NPK                          | Nitrogen, Phosphorous, Potassium              |
| NR                           | Northern Region                               |
| O <sub>3</sub>               | Ozone   |
| OBP                          | Open Burning Proportion                       |
| OC                           | Organic Carbon                                |
| OF                           | Organic Fertilizer                            |
| PAHs                         | Polycyclic Aromatic Hydrocarbons              |
| PB                           | Punjab  |

|                 |   |
|-----------------|---|
| PM              | Particulate Matter                                      |
| PRE-M           | Premature Mortality                                     |
| QFED            | Quick Fire Emissions Dataset                            |
| REAS            | Regional Emission inventory in Asia                     |
| RJ              | Rajasthan   |
| RMSE            | Root Mean Square Error                                  |
| SAT-D           | Satellite Derived                                       |
| SCRMPs          | Sustainable Crop Residue Management Practices           |
| SIA             | Secondary Inorganic Aerosol                             |
| SM              | Soil Moisture   |
| SMoG            | Speciated Multipollutant Generator                      |
| SO <sub>2</sub> | Sulphur Dioxide   |
| SOA             | Secondary Organic Aerosol                               |
| SO <sub>x</sub> | Sulphur Oxides  |
| SR              | Southern Region   |
| SS              | Soil Silt   |
| β               | Total Tilled Area                                       |
| ST              | Soil Texture  |
| TA              | Tillage Activity  |
| TDN             | Total Digestible Nutrients                              |
| TG              | Telangana   |
| TGRP            | Trans-Gangetic Plain Region                             |
| TN              | Tamil Nadu  |
| TSP             | Total Suspended Particulates                            |
| UGPR            | Upper Gangetic Plain Region                             |
| UK              | Uttarakhand   |
| UP              | Uttar Pradesh   |
| UT              | Union Territory   |
| VCDs            | Vertical Column Densities                               |
| VOCs            | Volatile Organic Compounds                              |
| WB              | West Bengal   |
| WDR             | Western Dry Region                                      |
| WHO             | World Health Organization                               |
| WR              | Western Region  |
| WRF             | Weather Research and Forecasting                        |
| WRF-Chem        | Weather Research and Forecasting coupled with Chemistry |
| WS              | Wind Speed  |
| Y <sub>m</sub>  | Methane Conversion Factor                               |
| ZT              | Zero Tillage  |