DIFFERENTIAL IMPACTS OF EXPOSURE TO AMBIENT $PM_{2.5}$ AND ITS COMPONENTS ON MATERNAL AND CHILD HEALTH IN INDIA

EKTA CHAUDHARY

CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY, DELHI

JULY 2024

Differential Impacts of Exposure to Ambient $PM_{2.5}$ and its Components on Maternal and Child Health in India

by

Ekta Chaudhary

Centre for Atmospheric Sciences

Submitted
In fulfillment of the requirements of the degree of
Doctor of Philosophy
to the

Indian Institute of Technology, Delhi

JULY 2024

Dedicated To My Parents

Certificate

This is to certify that the thesis entitled "**Differential Impacts of Exposure to Ambient $PM_{2.5}$ and its Components on Maternal and Child Health in India**" being submitted by Ms. **Ekta Chaudhary** for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis. The results presented in this thesis have not been submitted in part or full to any University or Institution for the award of any degree/diploma.

Sagnik Dey

Prof. Sagnik Dey

Centre for Atmospheric Sciences,

Indian Institute of Technology Delhi,

Hauz Khas, New Delhi-110016, India

Acknowledgment

I want to begin by expressing my sincere gratitude to my supervisor, Prof. Sagnik Dey, for his invaluable guidance, constructive feedback, warmth, and unwavering encouragement. His mentorship has not only helped me evolve into a proficient researcher but also a confident individual on a personal front. As the strongest source of inspiration during the most challenging moments of my entire Ph.D. journey, I would like to attribute my success to Prof. Dey. Aside from his subject expertise and academic experience that developed my Ph.D. tenure into an enlightening, cheerful, and motivating experience, Prof. Dey also provided me with insightful suggestions and support in developing independent thinking and research skills.

Fulfilling any goal that we set up in life is always a team effort laced with several small steps of perseverance, and this thesis is no different. I want to express gratitude to my mentor Dr Santu Ghosh for his valuable guidance, help, and support during my research based on statistical modelling. He has always initiated scientific curiosity with his interesting discussions which majorly helped me develop critical and analytical thinking abilities. I thank Prof Kalpana Balakrishnan, the whole team of the DAPHNE project, Prof Chandra Venkataraman, Prof Aaron Cohen, Dr Anura Kurpad, Dr Tinku Thomas, and Dr Sumit Sharma, for their helpful discussions and insights during various stages of my Ph.D. tenure.

I sincerely thank my SRC (Student Research Committee) members – Prof Manju Mohan (SRC Chairperson), Prof Ravi Kumar Kunchala (Expert from the Centre), and Dr Harshal Salve (as an external expert) for generously sharing their knowledge and time. I would also like to thank Prof Somnath Baidya Roy, the Head of the Centre, my CRC (Centre Research Committee) chairperson, and all the faculty members and staff at the Centre for Atmospheric Sciences (CAS), IIT Delhi, for providing all the necessary facilities and a great environment to learn and grow. During my Ph.D. tenure, they have always been available for discussion, suggestions, and other academic and non-academic help. Moreover, I want to acknowledge the SUPRA project for funding my PhD at IIT Delhi.

I want to thank my friends and colleagues from IIT Delhi for their friendship and extended help, making my PhD journey beautiful and memorable. I would also like to thank the remote sensing research group members for helping and supporting me in my project.

Finally, I thank my parents and family for making all the efforts to nurture and support my achievements in terms of personal and professional heights. My father taught me to dream big, understand the virtues of life, and practice sincere goodwill, thus pushing me to be a good human being above all. I dedicate my thesis to my parents and hope to keep on making them proud. Last but not least, I want to thank my fiancée Sumit for his unrelenting support and encouragement that helped us grow together in our lives with hope and patience.

Growth is Beautiful.

Ekta Chaudhary

July 2024 Ekta Chaudhary

Abstract

In India, air pollution exposure has been identified as the second-largest health risk, following maternal and child malnutrition. The well-established causal linkage between exposure to ambient fine particulate matter ($PM_{2.5}$) and adverse health effects contributes significantly to morbidity and premature mortality in adults due to chronic obstructive pulmonary diseases, ischemic heart diseases, stroke, and lung cancer. While $PM_{2.5}$ affects the health of individuals across all age groups globally, women and children are notably vulnerable, facing high levels of ambient $PM_{2.5}$ exposure. Children in lower- and middle-income countries (LMICs) are likely to experience disproportionately higher rates of these morbidities and mortality due to prenatal and early childhood exposure to ambient $PM_{2.5}$. These health conditions could increase children's vulnerability to a range of diseases associated with higher risks of long-term disabilities.

$PM_{2.5}$ is a deadly mixture of multiple chemical species, each with potentially different toxicities and mass fractions. Its chemical composition exhibits significant variability in space and time since it consists of chemical species that originate from a variety of sources and sectors, and are affected by atmospheric processes. There is hardly any evidence from LMICs whether the health risk also varies with exposure to various $PM_{2.5}$ components at a population scale.

The broad objective of this thesis is to assess the differential impacts of $PM_{2.5}$ and its components on maternal and child health in India. To establish such associations, exposure datasets are integrated with anthropometric measurements, blood biomarkers, and sociodemographic information from the National Family Health Survey (NFHS-4) data.

Segregating sectoral contributions to total ambient $PM_{2.5}$ exposure is not only critical for understanding the changes in its composition but also relevant for policymakers. This thesis

undertakes health impact assessments on a relative scale for $PM_{2.5}$ exposure contributed by various sources. This approach enables the prioritization of sectoral interventions aimed at reducing air pollution to establish maximum health benefits.

India exhibits one of the highest (53%) prevalence of anemia among women of reproductive age (WRA) globally. This thesis employs cross-sectional analyses to assess the effects of $PM_{2.5}$ on anemia prevalence among WRA. The satellite-derived $PM_{2.5}$ (at 1 km^2 spatial resolution) data is used to assess exposure by merging it with the NFHS-4 dataset. A multiple logistic regression model adjusted with potential risk factors is used to estimate the effects of $PM_{2.5}$ and its species on anemia prevalence. Exposure datasets for $PM_{2.5}$ components are derived from reanalysis datasets and chemical transport model (CTM) outputs. The findings reveal that with every 10 $\mu g\ m^{-3}$ increase in ambient $PM_{2.5}$ exposure, the average anemia prevalence among WRA increases by 7.23% (95% confidence interval, CI: 6.82-7.63). Notably, sulfate and elemental carbon among $PM_{2.5}$ species exhibit a stronger association with anemia compared to organics and dust. Among sectoral contributors, $PM_{2.5}$ contributed from the industrial sector showed the highest odds ratio (OR) with anemia, followed by the unorganized, domestic, power, road dust, agricultural waste burning, and transport sectors.

The study also utilizes health outcomes such as low birthweight (LBW), anemia, acute respiratory infection (ARI), stunting, wasting, and underweight to represent the health burden among children under five years. These outcomes are considered due to their prevalence as common public health issues in India, their pathophysiological frameworks involving air pollution, and their manifestation in various temporal and organ system contexts. A positive association is observed between exposure to pollutants and a range of health outcomes among children of age under five years. Health outcomes such as LBW, anemia, ARI, stunting, and underweight exhibit a significant association with ambient $PM_{2.5}$, while wasting represents a relatively weaker association with the exposure of interest. Using multiple logistic regression, it is estimated that for every 10 μg m^{-3} increase in $PM_{2.5}$ exposure, the prevalence of anemia, ARI, and low birth weight increases by 10% (95% Confidence Interval, CI: 9-11), 11% (8-13), and 5% (4-6), respectively, among children in India. Species like nitrate (NO_3^-), elemental carbon, and ammonium (NH_4^+) exhibit a stronger association with the three child health outcomes compared to other $PM_{2.5}$ species.

The cumulative odds ratio (OR) of $PM_{2.5}$ components for 10 μg m^{-3} increase in $PM_{2.5}$ mass is estimated as 1.23 (1.21 - 1.26) for LBW, 1.49 (1.45 - 1.52) for anemia, 1.35 (1.29 - 1.41) for ARI, 1.22 (1.94, 1.26) for stunting, 1.002 (1.001, 1.003) for wasting, and 1.301 (1.267, 1.336) for underweight while for every 10 μg m^{-3} increase in $PM_{2.5}$ mass, ORs were estimated as 1.05 (1.04 - 1.06), 1.10 (1.09 - 1.11), 1.11 (1.08 - 1.13), 1.31 (1.2, 1.41), 1.013 (1.011, 1.014), 1.36 (1.31, 1.42) for LBW, anemia, ARI, stunting, wasting, and underweight respectively. These results suggest that relying on total $PM_{2.5}$ mass as a surrogate marker for air pollution exposure could substantially underestimate the true composite impact of various components within $PM_{2.5}$.

This study estimates the potential health benefits of reducing ambient $PM_{2.5}$ exposure by meeting various clean air targets set by the Government of India using the indigenous exposure-risk functions. The results suggest that if India meets the National Ambient Air Quality Standards (NAAQS) air quality standards of 40 μg m^{-3}, the national anemia prevalence would come down to 44% from 53%. Hence, the transition to clean energy would accelerate India's progress towards the 'anemia-free' mission target. Furthermore, the findings provide key indigenous evidence to prioritize control strategies for reducing exposure to more toxic species for greater child health benefits in India.

The critical message from this thesis is that $PM_{2.5}$ composition matters and the assumption of uniform toxicity across $PM_{2.5}$ species in the Global Burden of Disease framework may underestimate the ‘true’ impact of air pollution on human health. This thesis also bridges the evidence gaps in LMICs for a range of child and maternal health outcomes using indigenous health data. The findings presented as part of this thesis are expected to assist the policymakers in prioritizing interventions aligned with health-benefit assessments linked to specific clean air targets that are more realistic for Indian demography.

सार

भारत में, वायु प्रदूषण जोखिम को मातृ एवं शिशु कुपोषण के बाद दूसरे सबसे बड़े स्वास्थ्य जोखिम के रूप में पहचाना गया है। परिवेशीय सूक्ष्म कण पदार्थ ($PM_{2.5}$) के संपर्क और प्रतिकूल स्वास्थ्य प्रभावों के बीच अच्छी तरह से स्थापित कारण संबंध क्रोनिक ऑब्सट्रक्टिव पल्मोनरी डिजीज, इस्केमिक हृदय रोग, स्ट्रोक और फेफड़ों के कैंसर के कारण वयस्कों में रुग्णता और समय से पहले मृत्यु दर में महत्वपूर्ण योगदान देता है। जबकि $PM_{2.5}$ वैश्विक स्तर पर सभी आयु समूहों के व्यक्तियों के स्वास्थ्य को प्रभावित करता है, महिलाएं और बच्चे विशेष रूप से असुरक्षित हैं, जो परिवेशीय $PM_{2.5}$ के उच्च स्तर के जोखिम का सामना कर रहे हैं। निम्न और मध्यम आय वाले देशों (LMIC) में बच्चों को जन्मपूर्व और प्रारंभिक बचपन में परिवेशी $PM_{2.5}$ के संपर्क के कारण इन रुग्णताओं और मृत्यु दर की असंगत रूप से उच्च दर का अनुभव होने की संभावना है। ये स्वास्थ्य स्थितियाँ बच्चों में दीर्घकालिक विकलांगता के उच्च जोखिम से जुड़ी कई प्रकार की बीमारियों के प्रति संवेदनशीलता को बढ़ा सकती हैं।

$PM_{2.5}$ कई रासायनिक प्रजातियों का एक घातक मिश्रण है, जिनमें से प्रत्येक में संभावित रूप से अलग-अलग विषाक्तता और द्रव्यमान अंश होते हैं। इसकी रासायनिक संरचना अंतरिक्ष और समय में महत्वपूर्ण परिवर्तनशीलता दर्शाती है क्योंकि इसमें रासायनिक प्रजातियां शामिल हैं जो विभिन्न स्रोतों और क्षेत्रों से उत्पन्न होती हैं, और वायुमंडलीय प्रक्रियाओं से प्रभावित होती हैं। LMIC से इस बात का शायद ही कोई सबूत है कि जनसंख्या पैमाने पर विभिन्न $PM_{2.5}$ घटकों के संपर्क में आने से स्वास्थ्य जोखिम भी भिन्न होता है।

इस थीसिस का व्यापक उद्देश्य भारत में मातृ एवं शिशु स्वास्थ्य पर $PM_{2.5}$ और इसके घटकों के विभिन्न प्रभावों का आकलन करना है। ऐसे संघों को स्थापित करने के लिए, एक्सपोज़र डेटासेट को राष्ट्रीय परिवार स्वास्थ्य सर्वेक्षण (NFHS-4) डेटा से मानवविज्ञान माप, रक्त बायोमार्कर और समाजशास्त्रीय जानकारी के साथ एकीकृत किया जाता है।

कुल परिवेशी $PM_{2.5}$ एक्सपोज़र में क्षेत्रीय योगदान को अलग करना न केवल इसकी संरचना में परिवर्तनों को समझने के लिए महत्वपूर्ण है, बल्कि नीति निर्माताओं के लिए भी प्रासंगिक है। यह थीसिस विभिन्न स्रोतों द्वारा योगदान किए गए $PM_{2.5}$ जोखिम के लिए सापेक्ष पैमाने पर स्वास्थ्य प्रभाव का आकलन करती है। यह दृष्टिकोण अधिकतम स्वास्थ्य लाभ स्थापित करने के लिए वायु प्रदूषण को कम करने के उद्देश्य से क्षेत्रीय हस्तक्षेपों को प्राथमिकता देने में सक्षम बनाता है।

भारत वैश्विक स्तर पर प्रजनन आयु (WRA) की महिलाओं में एनीमिया के सबसे अधिक (53%) प्रसार में से एक को प्रदर्शित करता है। यह थीसिस WRA के बीच एनीमिया के प्रसार पर $PM_{2.5}$ के प्रभावों का आकलन करने के लिए क्रॉस-सेक्शनल विश्लेषण का उपयोग करती है। उपग्रह-व्युत्पन्न $PM_{2.5}$ (1 किमी x 1 किमी स्थानिक रिज़ॉल्यूशन पर) डेटा का उपयोग NFHS-4 डेटासेट के साथ विलय करके जोखिम का आकलन करने के लिए किया जाता है। एनीमिया के प्रसार पर $PM_{2.5}$ और इसकी प्रजातियों के प्रभावों का अनुमान लगाने के लिए संभावित जोखिम कारकों के साथ समायोजित एक मल्टीपल लॉजिस्टिक रिग्रेशन मॉडल का उपयोग किया जाता है। $PM_{2.5}$ घटकों के लिए एक्सपोज़र डेटासेट रीएनालिसिस डेटासेट और रासायनिक परिवहन मॉडल (सीटीएम) आउटपुट से प्राप्त होते हैं। निष्कर्षों से पता चलता है कि परिवेशी $PM_{2.5}$ एक्सपोज़र में प्रत्येक 10 $\mu g\ m^{-3}$ की वृद्धि के साथ, WRA के बीच औसत एनीमिया का प्रसार 7.23% (95% आत्मविश्वास अंतराल, CI: 6.82-7.63) बढ़ जाता है। विशेष रूप से, $PM_{2.5}$ प्रजातियों में सल्फेट और मौलिक कार्बन कार्बनिक पदार्थों और धूल की तुलना में एनीमिया के साथ एक मजबूत संबंध प्रदर्शित करते हैं। क्षेत्रीय योगदानकर्ताओं में, औद्योगिक क्षेत्र से योगदान करने वाले $PM_{2.5}$ में एनीमिया के साथ उच्चतम अंतर अनुपात (OR) दिखाया गया, इसके बाद असंगठित, घरेलू, बिजली, सड़क की धूल, कृषि अपशिष्ट जलाना और परिवहन क्षेत्रों का स्थान है।

अध्ययन में पांच साल से कम उम्र के बच्चों के बीच स्वास्थ्य बोझ का प्रतिनिधित्व करने के लिए कम वजन (LBW), एनीमिया, तीव्र श्वसन संक्रमण (ARI), स्टंटिंग, वेस्टिंग और कम वजन जैसे स्वास्थ्य परिणामों का

भी उपयोग किया जाता है। इन परिणामों को भारत में आम सार्वजनिक स्वास्थ्य मुद्दों के रूप में उनकी व्यापकता, वायु प्रदूषण से जुड़े उनके पैथोफिजियोलॉजिकल ढांचे और विभिन्न अस्थायी और अंग प्रणाली संदर्भों में उनकी अभिव्यक्ति के कारण माना जाता है। पांच वर्ष से कम उम्र के बच्चों में प्रदूषकों के संपर्क और स्वास्थ्य परिणामों की श्रृंखला के बीच एक सकारात्मक संबंध देखा गया है। LBW, एनीमिया, ARI, स्टंटिंग और कम वजन जैसे स्वास्थ्य परिणाम परिवेशीय $PM_{2.5}$ के साथ एक महत्वपूर्ण संबंध दर्शाते हैं, जबकि बर्बादी ब्याज के जोखिम के साथ अपेक्षाकृत कमजोर संबंध दर्शाती है। मल्टीपल लॉजिस्टिक रिग्रेशन का उपयोग करते हुए, यह अनुमान लगाया गया है कि $PM_{2.5}$ एक्सपोज़र में प्रत्येक 10 $\mu g\ m^{-3}$ की वृद्धि के लिए, एनीमिया, ARI और जन्म के समय कम वजन (LBW) की व्यापकता 10% बढ़ जाती है (95% कॉन्फिडेंस इंटरवल, CI: 9-11)), भारत में बच्चों में क्रमशः 11% (8-13), और 5% (4-6)। नाइट्रेट (NO_3^-), मौलिक कार्बन और अमोनियम (NH_4^+) जैसी प्रजातियां अन्य $PM_{2.5}$ प्रजातियों की तुलना में तीन बाल स्वास्थ्य परिणामों के साथ एक मजबूत संबंध प्रदर्शित करती हैं।

$PM_{2.5}$ द्रव्यमान में 10 $\mu g\ m^{-3}$ की वृद्धि के लिए $PM_{2.5}$ घटकों का संचयी विषम अनुपात (OR) LBW के लिए 1.23 (1.21 - 1.26), एनीमिया के लिए 1.49 (1.45 - 1.52), 1.35 (1.29 - 1.41) ARI के लिए, 1.22 (1.94, 1.26) स्टंटिंग के लिए, 1.002 (1.001, 1.003) वेस्टिंग के लिए, और 1.301 (1.267, 1.336) कम वजन के लिए, जबकि $PM_{2.5}$ द्रव्यमान में प्रत्येक 10 $\mu g\ m^{-3}$ वृद्धि के लिए, ORs का अनुमान लगाया गया था 1.05 (1.04 - 1.06), 1.10 (1.09 - 1.11), 1.11 (1.08 - 1.13), 1.31 (1.2, 1.41), 1.013 (1.011, 1.014), 1.36 (1.31, 1.42) LBW, एनीमिया, ARI, स्टंटिंग, कमज़ोर होना और कम वज़न होना। इन परिणामों से पता चलता है कि वायु प्रदूषण जोखिम के लिए सरोगेट मार्कर के रूप में कुल $PM_{2.5}$ द्रव्यमान पर भरोसा करने से $PM_{2.5}$ के भीतर विभिन्न घटकों के वास्तविक समग्र प्रभाव को काफी हद तक कम आंका जा सकता है।

यह अध्ययन स्वदेशी जोखिम-जोखिम कार्यों का उपयोग करके भारत सरकार द्वारा निर्धारित विभिन्न स्वच्छ वायु लक्ष्यों को पूरा करके परिवेशी $PM_{2.5}$ जोखिम को कम करने के संभावित स्वास्थ्य लाभों का अनुमान लगाता है। परिणाम बताते हैं कि यदि भारत राष्ट्रीय परिवेश वायु गुणवत्ता मानक (NAAQS) 40 $\mu g\ m^{-3}$ के वायु गुणवत्ता मानकों को पूरा करता है, तो राष्ट्रीय एनीमिया का प्रसार 53% से कम होकर 44% हो जाएगा। इसलिए, स्वच्छ ऊर्जा में परिवर्तन से 'एनीमिया-मुक्त' मिशन लक्ष्य की दिशा में भारत की प्रगति में तेजी आएगी। इसके अलावा, निष्कर्ष भारत में अधिक बाल स्वास्थ्य लाभ के लिए अधिक जहरीली प्रजातियों के संपर्क को कम करने के लिए नियंत्रण रणनीतियों को प्राथमिकता देने के लिए महत्वपूर्ण स्वदेशी साक्ष्य प्रदान करते हैं।

इस थीसिस से महत्वपूर्ण संदेश यह है कि $PM_{2.5}$ की संरचना मायने रखती है और ग्लोबल बर्डन ऑफ डिजीज फ्रेमवर्क में $PM_{2.5}$ प्रजातियों में एक समान विषाक्तता की धारणा मानव स्वास्थ्य पर वायु प्रदूषण के 'सही' प्रभाव को कम आंक सकती है। यह थीसिस स्वदेशी स्वास्थ्य डेटा का उपयोग करके बच्चे और मातृ स्वास्थ्य परिणामों की एक श्रृंखला के लिए LMIC में साक्ष्य अंतराल को भी पाटती है। इस थीसिस के हिस्से के रूप में प्रस्तुत निष्कर्षों से नीति निर्माताओं को विशिष्ट स्वच्छ वायु लक्ष्यों से जुड़े स्वास्थ्य-लाभ आकलन के साथ जुड़े हस्तक्षेपों को प्राथमिकता देने में सहायता मिलने की उम्मीद है जो भारतीय जनसांख्यिकी के लिए अधिक यथार्थवादी हैं।

Contents

Certificate i

Acknowledgment ii

Abstract iv

सार (Hindi abstract) viii

Contents xii

List of Figures xvi

List of Tables xxii

Abbreviations xxiv

Chapter 1 1

Introduction 1

1.1 Air Pollution 3
1.2 Impact of air pollution on human health: Global and National level status 5
1.2.1 International studies 5
1.2.2 Indian studies 6
1.2.3 Who is at high risk of air pollution exposure? 8
1.2.4 Child health burden attributable to air pollution in India 10
1.3 Looking beyond $PM_{2.5}$ mass 13
1.3.1 Lack of India-specific studies on the impact of $PM_{2.5}$ species 14
1.4 Integrating evidence on children's health into clean air policies 15
1.5 Research gaps 16
1.6 Objectives 17
1.7 Structure of the Thesis 18
Chapter 2 19

The spatio-temporal dimension of exposure and health datasets in India 19

2.1 Introduction 21
2.2 Spatio-temporal variability of $PM_{2.5}$ exposure dataset 21
2.2.1 Ambient $PM_{2.5}$ exposure assessment 21
2.2.2 Validation of satellite-derived ambient $PM_{2.5}$ dataset 24

2.3 Spatio-temporal variability of ambient $PM_{2.5}$ components and contributing sectors 25
2.3.1 WRF- CMAQ model 26
2.3.2 Sectoral contribution to $PM_{2.5}$ 31
2.4 Health dataset – National Family Health Survey (NFHS) 36
2.4.1 Why NFHS-4? 37
2.5 NFHS-4 survey sampling strategy 38
2.6 Health status of women of reproductive age in India, captured in NFHS-4 39
2.7 Health status of children of age under five years in India 41
2.8 Exposure attribution strategy and statistics 43
2.9 Exposure assignment strategy 47
2.10 Overall Framework for datasets utilized in the study 48
2.11 Summary 49
Chapter 3 51
Impact of exposure to $PM_{2.5}$ and its components on women of reproductive age in India 51
3.1 Introduction 53
3.2 Survey dataset, health outcomes, and potential confounders 53
3.2.1 Survey dataset 53
3.2.2 Health outcomes: hemoglobin concentrations and anemia prevalence 56
3.2.3 Potential confounders 59
3.3 Exposure datasets 60
3.4 Directed Acyclic Graph (DAG) 61
3.5 Statistical modelling strategy 61
3.5 Estimation of association between exposure to $PM_{2.5}$ components and anemia prevalence 63
3.6 Impact of ambient $PM_{2.5}$ contributed by sources from a chemical transport model - WRF-CMAQ 64
3.7 Exposure – Response curve 67
3.8 Hypothesis of biological plausibility 67
3.9 Summary 69
Chapter 4 72
Impact of $PM_{2.5}$ components on children of age under 5 years in India 72
4.1 Introduction 74
4.2 Survey dataset, health outcomes, and potential confounders 75
4.2.1 Survey dataset 75

4.2.2 Health outcomes: Low Birth Weight (LBW), Anemia, Acute Respiratory Infection (ARI), and Malnutrition 76
4.2.3 Potential confounders 82
4.3 Exposure assignment and statistical model 83
4.4 Association between exposure to ambient $PM_{2.5}$ and child health outcomes 85
4.4.1 Association between exposure to ambient $PM_{2.5}$ and different types of anemia 85
4.5 Effects of exposure to $PM_{2.5}$ components on child health 87
4.6 Estimating cumulative effects of $PM_{2.5}$ components on child health outcomes 89
4.7 Association between exposure to $PM_{2.5}$ sources and child health outcomes 91
4.8 Estimation of non-linearities between exposure to $PM_{2.5}$ components and sources and child health outcomes 94
4.8.1 Non-linearities between exposure to $PM_{2.5}$ components and LBW 95
4.8.2 Non-linearities between exposure to $PM_{2.5}$ components and anemia 96
4.8.3 Non-linearities between exposure to $PM_{2.5}$ components and ARI 97
4.8.4 Non-linearities between exposure to $PM_{2.5}$ components and stunting 99
4.8.5 Non-linearities between exposure to $PM_{2.5}$ components and wasting 100
4.8.6 Non-linearities between exposure to $PM_{2.5}$ components and underweight 101
4.9 Hypothesis on biological plausibility 102
4.10 Summary 103
4.11 Limitations 104
Chapter 5 105
Risk factors modifying exposure-health relationships 105
5.1 Introduction 107
5.2 Effect modifiers that influence the relationship between $PM_{2.5}$ exposure and anemia prevalence among women of reproductive age 108
5.2.1 Household level effect modifiers 108
5.2.2 Individual level effect modifiers 110
5.3 Estimation of relative excess risk of anemia among WRA due to Interaction 112
5.4 Effect modifiers that Influence the relationship between $PM_{2.5}$ exposure and the health of children 115
5.4.1 Effects of $PM_{2.5}$ components on anemia and ARI stratified by birth weight status: low birth weight (LBW) and normal birth weight (NBW) 115
5.4.2 Effects of emission sources contributing to $PM_{2.5}$ on anemia and ARI stratified by birthweight status 116
5.4.3 Effect modification due to birthweight status on the association between $PM_{2.5}$ components and malnutrition outcomes: stunting, wasting, and underweight 118

5.4.4 Effects of sources contributing to $PM_{2.5}$ on stunting, wasting, and underweight stratified by birthweight status 119
5.5 Summary 121
Chapter 6 122
Health benefits of meeting clean air targets: Policy Implications 122
6.1 Introduction 124
6.2 Clean air targets for India 125
6.2.1 National Clean Air Program (NCAP) 125
6.2.2 Pradhan Mantri Ujjwala Yojana (PMUY) 126
6.2.3 Air quality guidelines for air pollution 127
6.3 Approach to estimate expected health benefits for WRA and U5 children by achieving social programs (clean air action plans) and air quality guidelines 128
6.4 Expected health benefits for women of reproductive age by achieving targets of social programs and air quality guidelines 130
6.5 Expected health benefits for children of age under 5 years by achieving clean air action plans and air quality guidelines 133
6.6 Summary 136
6.7 Limitations 137
Chapter 7 138
Summary and Future Direction 138
7.1 Summary 140
7.2 Limitations 143
7.3 Future directions 144
References 145
Appendices 165
Appendix A Table 1 District-level ambient $PM_{2.5}$ exposure (unit: $\mu g\ m^{-3}$) for the period 2007-2016, anemia prevalence (in %) captured by the NHFS-4, anemia prevalence after meeting clean air targets and the WHO AQG. 165
Publications 181
Brief Biodata 184

List of Figures

Figure 1.1 Size comparisons for PM particles to a human hair (source: US EPA, 2016) https://www.niehs.nih.gov/health/topics/agents/air-pollution..4

Figure 1.2 Age-standardized death rates attributable to air pollution in India from 2000 to 2019 (GBD India). The shaded region represents a 95% Confidence Interval (CI). Data Source: GBD https://vizhub.healthdata.org/gbd-compare/ 7

Figure 1.3 Distribution of global deaths attributable to $PM_{2.5}$, ozone, and household air pollution, by age. Source- SOGA report 2020. 10

Figure 1.4 Forest plot representing the Indian studies that assessed the association between $PM_{2.5}$ exposure and a range of health outcomes among U5 children. Black dots represent OR and color lines show 95% CI. 12

Figure 1.5 Infographic showing child health outcomes attributed to in-utero and early-life $PM_{2.5}$ exposure. 13

Figure 2.1 Spatial pattern of ambient $PM_{2.5}$ exposure (averaged from 2007-2016) by the district in each state, measured in µg m^{-3}. Data source: Dey et al., 2020. 23

Figure 2.2 Ambient $PM_{2.5}$ exposure (averaged from 2007-2016) by the states, measured in µg m^{-3}. Data source: Dey et al., 2020..24

Figure 2.3 Validation plot showing correlation between daily (left), annual (right) satellite-based data with ground-based $PM_{2.5}$ concentrations over India. Data points falling outside the 1:2 and 2:1 lines (depicted as dotted lines) are identified as outliers, accounting for less than 0.5% of the daily $PM_{2.5}$ product, source: Dey et al., 2020..25

Figure 2.4 Density distribution of $PM_{2.5}$ components from the WRF-CMAQ model (2016) data. The x-axis and y-axis represent the concentration (in μg m^{-3}) and density of each species respectively, across India. 29

Figure 2.5 Spatial patterns of $PM_{2.5}$ species from the WRF-CMAQ model (2016) data. 30

Figure 2.6 Sectoral contribution to total $PM_{2.5}$ from the WRF- CMAQ model (2016). 32

Figure 2.7 Density distribution of various sectors contributing to $PM_{2.5}$ in the WRF-CMAQ model (2016) data. The x-axis and y-axis represent the concentration (in μg m^{-3}) and density of each species respectively, across India. 33

Figure 2.8 Spatial patterns of sector-specific $PM_{2.5}$ from the CMAQ model (2016) data.......35

Figure 2.9 Overall percent contribution of each component in each sector. Sector 'other' involves refused burning, construction, crematoria, NH_3, biogenic emissions, and evaporative non-methane volatile organic compounds (NMVOCs). Whereas component 'other' involves chloride, sodium, magnesium, calcium, soil, water molecules, and unspecified species. 36

Figure 2.10 National Family Health Survey (NFHS) timeline and versions. 38

Figure 2.11 Spatial pattern of prevalence of anemia amongst women of reproductive age by district within each state in India 40

Figure 2.12 Anemia prevalence amongst women of reproductive age by states of India. 40

Figure 2.13 Spatial pattern of prevalences of anemia, LBW, ARI, stunting, wasting, and underweight amongst U5 children by district within each state in India. 43

Figure 2.14 Exposure data extraction strategy on NFHS geolocations. 44

Figure 2.15 Infographic representing exposure assignment based on outcome variable for the targeted population. 48

Figure 2.16 Infographic representing types of exposure datasets combined with health data.49

Figure 3.1 Missing observations of WRA population from NFHS-4 that were omitted and filtered by variables of interest. 56

Figure 3.2 A DAG representing the association between long-term PM2.5 exposure and anemia prevalence among WRA, adjusted with potential confounders. 61

Figure 3.3 Adjusted odds ratio (OR) of anemia in WRA for every inter-quartile range (IQR) increase of exposure to WRF-CMAQ ambient $PM_{2.5}$ components. 64

Figure 3.4 Odds of anemia in WRA for every inter-quartile range (IQR) increase of exposure to ambient $PM_{2.5}$ contributed by various sectors captured from the WRF-CMAQ model dataset. 66

Figure 3.5 Exposure-response curve of ambient $PM_{2.5}$ long-term (2007-2016) exposure against anemia prevalence and hemoglobin level. Shaded regions denote 95% CI. 67

Figure 3.6 Potential pathway to explain the association between exposure to $PM_{2.5}$ and anemia prevalence. 69

Figure 4.1 Schematic consort diagram demonstrating the exclusion criteria of observations in the NFHS-4 dataset. 76

Figure 4.2 Dose response curve between probability of overall anemia prevalence and ambient $PM_{2.5}$. 86

Figure 4.3 Dose response curve between probability of severe, moderate, and mild anemia prevalence and ambient $PM_{2.5}$. 86

Figure 4.4 Association between exposure to $PM_{2.5}$ components and child health outcomes. Odds ratio per IQR of $PM_{2.5}$ components concentrations with their 95% confidence intervals (black dots with error bars) for given health outcomes i.e., LBW, Anemia, and ARI. 88

Figure 4.5 Association between exposure to $PM_{2.5}$ components and child health outcomes. Odds ratio per IQR of $PM_{2.5}$ components concentrations with their 95% confidence intervals (black dots with error bars) for given health outcomes i.e., stunting, wasting, and underweight. 89

Figure 4.6 Association between exposure to $PM_{2.5}$ contributed from various sectors and child health outcomes. Odds ratio per IQR of $PM_{2.5}$ sectoral concentrations with their 95% confidence intervals (black dots with error bars) for given health outcomes i.e., LBW, Anemia, and ARI. 93

Figure 4.7 Association between exposure to $PM_{2.5}$ contributed from various sectors and child health outcomes. Odds ratio per IQR of $PM_{2.5}$ sectoral concentrations with their 95% confidence intervals (black dots with error bars) for given health outcomes i.e., stunting, wasting, and underweight. 94

Figure 4.8 Exposure-response curves for LBW against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% confidence interval. 96

Figure 4.9 Exposure-response curves for anemia against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% confidence interval. 97

Figure 4.10 Exposure-response curves for ARI against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% confidence interval. 98

Figure 4.11 Exposure-response curves for stunting against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% CI. 99

Figure 4.12 Exposure-response curves for wasting against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% confidence interval. 100

Figure 4.13 Exposure-response curves for underweight against components and sectors contributing to $PM_{2.5}$. The shaded region represents a 95% confidence interval. 101

Figure 5.1 Effect of $PM_{2.5}$ exposure on odds of anemia and hemoglobin level among WRA in India. 111

Figure 5.2 Association between per IQR of $PM_{2.5}$ components concentrations with an interaction of birthweight status and health outcomes such as anemia and ARI. The odds ratios with their 95% confidence intervals are represented in black dots with error bars. LBW represents low birthweight; NBW represents normal birthweight. 116

Figure 5.3 Association between per IQR of sectoral $PM_{2.5}$ concentrations with an interaction of birthweight status and health outcomes such as anemia and ARI. Odds ratios with their 95% confidence intervals are represented in black dots with error bars. LBW represents low birthweight; NBW represents normal birthweight. 117

Figure 5.4 Association between per IQR of $PM_{2.5}$ components concentrations with an interaction of birthweight status and health outcomes such as stunting, wasting, and underweight. Odds ratios with their 95% confidence intervals are represented in black dots with error bars. LBW represents low birthweight; NBW represents normal birthweight. 119

Figure 5.5 Association between per IQR of sectoral $PM_{2.5}$ concentrations with an interaction of birthweight status and health outcomes such as stunting, wasting, and underweight. Odds ratios with their 95% confidence intervals are represented in black dots with error bars. LBW represents low birthweight; NBW represents normal birthweight. 120

Figure 6.1 Contribution of the residential emission to ambient $PM_{2.5}$ at the district level from the CMAQ model (2016). 129

Figure 6.2 Anemia prevalence and clean air targets concerning the WRA population. Anemia prevalence (A) after the NCAP implementation where ambient $PM_{2.5}$ exposure is reduced by

30%, (B) after mitigating domestic emissions by implementing PMUY and DDUGJY, (C) after reduction in ambient $PM_{2.5}$ exposure by the combined impact of the NCAP, PMUY, and DDUGJY, and (D) if India meets the WHO AQG. 132

Figure 6.3 Benefits of meeting clean air targets concerning ambient $PM_{2.5}$ mass. A- LBW prevalence (%) across Indian districts, B- LBW (%) after NAAQS implementation, C- LBW prevalence (%) after next air quality standards implementation; D- anemia prevalence (%) across Indian districts, E- anemia prevalence (%) after NAAQS implementation, F- anemia prevalence (%) after next air quality standards implementation; G- ARI prevalence (%) across Indian districts, H- ARI prevalence (%) after NAAQS implementation, I- ARI prevalence (%) after next air quality standards implementation; J- stunting prevalence (%) across Indian districts, K- stunting (%) after NAAQS implementation, L- stunting prevalence (%) after next air quality standards implementation, followed by wasting (M,N,O) and underweight (P,Q,R) 135

List of Tables

Table 2.1 WRF-CMAQ Model set-up details. 27

Table 2.2 Distribution of $PM_{2.5}$ exposure along with its components and sectoral contribution at PSU level. All units are in µg m^{-3}. 45

Table 2.3 Sectoral contribution of $PM_{2.5}$ exposure at PSU level (total PSU numbers are 27828). All units are in µg m^{-3}. 46

Table 3.1 Prevalence of anemia among WRA (640,557 sample size) across levels of covariates used in the study. The estimates presented in the table hold statistical significance, with p-values <0.05. 57

Table 3.2 Prevalence of types of anemia among WRA across maternity status. 59

Table 3.3 Ecological (district) and individual-level effects of every 10 µg m^{-3} increase in ambient $PM_{2.5}$ exposure on anemia and hemoglobin across India (districts included: 636 and sample size: 640557). The estimates presented in the table hold statistical significance, with p-values <0.05. 62

Table 4.1 Prevalence of ARI, LBW, anemia, and malnutrition (stunting, wasting, and underweight) of U5 children in India, stratified by potential predictors. The estimates presented in the table hold statistical significance, with p-values <0.05. 78

Table 4.2 Odds ratios (OR) between $PM_{2.5}$ mass and health outcomes, as well as the OR of cumulative $PM_{2.5}$ components and health outcomes. The estimates presented in the table hold statistical significance, with p-values <0.05. 91

Table 5.1 Regression coefficients for Relative Excess Risk due to Interaction (RERI) generated using various risk factors and the $PM_{2.5}$ exposure dataset used in the study. The estimates presented in the table hold statistical significance, with p-values <0.05. 114

Table 6.1 Expected reduction in anemia prevalence among WRA when social programs focused on clean air targets are implemented.. 131

Table 6.2 Expected reduction in LBW, anemia, ARI, stunting, wasting, and underweight prevalences among U5 children when clean air targets are implemented. The estimates presented in the table hold statistical significance, with p-values <0.05. 134

Abbreviations

AOD – Aerosol Optical Depth

AQG – Air Quality Guidelines

BC – Black Carbon

CI – Confidence Intervals

CMAQ – Community Multiscale Air Quality Modelling System

COPD – Chronic Obstructive Pulmonary Diseases

CPCB – Central Pollution Control Board

CTM – Chemical Transport Model

DALY – Disability-Adjusted Life years

DDUGY – Deen Dayal Upadhyaya Gram Jyoti Yojana

DHS – Demographic Health Survey

ECLIPSE – Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants

ECMWF – European Center for Medium-range Weather Forecasting

EDGAR – Emissions Database for Global Atmospheric Research

ERA – ECMWF Re-Analysis

GBD – Global Burden of Diseases

GEOS-Chem – Goddard Earth Observing System Chemical Transport Model

GHS – Global Human Settlement.

GHSL – Global Human Settlement Layer

GHS-SMOD – Global Human Settlement – Settlement Grid

GoI – Government of India

HAP – Household Air Pollution

HEI – Health Effects Institute

IGP – Indo Gangetic Plain

IHD – Ischemic Heart Diseases

IT – Interim Targets

LBW – Low Birth Weight

LPG – Liquified Petroleum Gas

MAIAC – Multi-Angle Implementation of Atmospheric Correction

MISR – Multi-angle Imaging Spectro-Radiometer

MODIS – Moderate Resolution Imaging Spectroradiometer

NAAQS – National Ambient Air Quality Standards

NBW – Normal Birth Weight

NCAP – National Clean Air Programme

NO_3 - Nitrate

PM – Particulate Matter

PM10 – Particulate matter with aerodynamical diameter less than 10µm

PM2.5 – Particulate matter with aerodynamical diameter less than 2.5µm

PMUY – Pradhan Mantri Ujjwala Yojana

POA – Primary Organic Aerosol

RR – Relative Risk

SO_4^{2-} – Sulfate

SOA – Secondary Organic Aerosol

U5 – Under 5 years

VOC – Volatile Organic Carbon

WHO – World Health Organization

WRA – Women of Reproductive Age

WRF – Weather Research and Forecasting

WRF Chem – Weather Research and Forecasting Chemical Transport Model

WRF CMAQ – Weather Research and Forecasting Community Multi-scale Air Quality Modelling System

YLL – Years of Life Lost