

DETERMINANTS OF DISPARITY IN AMBIENT AIR POLLUTION EXPOSURE AND ITS ASSOCIATED HEALTH BURDEN IN INDIA

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by

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Certificate

This is to certify that the thesis entitled “**Determinants of disparity in ambient air pollution exposure and its associated health burden in India**” being submitted by Mr. **Debajit Sarkar** for the award of the degree of **Doctor of Philosophy**, is a record of the original bonafide research work carried out by him. He 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 award of any degree/diploma.

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Date:

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Abstract

Ambient air pollution is the largest environmental risk factor for public health globally, which claimed around one-seventh of the total health causalities. In India, ambient PM_{2.5}-attributable health burden is expected to elevate over the upcoming decades and the populace may face calamitous consequences due to its enormous population size and aging factor. To alleviate the growing mortality burden, India aspired to achieve the United Nations' Sustainable Development Goal (SDG-3.4) target, which is to reduce the health burden by one-third by 2030 relative to that of 2015. It is unknown whether the existing emission control pathways are sufficient for this attainment nationally and at subregional level; and if not, then what would be the subsequent exposure-reduction targets? Moreover, the current trajectory of emissions would further degrade air quality and potentially lead to increasing warming in foreseeable future, which may increase the health causalities by manifolds. Therefore, it is necessary to have an ahead-of-time estimate of potential health benefits due to following the air pollution and climate-control pathway as compared to the business-as-usual trends. Consequently, the exiting environmental policies to combat air pollution burden and its attributable health effects have met limited success. This is because the effect of demographic distribution of the sub-populations, leading to differential air pollution exposure levels across the subregions, is unknown in India and has yet to be incorporated into the strategic implementation of such policies and interventions. Evolving studies have reported strong association between ambient PM_{2.5} with the non-communicable diseases (NCDs); however, its distribution across diverse demographic subgroups is unknown in this socially diverse country. More importantly, knowledge-gaps exist if such exposure disparity is associated with differential health effects among the sub-

populations; and hence, lead to disproportionated PM_{2.5}-attributable health burden for various NCDs, which is currently missing in the global burden of disease (GBD) framework.

In this thesis, the disparity in ambient PM_{2.5} exposure is examined across various population subgroups in urban and rural India and its changes in recent years are analyzed by integrating satellite-derived PM_{2.5} concentrations (1-km×1-km) with the socio-demographic information from the 4th (2015-16) and 5th (2019-21) rounds of the National Family Health Survey (NFHS). Then, the hierarchical logistic mixed effect model is used to estimate the association between the odds of diabetes, high blood pressure (HBP), and heart disease with satellite-derived PM_{2.5} exposure stratified by participants' gender, wealth, and caste; adjusting for socio-demographic confounders. And then, following the global burden of disease (GBD) framework, the model-derived risk estimates are used to assess ambient PM_{2.5}-attributable health burden across the subgroups. Larger absolute disparity (60-90 µg/m³) is estimated across the states with high socio-demographic index (SDI) as compared to the middle and lower SDI states. Moreover, it is discovered that ambient PM_{2.5} exposure is higher (indicated by relative disparities in terms of Z_{score}) among the top and bottom quantiles of wealth-index and the other backward caste subgroup (Z_{score}>±0.02, p<0.1) than among their demographic counterparts in middle and high SDI states. From 2015-16 to 2019-21, the disparity in ambient PM_{2.5} exposure across subgroups increased in urban areas, while it either remained static or decreased in rural areas. Consequently, ambient PM_{2.5}-diseases' association varies across sub-populations and is higher among males (mean odds ratio 1.049 vs 1.039) and OBC (1.078 vs 1.044) relative to females and other caste-subgroups, respectively. The PM_{2.5}-diabetes association consistently increases from poorest to richest (1.025 to 1.062), while decreases for other two diseases of concern. Additionally, it is estimated that males, OBC, and deprived subgroups suffer from excess

morbidities [2.02-11.79 million (1.86-13.92)] than their demographic counterparts, predominantly from diabetes and heart disease. India's urban-centric approach to addressing air pollution may further exacerbate disparities among diverse demographics. Therefore, it is recommended to formulate targeted policies, aimed at reducing ambient PM_{2.5} exposure and alleviating disparities, by prioritizing action plans, policies, and interventions for the vulnerable subgroups. India should implement air pollution mitigation mandates prioritizing the vulnerable subgroups, along with controlling other modifiable risk-factors, simultaneously, to achieve environmental and health equities in the foreseeable future.

To assess the effects of ambient PM_{2.5} exposure and its sectoral contributions in shaping future air quality and its health and economic futures. The health burden attributable to sector-specific primary and secondary emissions is apportioned from local and regional sources at state levels for the base year of 2015 and projected for 2030 under three GAINS-simulated contrasting air pollution emission pathways [Business-as-usual (BAU), Advanced Control Technology (ACT), and Sustainable Development Scenario (SDS)] by integrating into the Global Burden of Disease (GBD) framework. It is estimated that PM_{2.5}-attributable premature deaths to change from 0.72 million (95% uncertainty intervals, UIs: 0.53-0.89) in 2015 to 0.79 (0.57-1.1), 0.76 (0.6-1.1), and 0.63 (0.48-0.81) million in 2030 under these pathways, respectively. Only 13 states in India will achieve the SDG-3.4 goal if they meet their closest clean-air targets (40 µg/m³ or below). For the remaining states, the exposure targets are far-fetched and will require larger efforts than those envisioned under the aspirational SDS pathway. Following the decarbonization scenario (2°C-Warming Scenario), resulting in lower PM_{2.5} concentration and may restrict the warming level below 2°C by the end of the century, may prevent 0.77±0.19 million premature deaths and 18.7±4.3 million morbidities by mid-century. These translate to an aggregated

economic benefit of 18.9 ± 4.4 billion Euros annually. Domestic and energy sectors (power plant and industries) would have largest shares in future health casualties; but these sectors would also provide maximal health benefits upon prioritization. However, the projected health impacts are not necessarily lower in climate-control scenario than baseline; because of increasing size of vulnerable population may elevate PM_{2.5}-related health effects. For most states, changes in socio-demographic factors (population growth, its aging, and declining baseline mortality/morbidity rates) would play predominant roles than the exposure level in shaping future health impacts. India should adopt the strictest implementation strategy to curb emissions of primary PM_{2.5} and precursor gases, with priority on residential and commercial sectors through a multistate conjugate action plan and an accelerated transition to clean energy. Policies aiming to reduce PM_{2.5} exposure alone are not sufficient, and the policies should plan beyond the current National Clean Air Program and make efforts to control other risk factors (that co-impact baseline mortality rates) simultaneously for considerable health benefits.

सारांश

वातावरणीय वायु प्रदूषण वैश्विक स्तर पर सार्वजनिक स्वास्थ्य के लिए सबसे बड़ा पर्यावरणीय जोखिम कारक है, जो कुल स्वास्थ्य हानियों का लगभग सातवां हिस्सा बनता है। भारत में, $PM_{2.5}$ के कारण होने वाला स्वास्थ्य बोझ आने वाले दशकों में और अधिक बढ़ने की संभावना है, और इसकी विशाल जनसंख्या और वृद्ध होती जनसंख्या के कारण देश को गंभीर परिणामों का सामना करना पड़ सकता है। बढ़ती मृत्यु दर को कम करने के लिए, भारत ने संयुक्त राष्ट्र के सतत विकास लक्ष्य (SDG-3.4) को प्राप्त करने की आकांक्षा जताई है, जिसका उद्देश्य 2015 की तुलना में 2030 तक स्वास्थ्य बोझ को एक-तिहाई तक कम करना है। यह ज्ञात नहीं है कि वर्तमान उत्सर्जन नियंत्रण मार्ग इस लक्ष्य को राष्ट्रीय और उप-क्षेत्रीय स्तर पर प्राप्त करने के लिए पर्याप्त हैं या नहीं; और यदि नहीं, तो फिर आवश्यक प्रदूषण-उत्सर्जन में कटौती के लक्ष्य क्या होने चाहिए? इसके अलावा, वर्तमान उत्सर्जन प्रवृत्ति वायु गुणवत्ता को और बिगाड़ सकती है और संभावित रूप से भविष्य में गर्मी को बढ़ा सकती है, जिससे स्वास्थ्य हानियाँ कई गुना बढ़ सकती हैं। अतः यह आवश्यक है कि वायु प्रदूषण और जलवायु नियंत्रण मार्गों का पालन करने से होने वाले संभावित स्वास्थ्य लाभों का समय से पहले अनुमान लगाया जाए, ताकि व्यवसाय-यथावत प्रवृत्तियों की तुलना में बेहतर रणनीति बनाई जा सके। इसके परिणामस्वरूप, वायु प्रदूषण से होने वाले स्वास्थ्य प्रभावों से निपटने के लिए मौजूदा पर्यावरणीय नीतियों को सीमित सफलता मिली है। इसका कारण यह है कि भारत में उप-जनसंख्या समूहों के जनसांख्यिकीय वितरण और इससे उत्पन्न वायु प्रदूषण की असमानता के प्रभावों को अभी तक रणनीतिक नीतियों और हस्तक्षेपों में शामिल नहीं किया गया है। उभरते हुए अध्ययन दर्शाते हैं कि $PM_{2.5}$ और गैर-संक्रामक रोगों (NCDs) के बीच मजबूत संबंध है; लेकिन इस विविध सामाजिक देश में विभिन्न जनसांख्यिकीय समूहों के बीच $PM_{2.5}$ के वितरण की जानकारी अब भी अधूरी है। सबसे महत्वपूर्ण बात यह है कि यह ज्ञात नहीं है कि क्या इस असमानता का संबंध विभिन्न स्वास्थ्य प्रभावों से है; और इस तरह से यह

विभिन्न उप-जनसंख्याओं के लिए असमान $PM_{2.5}$ -जनित स्वास्थ्य बोझ उत्पन्न करता है, जिसे वर्तमान में वैश्विक रोग भार (GBD) ढांचे में शामिल नहीं किया गया है।

इस शोध में, शहरी और ग्रामीण भारत में विभिन्न जनसंख्या उप-समूहों के बीच $PM_{2.5}$ की असमानता का विश्लेषण किया गया है और हाल के वर्षों में इसके परिवर्तनों का अध्ययन किया गया है। इसके लिए उपग्रह-व्युत्पन्न $PM_{2.5}$ सांद्रता (1-किमी $\times$ 1-किमी) को राष्ट्रीय पारिवारिक स्वास्थ्य सर्वेक्षण (NFHS) के चौथे (2015-16) और पांचवें (2019-21) दौर की सामाजिक-जनसांख्यिकीय जानकारी से जोड़ा गया है। फिर, लॉजिस्टिक मिक्स्ड इफेक्ट मॉडल का उपयोग करके, मधुमेह, उच्च रक्तचाप (HBP), और हृदय रोग के लिए उपग्रह-आधारित $PM_{2.5}$ के संपर्क के साथ संबंधों का अनुमान प्रतिभागियों के लिंग, संपत्ति, और जाति के अनुसार किया गया है; साथ ही सामाजिक-जनसांख्यिकीय भ्रम कारकों के लिए समायोजन किया गया है। इसके बाद, GBD ढांचे के अनुसार, मॉडल-व्युत्पन्न जोखिम अनुमानों का उपयोग करके उप-समूहों के बीच $PM_{2.5}$ से जुड़ा स्वास्थ्य बोझ आंका गया है। उच्च सामाजिक-जनसांख्यिकीय सूचकांक (SDI) वाले राज्यों में अधिक ($60-90 \mu g/m^3$) असमानता का अनुमान है, जबकि मध्यम और निम्न SDI राज्यों में यह कम है। इसके अलावा, यह पाया गया कि शीर्ष और निम्न संपत्ति-सूचकांक वाले तथा पिछड़ा वर्ग (OBC) के उप-समूहों में $PM_{2.5}$ का संपर्क उच्च ($Z_{score} > \pm 0.02$, $p < 0.1$) है, विशेषकर मध्यम और उच्च SDI राज्यों में। 2015-16 से 2019-21 के बीच, शहरी क्षेत्रों में उप-समूहों के बीच $PM_{2.5}$ संपर्क में असमानता बढ़ी है, जबकि ग्रामीण क्षेत्रों में यह स्थिर रही या घटी है। इसके परिणामस्वरूप, $PM_{2.5}$ और बीमारियों के बीच संबंध विभिन्न उप-जनसंख्याओं में भिन्न होता है और यह पुरुषों (औसत ऑड्स अनुपात 1.049 बनाम 1.039) और OBC (1.078 बनाम 1.044) में महिलाओं और अन्य जातियों की तुलना में अधिक है। $PM_{2.5}$ और मधुमेह के बीच संबंध सबसे गरीब से सबसे अमीर तक बढ़ता है (1.025 से 1.062 तक), जबकि अन्य दो बीमारियों के लिए यह घटता है। इसके अतिरिक्त, यह अनुमान है कि पुरुष, OBC, और वंचित समूह अधिक बीमारियों से

ग्रस्त हैं [2.02-11.79 मिलियन (1.86-13.92)] – विशेष रूप से मधुमेह और हृदय रोग से। भारत की शहरी-केंद्रित वायु प्रदूषण नीति विविध जनसांख्यिकीय समूहों में असमानता को और बढ़ा सकती है। अतः यह सिफारिश की जाती है कि लक्षित नीतियां बनाई जाएँ, जो $PM_{2.5}$ संपर्क को कम करें और असमानताओं को घटाएँ, विशेषकर कमजोर उप-समूहों के लिए। भारत को ऐसी वायु प्रदूषण न्यूनीकरण रणनीतियाँ अपनानी चाहिए जो कमजोर जनसंख्या समूहों को प्राथमिकता दें और अन्य परिवर्तनीय जोखिम कारकों को भी नियंत्रित करें, जिससे पर्यावरण और स्वास्थ्य में समता प्राप्त की जा सके।

$PM_{2.5}$ संपर्क और इसके क्षेत्रीय योगदानों के स्वास्थ्य, वायु गुणवत्ता, और आर्थिक प्रभावों का भविष्य में आकलन करने के लिए, क्षेत्रीय और राज्य-स्तरीय स्रोतों से प्राथमिक और द्वितीयक उत्सर्जनों से उत्पन्न स्वास्थ्य बोझ का 2015 के आधार वर्ष और 2030 के लिए अनुमान लगाया गया है। इसके लिए तीन GAINS-सिमुलेटेड वायु प्रदूषण उत्सर्जन मार्गों [व्यवसाय-यथावत (BAU), उन्नत नियंत्रण प्रौद्योगिकी (ACT), और सतत विकास परिदृश्य (SDS)] को GBD ढांचे में जोड़ा गया है। अनुमान है कि $PM_{2.5}$ -जन्य समय से पूर्व मौतें 2015 में 0.72 मिलियन (95% अनिश्चितता अंतराल: 0.53-0.89) से बढ़कर 2030 में क्रमशः 0.79 (0.57-1.1), 0.76 (0.6-1.1), और 0.63 (0.48-0.81) मिलियन तक पहुँच सकती हैं। केवल 13 भारतीय राज्य SDG-3.4 लक्ष्य को प्राप्त कर पाएंगे यदि वे अपने सबसे नजदीकी स्वच्छ वायु लक्ष्यों ($40 \mu g/m^3$ या उससे कम) को पूरा करें। अन्य राज्यों के लिए लक्ष्य अत्यधिक हैं और SDS मार्ग के मुकाबले अधिक प्रयासों की आवश्यकता होगी। डिकार्बोनाइजेशन परिदृश्य ($2^\circ C$ तापवृद्धि परिदृश्य), जिससे $PM_{2.5}$ की सांद्रता कम हो सकती है और शताब्दी के अंत तक तापमान वृद्धि को $2^\circ C$ से नीचे सीमित किया जा सकता है, उससे लगभग 0.77 ± 0.19 मिलियन समय से पूर्व मौतें और 18.7 ± 4.3 मिलियन बीमारियाँ रोकी जा सकती हैं। इसका कुल वार्षिक आर्थिक लाभ लगभग 18.9 ± 4.4 बिलियन यूरो होगा। घरेलू और ऊर्जा क्षेत्र (बिजली संयंत्र और उद्योग) भविष्य में स्वास्थ्य हानियों में सबसे बड़े योगदानकर्ता होंगे; लेकिन इन क्षेत्रों को

प्राथमिकता देने से सबसे अधिक स्वास्थ्य लाभ भी मिल सकते हैं। हालांकि, यह आवश्यक नहीं है कि जलवायु-नियंत्रण परिदृश्य में स्वास्थ्य प्रभाव बेसलाइन की तुलना में कम हों; क्योंकि बढ़ती संवेदनशील जनसंख्या का आकार $PM_{2.5}$ से संबंधित स्वास्थ्य प्रभावों को बढ़ा सकता है। अधिकांश राज्यों में सामाजिक-जनसांख्यिकीय कारकों (जनसंख्या वृद्धि, वृद्धावस्था, और घटती बुनियादी मृत्यु/रुग्णता दरें) का प्रभाव $PM_{2.5}$ संपर्क स्तर से अधिक होगा। भारत को प्राथमिक $PM_{2.5}$ और उसके अग्रदूत गैसों के उत्सर्जन को रोकने के लिए सबसे कठोर रणनीति अपनानी चाहिए, जिसमें बहुराज्यीय संयुक्त कार्य योजना और स्वच्छ ऊर्जा की ओर त्वरित संक्रमण की आवश्यकता है। केवल $PM_{2.5}$ संपर्क को कम करने वाली नीतियाँ पर्याप्त नहीं हैं, बल्कि उन्हें वर्तमान राष्ट्रीय स्वच्छ वायु कार्यक्रम से आगे बढ़ते हुए अन्य जोखिम कारकों को भी नियंत्रित करना चाहिए, जिससे उल्लेखनीय स्वास्थ्य लाभ प्राप्त किया जा सके।

Contents

Acknowledgement	i
Abstract	iii
Hindi Abstract	vii
Contents	xi
List of Figures	xvi
List of Tables	xxii
Chapter 1	1
1.1 Air pollution	2
1.2 Sectoral contributions of ambient PM _{2.5}	3
1.3 Environmental health pathways	4
1.4 Health impacts of ambient PM _{2.5}	5
1.5 Socio-demographic determinants of health burden	5
1.6 Disparity in ambient PM _{2.5} exposure	7
1.7 Differential health effects of ambient PM _{2.5} exposure	8
1.8 Air quality standards and guidelines	10
1.9 Environmental norms to combat air pollution and social inequality	11
1.10 Definition of the problem	10
1.11 Synthesis of existing evidence and research gaps	14
1.12 Objectives of the Doctoral Thesis	16
1.13 Framework of the thesis	17
Chapter 2	18
2.1 Background	19
2.2 Approach	
2.2.1 National Family Health Survey	21

2.2.1.1 Sampling framework	22
2.2.1.2 Strategy to ensure survey data quality	23
2.2.1.3 Socio-demographic information	23
2.2.2 Ambient PM _{2.5} concentration	25
2.2.2.1 XGBoost model to fill AOD retrieval gap	26
2.2.2.2 Random forest model to predict ambient PM _{2.5} estimate	27
2.2.3 Population-weighted PM _{2.5} exposure for the subgroups	29
2.2.3.1 Assessment of absolute disparity	32
2.2.3.2 Assessment of relative disparity	32
2.2.4 National level disparity in ambient PM _{2.5} exposure across the subgroups	33
2.2.5 Urban-rural heterogeneity in ambient PM _{2.5} exposure	39
2.2.5.1 Variation in ambient PM _{2.5} exposure within the sub-populations	48
2.2.6 Identifying the subgroups burdened by higher ambient air pollution	50
2.2.7 Interplay between demographic and ambient PM _{2.5} distributions	52
2.2.8 Relative disparity across the states	54
2.3 Discussion	59
Chapter 3	64
3.1 Background	65
3.2 Approach	
3.2.1 National Family Health Survey (NFHS)	68
3.2.1.1 Socio-demographic information	68
3.2.1.2 Covariates and model estimate	69
3.2.1.3 Health outcome assessment	71
3.2.2 Ambient PM _{2.5} exposure assessment	72
3.2.3 Socio-demographic characteristics of the sub-populations	73

3.2.3 Multivariate logistic regression model	75
3.2.4 Disparity in ambient PM _{2.5} -diseases association across the sub-populations	78
3.2.5 Feature importance of the covariates	79
3.2.5.1 XGBoost model	79
3.2.5.2 Hyperparameter optimization	82
3.2.6 Non-linearity in exposure-response functions	88
3.2.7 DALYs burden across the sub-populations	91
3.2.8 Disparity in combined effects of PM _{2.5} with other modifiable risk factors across the subgroups	99
3.2.9 Health benefits assessment	102
3.3 Discussion	105
Chapter 4	113
4.1 Background	114
4.2 Approach	
4.2.1 GAINS-model framework and exposure attribution	118
4.2.1.1 Estimation of health burden apportioned to local and regional sources	125
4.2.2 Sub-national level health burden apportionment for the baseline	134
4.2.2.1 Health benefits assessment	141
4.2.2.2 Health benefits due to meeting the NCAP target	142
4.2.3 Progress towards achieving the SDG-3.4 target due to ambient air pollution abatement	145
4.2.3.1 Potential mitigation pathways for India to alleviate ambient PM _{2.5} attributable health burden	146
4.2.3.2 Setting the Baseline Mortality Rate reduction target for 2030	155
4.3 Discussion	158
4.3.1 Assumptions and uncertainty	164
Chapter 5	168

5.1 Background	169
5.2 Approach	
5.2.1 GAINS-model framework and exposure attribution	173
5.2.1.1 Estimation of health burden apportioned to source contributions of ambient PM _{2.5}	180
5.2.1.1.1 (Age-distributed population) POP	181
5.2.1.1.2 Baseline Mortality Rate (BMR)	181
5.2.1.1.3 Population Attributable Fraction (PAF)	195
5.2.2 Health benefit assessment of climate actions	196
5.2.3 Role of socio-demographic factors in driving future health burden	199
5.2.3.1 Effects of socio-demographic determinants on PM _{2.5} -attributable health burden	202
5.2.4 Source contributions of air pollution attributable health burden	206
5.2.4.1 Sectoral contributions to health benefits due to climate actions	213
5.2.5 Assessment of economic impact attributable to health burden	215
5.2.5.1 Ambient PM _{2.5} attributable economic burden	219
5.3.1 Discussion	226
5.3.1 Assumptions and uncertainty	231
5.3.2 Recommendations for new directions	223
Chapter 6	235
6.1 Summary of the Doctoral Thesis	236
6.2 Future research scopes	239
Appendix A: Geographic regions of India	241
Appendix B: Conceptual causal diagrams (Directed Acyclic Graphs, DAGs).	242
Appendix C: Sensitivity assessment of ambient PM_{2.5} related burden.	243

Appendix D: Publications from the Doctoral Thesis	244
References	245
Brief Biodata	271

List of Figures

2.1 Correlation between daily satellite-derived $PM_{2.5}$ estimates with the ground-based observations across India from 2019 to 2021.	28
2.2 Ambient mean $PM_{2.5}$ concentration in the NFHS clusters.	31
2.3 Estimated absolute disparity (AD, in $\mu g/m^3$) in ambient $PM_{2.5}$ concentration across urban and rural regions of the states.	39
2.4.A. The sub-population fraction at the district level across the gender-subgroups in urban and rural regions of NFHS-5 and NFHS-4.	41
2.4.B. The sub-population fraction at the district level across the wealth-subgroup categories in the urban and rural regions of NFHS rounds.	42
2.4.C. The sub-population fraction at the district level across the caste-subgroup categories in the urban and rural regions of NFHS rounds.	43
2.5.A. The estimated standard deviation of population distribution in urban regions of NFHS-5.	44
2.5.B. The estimated standard deviation of population distribution in rural regions of NFHS-5.	45
2.5.C. The estimated standard deviation of population distribution in urban regions of NFHS-4.	46
2.5.D. The estimated standard deviation of population distribution in rural regions of NFHS-4.	47
2.6. Absolute disparity in ambient $PM_{2.5}$ concentration within each population subgroup across the urban and rural regions of the high, middle, and low SDI states.	48
2.7. Estimated relative disparity (denoted by Z_{score}) across the subgroups in the urban and rural regions in high, middle, and low SDI states in NFHS-5; and its changes (in-%) from NFHS-4.	50
2.8. Estimated state-level relative disparity (denoted by Z_{score}) across the subgroups stratified by gender, wealth, caste in the urban and rural regions across the states in NFHS-5.	56
2.9. Estimated Z_{score} across the sub-populations stratified by gender, wealth, and caste subgroups in urban and rural regions across the states in NFHS-4.	57

2.10. Changes (in-%, absolute values of Z_{score}) in relative disparity in ambient $PM_{2.5}$ concentration among the subgroups from NFHS-4 (2015-16) to NFHS-5 (2019-21) for urban (U) and rural (R) regions across the states.	79
3.1. Association between ambient $PM_{2.5}$ exposure and diabetes, HBP, and heart disease across the population subgroups stratified by gender, wealth, and caste.	85
3.2A. Estimated variable importance (for all-population) of the covariates used in the hierarchical regression model.	85
3.2B. Estimated variable importance of the covariates used in the hierarchical regression model across the sub-populations for Diabetes.	86
3.2C. Estimated variable importance of the covariates used in the hierarchical regression model across the sub-populations for High Blood Pressure (HBP).	86
3.2D. Estimated variable importance of the covariates used in the hierarchical regression model across the sub-populations for Heart Disease.	86
3.3. GAM-model derived exposure-response functions for the three chronic diseases (Diabetes; High Blood Pressure; Heart Disease) across the sub-populations stratified by gender, wealth, and caste.	89
Figure 3.4. Estimated DALYs burden (in Millions) across the population subgroups during NFHS-5 stratified by gender, wealth, and caste subgroup categories and its changes (in-%) from NFHS-4.	94
Figure 3.5. Effect of ambient $PM_{2.5}$ due to the moderation of three modifiable risk factors (poor lifestyle-practices, unhealthy diet, and solid-fuel usage in the household) on diabetes, high blood pressure (HBP), and heart disease across the population subgroups.	101
3.6. Disease prevalence (in-%) during NFHS across the population subgroups and the estimated reduced prevalence if India succeeds to meet the clean-air targets in future.	103
3.7. Correlation between the model-derived DALYs burden (aggregated for diabetes, HBP, and heart disease) with the ambient $PM_{2.5}$ attributable DALYs burden (GBD-India) across the states and together for NFHS-4 and NFHS-5.	106
4.1. GAINS-model framework.	122
4.2. Correlation statistics between GAINS-derived and satellite-derived population-weighted annual ambient $PM_{2.5}$ exposure at state levels in the baseline year of 2015.	124
4.3. Percentage change in age-distributed population from 2015 to 2030 for three different age-groups; denoted by three bars for children, adults, and aged.	127

4.4.A-D. Percentage change in baseline mortality rates for six diseases.	129
4.5. Modeling framework of the health burden assessment.	133
4.6. Apportionment of mortality burden attributable to GAINS-simulated regional and sectoral emissions in the baseline.	137
4.7. State-wise DALYs apportionment attributable to GAINS model-simulated regional and sectoral emissions in 2015.	138
4.8. The disease apportionments to the total air pollution related premature deaths in each 23 states for the baseline year of 2015.	139
4.9. Disability adjusted life years (DALYs) burden from the six diseases attributable to GAINS-simulated ambient PM _{2.5} exposure for three SDI states in India for the baseline.	140
4.10. Changes in mortality burden across the states from baseline to the near future (2026 and 2030) under the current NCAP mandate.	142
4.11. Changes in DALYs burden across the states from baseline to the near future (2026 and 2030) under the current NCAP mandate.	144
4.12. The mortality burden scenario in the baseline and achievable (in-%) SDG-3.4 target by 2030 across the states attributable to ambient PM _{2.5} mitigation.	145
4.13. Health burden (premature deaths) apportionment among the regional and sectoral PM _{2.5} -emission in different SDI states under the three GAINS-simulated pathways (BAU, ACT, and SDS) from left to right.	147
4.14. Premature deaths apportioned into regional and sectoral emissions across the three SDI states (aggregated) under the GAINS-simulated contrasting air pollution emission pathways for 2030.	149
4.15. Disability adjusted life years (DALYs) burden from the six diseases attributable to ambient PM _{2.5} exposure for three SDI states in India for the three GAINS-simulated pathways.	153
4.16. Changes in all risk factors attributable mortality burden (per 100,000 population) by temporal changes in ambient air pollution exposure following the three GAINS-simulated emission pathways - business-as-usual, ACT, and SDS with respect to the baseline period of 2015.	155
4.17. Estimated required reduction in baseline mortality rates (with 95% UI, denoted by black whiskers) for IHD, stroke, COPD, and T2-diabetes.	157
4.18. The MR-BRT exposure-risk functions for six diseases (considered in this study) correspondent to the mean PM _{2.5} exposure levels.	159

5.1. Difference in ambient PM _{2.5} concentrations calculated by the full EMEP-CTM, compared to the result using GAINS linear transfer coefficients, for a low emission scenario in 2040.	177
5.2. State-specific population for four age-groups in the baseline period and in mid-century.	183
5.3.A. Baseline DALYs rate (per 100,000 populations) for Chronic Obstructive Pulmonary Disease (COPD) for different age-groups in the baseline period and in mid-century.	184
5.3.B. Baseline mortality rate (per 100,000 populations) for Chronic Obstructive Pulmonary Disease (COPD) for different age-groups in the baseline period and in mid-century.	185
5.3.C. Baseline DALYs rate (per 100,000 populations) for Type-2 Diabetes (T2D) for different age-groups in the baseline period and in mid-century.	186
5.3.D. Baseline mortality rate (per 100,000 populations) for Type-2 Diabetes (T2D) for different age-groups in the baseline period and in mid-century.	187
5.3.E. Baseline DALYs rate (per 100,000 populations) for Ischemic Heart Disease (IHD) for different age-groups in the baseline period and in mid-century.	188
5.3.F. Baseline mortality rate (per 100,000 populations) for Ischemic Heart Disease (IHD) for different age-groups in the baseline period and in mid-century.	189
5.3.G. Baseline DALYs rate (per 100,000 populations) for stroke for different age-groups in the baseline period and in mid-century.	190
5.3.H. Baseline mortality rate (per 100,000 populations) for stroke for different age-groups in the baseline period and in mid-century.	191
5.3.I. Baseline DALYs rates (per 100,000 populations) for Lower Respiratory Infection (LRI) and Pre-term Birth (PTB) for different age-groups in the baseline period and in mid-century.	192
5.3.J. Baseline mortality rates (per 100,000 populations) for Lower Respiratory Infection (LRI) and Pre-term Birth (PTB) for different age-groups in the baseline period and in mid-century.	193
5.4.A. Correlation statistics between the polynomial function (10 th order) estimated baseline mortality rates for the six diseases across the age-groups and the India-GBD estimates over the time period of 1990 to 2019.	194
Figure 5.4.B. Correlation statistics between the polynomial function (10 th order) estimated baseline DALYs rates for the six diseases across the age-groups and the India-GBD estimates over the time period of 1990 to 2019.	194

5.5. Estimated annual air pollution attributable premature deaths under the BAU and 2°C-WS scenario in 2050.	196
5.6. The top panel shows the aggregated DALYs burden for the base year 2015, and under the projected BAU and 2°C-Warming Scenario in mid-century.	199
5.7. The relative contributions of population growth and aging, changes in baseline mortality rate, and changes in PM _{2.5} exposure (BAU and 2°C-WS) on the change in premature deaths under the two air pollution emission pathways.	202
5.8. The relative effects of four socio-demographic factors: population growth and its aging, changes in baseline DALYs rate, and change in PM _{2.5} -exposure on the aggregated DALYs burden were estimated.	203
5.9.A. Disease proportions of six diseases under the BAU pathway for air pollution-related premature deaths and DALYs.	205
5.9.B. Disease proportions of six diseases under the 2°C warming scenario (depicted by SDS) for air pollution-related premature deaths and DALYs.	206
5.10.A. State-wise burden (premature deaths) apportionment from the GAINS-model estimated regional and sectoral emissions in mid-century following the BAU pathway.	208
5.10.B. State-wise burden (DALYs) apportionment from the GAINS model-estimated regional and sectoral emissions in mid-century following the BAU pathway.	209
5.10.C. State-wise burden (premature deaths) apportionment from the GAINS model-estimated regional and sectoral emissions in mid-century following the 2°C warming scenario.	210
5.10.D. State-wise burden (DALYs) apportionment from the GAINS model-estimated regional and sectoral emissions in mid-century following the 2°C warming scenario.	211
5.10.E. The distribution of health burden (premature deaths and DALYs) attributed to regional and sectoral emissions of airborne PM _{2.5} exposure under the BAU and 2°C-WS in 2050 (per year).	212
5.11. Relative contributions to aggregated benefits in premature deaths (BAU - 2°C-WS, in thousands) from regional and sectoral emissions across the 23 GAINS-simulated subregions by 2050.	213
Figure 5.12. The pie-charts denote the contributions from regional and sectoral emissions to the health benefits (in terms of DALYs, in millions) across the 23 subregions.	214
5.13. The sample weighted per-capita income is plotted with the best fitted polynomial function (order=8) for each age-groups between 15 to 70 years.	216

5.14. The economic assessments (per year) for mid-century across the subregions following the BAU and 2°C-WS pathways.	221
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List of Tables

2.1. Ambient PM _{2.5} concentration statistics (mean national estimates across 10 th , 33 rd , 50 th , 67 th , and 90 th percentiles) in the urban and rural regions across both the NFHS rounds.	34
2.2. Assessment of ambient PM _{2.5} exposure across the population subgroups stratified by gender, wealth, and caste subgroups of NFHS-5.	35
2.3. Assessment of ambient PM _{2.5} concentration across the population subgroups stratified by gender, wealth, and caste subgroups of NFHS-4.	37
2.4.A. Estimated correlation coefficients between the sub-population fractions and ambient PM _{2.5} concentration across the districts of high, middle, and low SDI states.	52
2.4.B. Estimated correlation coefficients between the sub-population fractions and ambient PM _{2.5} concentration across the districts of different subregions of India.	53
3.1. Socio-demographic characteristics of demographic sub-populations.	73
3.2. Estimated regression coefficients (with 95% uncertainty intervals) of the interaction terms among ambient PM _{2.5} and the socio-demographic factors (gender, wealth, caste, and resident type) across the population subgroups from the pooled database of NFHS-4 and NFHS-5.	76
3.3. Apportioned at-risk subgroup fractions and the baseline DALYs rates (per 100,000 population) for diabetes, HBP, and heart disease in NFHS-5 and its changes from NFHS-4.	92
3.4. Relative contribution (in-%) from the three socio-demographic determinants on ambient PM _{2.5} -attributable DALYs burden disparity across the sub-populations in NFHS rounds.	98
3.5.A. Apportioned at-risk subgroup fractions (poor lifestyle-practices) and the baseline DALYs rates (per 100,000 population) for the three diseases in NFHS-5 and its changes from NFHS-4.	108
3.5.B. Apportioned at-risk subgroup fractions (unhealthy dietary intakes) and the baseline DALYs rates (per 100,000 population) for the three diseases in NFHS-5 and its changes from NFHS-4.	109
3.5.C. Apportioned at-risk subgroup fractions (using solid-fuel for domestic practices) and the baseline DALYs rates (per 100,000 population) for the three diseases in NFHS-5 and its changes from NFHS-4.	109
3.6. Variations in socio-demographic determinants (ambient PM _{2.5} exposure, subgroup fraction, prevalence of Diabetes, HBP, and Heart Disease) across the sub-populations in urban and rural regions of India.	111
4.1. Description of three GAINS-model pathways and emission scenarios.	119

4.2. Projected baseline mortality rates (per 100,000 population) for all the diseases for 2030.	130
4.3. The post-NCAP clean-air targets and the projected ambient PM _{2.5} exposure (in µg/m ³) for the BAU, ACT, and SDS pathways across the subregions of India in 2030.	135
4.4. Estimated mortality burden (per 100,000 population) attributable to ambient air pollution exposure.	161
5.1. Description of the two GAINS model pathways and emission scenarios.	179
5.2. Estimated mean PM _{2.5} -exposure (in µg/m ³) simulated from GAINS-model for the baseline (2015) and for mid-century following the BAU and 2°C warming scenario across the high, middle, and low SDI states.	198
5.3. The economic assessments (losses and benefits) for various combinations of α (a reduction of 5-20%) and λ (0.25-0.35) across the high, middle, and low SDI states.	222
5.4. Sensitivity analysis of economic losses attributable to different ranges of working age groups among the populaces across the high, middle, and low SDI states.	223
5.5. The per-capita benefits in net productivity (1 st column) and its percentage share to total projected GDP (3 rd column) in mid-century across the subregions of India, stratified by high, middle, and low SDI classes.	223
5.6. The raw statistics for the economic assessments (in Billion Euros) for the baseline period and mid-century.	224
5.7. Estimated economic losses (in Billions) attributable to air pollution related premature deaths and YLDs in the baseline period across the subregions of India.	225