HEALTH BENEFITS OF EXPOSURE TO RESIDENTIAL GREENSPACE IN INDIAN ADULTS

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AND

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Health benefits of exposure to residential greenspace in Indian adults

by

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This thesis is lovingly dedicated to

my mother, **Smt. Bhanu Devi**, and my father, **Shri Ganesh Saw**,

whose boundless love, selfless sacrifices, heartfelt prayers, and unwavering faith in me

have been the foundation of all my achievements.

Your support has shaped who I am today.

Supervisor Certification

This is to certify that the thesis entitled "**Health benefits of exposure to residential greenspace in Indian adults**" being submitted by **Mr. Gautam Kumar Saw** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. **Mr. Gautam Kumar Saw** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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Gautam Kumar Saw

Abstract

The relationship between greenspaces and health outcomes has been examined in numerous studies, primarily focusing on mediation through increased physical activity, enhanced social interactions, and reduced psychological stress. However, the interaction between greenspaces and air pollution has seldom been examined. This is particularly important in India, where such interactions are complicated by heterogeneous exposures and a high prevalence of non-communicable diseases (NCD) related risk factors. Although some studies provide inconclusive evidence, there is growing interest in the potential role of residential greenspaces as public health assets, promoting physical and social well-being while potentially mitigating environmental exposures such as air pollution. Still, the combined effects of greenspace and air pollution on various health outcomes remain poorly understood, especially in low- and middle-income countries like India, where health and environmental exposure data are often limited or fragmented. This study addresses this gap by examining both the direct association between residential greenspace and three NCD-related health outcomes: anaemia among women of reproductive age, low birth weight (LBW) in newborns, and hypertension in adults; as well as the potential modifying role of ambient air pollution ($PM_{2.5}$) on these associations.

To conduct this study, we used nationally representative data from India's fourth and fifth rounds of the National Family Health Surveys (NFHS-4 and NFHS-5), which include detailed information on health and socioeconomic indicators. We defined anaemia and low birth weight based on the World Health Organization (WHO) guidelines. Anaemia was classified as haemoglobin level of $\leq$ 12 g/dl in non-pregnant women and $\leq$ 11 g/dl in pregnant women. Low birth weight (LBW) was defined as a birth weight of $\leq$ 2500 grams. Hypertension was defined according to the 2017 American Heart Association (AHA) guidelines as an average systolic blood pressure $\geq$ 130 mm Hg or diastolic blood pressure $\geq$ 80 mm Hg. For environmental exposure, we used the Enhanced Vegetation Index (EVI), a satellite-derived measure of vegetation greenness obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. EVI values range from -1 to +1, with higher values indicating greater vegetation density. The spatial resolution of EVI data ranges from 250 meters for monthly composites to 1 kilometre for annual aggregates. For ambient air pollution exposure, we used monthly and annual average $PM_{2.5}$ data at a 1 × 1 km resolution. These surface-level $PM_{2.5}$ estimates were generated using MODIS-based Aerosol Optical Depth (AOD), calibrated through a dynamic scaling factor obtained from Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis data. We applied multivariable logistic regression models to examine associations between environmental exposures and each health outcome. Models were adjusted for relevant covariates available in NFHS, including age, education, household wealth index, urban/rural residence, tobacco and alcohol use, dietary intake (fruit and leafy vegetable

consumption), type of cooking fuel, and geographic region. Interaction terms were included to assess potential effect modification by $PM_{2.5}$, and sensitivity analyses were conducted to test the robustness of the findings.

This study included 1,368,660 women of reproductive age (WRA) for the anaemia analysis, of whom 53.8% were classified as anaemic. Among 38,358 participants with available birth weight data, 13,677 (35.6%) had LBW infants. For the hypertension analysis, data were available for 708,226 participants, of whom 45.4% were classified as hypertensive. We observed a modest association between residential greenspace (EVI) and anaemia, while the associations with low birth weight (LBW) and hypertension were marginal or weak, with limited statistical significance. In fully adjusted models, a one standard deviation increase in EVI was associated with a 0.8% reduction in the odds of anaemia (OR = 0.992; 95% CI: 0.986–0.998), with stronger effects observed in low air pollution areas—9% reduction below the second quartile and 18% in the lowest quartile of $PM_{2.5}$. For LBW, EVI showed a marginally and non-significant protective effect overall (OR = 0.99; 95% CI: 0.95–1.03), with the strongest effect in areas with low $PM_{2.5}$ levels (OR = 0.92; 95% CI: 0.85–1.00), attenuated in medium-high exposure areas (OR = 0.97; 95% CI: 0.90–1.06), and reversed in high exposure areas (OR = 1.23; 95% CI: 1.13–1.34), indicating increased odds of LBW. Similarly, higher EVI was associated with a reduced risk of hypertension (OR = 0.99; 95% CI: 0.97–1.00), with sensitivity analyses indicating a 4% and 2% reduction in the odds of elevated blood pressure and stage 1 hypertension, respectively; however, a reversed association was noted for stage 2 hypertension.

In conclusion, this study provides evidence that higher residential greenspace (measured by EVI) is modestly protective against anaemia, with weaker and less consistent associations observed for low birth weight (LBW) and hypertension, particularly in areas with lower levels of air pollution. These findings underscore the dual role of greenspace in enhancing population health and mitigating environmental risks. They highlight the need for integrated urban and peri-urban planning approaches that combine greenspace development with air quality management to promote environmental justice, reduce health disparities, and foster sustainable urban development in India. Future research should adopt longitudinal designs and investigate the biological and environmental pathways underlying these associations to inform effective greenspace-based health interventions.

संक्षेप (**Abstract in Hindi)**

हरित क्षेत्रों और स्वास्थ्य परिणामों के बीच संबंध का अध्ययन अनेक शोधों में किया गया है, जिनमें मुख्य ध्यान शारीरिक गतिविधि में वृद्धि, सामाजिक जुड़ाव में सुधार तथा मनोवैज्ञानिक तनाव में कमी जैसे मध्यस्थ कारकों पर रहा है। हालांकि, हरित क्षेत्रों और वायु प्रदूषण के बीच पारस्परिक प्रभावों का परीक्षण बहुत कम हुआ है। यह विशेष रूप से भारत में महत्वपूर्ण है, जहां पर्यावरणीय जोखिम अत्यधिक विविध हैं और गैर-संचारी रोग (NCDs) व्यापक रूप से प्रचलित हैं। यद्यपि कुछ अध्ययनों में निर्णायक प्रमाण नहीं मिलते, फिर भी आवासीय हरित क्षेत्रों की संभावित सार्वजनिक स्वास्थ्य भूमिका, शारीरिक एवं सामाजिक कल्याण को बढ़ावा देना और वायु प्रदूषण जैसे जोखिमों को कम करना, के प्रति रुचि बढ़ रही है। फिर भी, हरित क्षेत्रों और वायु प्रदूषण के संयुक्त प्रभाव, विशेषकर निम्न एवं मध्यम आय वाले देशों में, अभी पर्याप्त रूप से समझे नहीं गए हैं। यह अध्ययन इस कमी को दूर करने के लिए आवासीय हरित क्षेत्रों और तीन स्वास्थ्य परिणामों—प्रजनन आयु की महिलाओं में एनीमिया, नवजात शिशुओं में कम जन्म भार (LBW) तथा वयस्कों में उच्च रक्तचाप—के बीच प्रत्यक्ष संबंध तथा इन संबंधों पर परिवेशी वायु प्रदूषण ($PM_{2.5}$) के संभावित संशोधक प्रभाव की जांच करता है।

इस अध्ययन में भारत के राष्ट्रीय परिवार स्वास्थ्य सर्वेक्षण (NFHS-4 और NFHS-5) के राष्ट्रीय-स्तर पर प्रतिनिधि आंकड़ों का उपयोग किया गया, जिनमें स्वास्थ्य तथा सामाजिक-आर्थिक संकेतकों की विस्तृत जानकारी उपलब्ध है। एनीमिया और कम जन्म भार की परिभाषाएँ विश्व स्वास्थ्य संगठन (WHO) के दिशानिर्देशों पर आधारित थीं। उच्च रक्तचाप को 2017 के अमेरिकन हार्ट एसोसिएशन (AHA) दिशानिर्देशों के अनुसार परिभाषित किया गया। पर्यावरणीय जोखिम के लिए हमने मॉडरेटकृत रिज़ॉल्यूशन इमेजिंग स्पेक्ट्रोरेडियोमीटर (MODIS) से प्राप्त उपग्रह-आधारित उन्नत वनस्पति सूचकांक (EVI) का उपयोग किया, जिसका मान –1 से +1 तक होता है। वायु प्रदूषण जोखिम के लिए 1 × 1 किमी रिज़ॉल्यूशन वाले मासिक एवं वार्षिक $PM_{2.5}$ अनुमानों का उपयोग किया गया, जिन्हें MODIS-आधारित ऐरोसोल ऑप्टिकल डेप्थ (AOD) तथा MERRA-2 रीएनालिसिस पर आधारित डायनेमिक स्केलिंग फैक्टर के माध्यम से कैलिब्रेट किया गया। इन जोखिमों और स्वास्थ्य परिणामों के बीच संबंधों का मूल्यांकन बहुविकल्पीय लॉजिस्टिक प्रतिगमन मॉडलों द्वारा किया गया, जिनमें आयु, शिक्षा, संपत्ति सूचकांक, शहरी/ग्रामीण निवास, तंबाकू एवं शराब सेवन, आहार, खाना पकाने का ईंधन तथा भौगोलिक क्षेत्र जैसे सहचर शामिल थे।

एनीमिया विश्लेषण में 13,68,660 प्रजनन आयु की महिलाओं को शामिल किया गया, जिनमें से 53.8% एनीमिक थीं। जन्म भार संबंधी आंकड़ों वाले 38,358 प्रतिभागियों में से 35.6% शिशु LBW थे। उच्च रक्तचाप विश्लेषण में 7,08,226 वयस्क शामिल थे, जिनमें से 45.4% को उच्च रक्तचाप था। हमने पाया कि आवासीय हरित क्षेत्र (EVI) और एनीमिया

के बीच एक मामूली सुरक्षात्मक संबंध है, जबकि LBW और उच्च रक्तचाप के साथ संबंध अपेक्षाकृत कमजोर और कई मामलों में गैर-महत्वपूर्ण थे। पूर्णतः समायोजित मॉडलों में EVI में एक मानक विचलन की वृद्धि एनीमिया की संभावना में 0.8% कमी से जुड़ी थी (OR = 0.992; 95% CI: 0.986–0.998)। यह प्रभाव कम वायु प्रदूषण वाले क्षेत्रों में अधिक स्पष्ट था—$PM_{2.5}$ के दूसरे चतुर्थक से नीचे 9% तथा सबसे निचले चतुर्थक में 18% कमी। LBW के लिए EVI का समग्र संबंध मामूली और गैर-महत्वपूर्ण था (OR = 0.99; 95% CI: 0.95–1.03), परंतु कम $PM_{2.5}$ स्तर वाले क्षेत्रों में सुरक्षात्मक प्रभाव (OR = 0.92; 95% CI: 0.85–1.00) देखा गया, जो मध्यम क्षेत्रों में घट गया और उच्च प्रदूषण वाले क्षेत्रों में उलट गया (OR = 1.23; 95% CI: 1.13–1.34)। इसी प्रकार, उच्च EVI उच्च रक्तचाप के अपेक्षाकृत कम जोखिम से जुड़ा था (OR = 0.99; 95% CI: 0.97–1.00), हालांकि चरण-2 उच्च रक्तचाप के लिए संबंध उलटा पाया गया।

निष्कर्षतः, यह अध्ययन दर्शाता है कि आवासीय हरित क्षेत्र (EVI) एनीमिया के विरुद्ध सीमित किंतु महत्वपूर्ण सुरक्षा प्रदान कर सकते हैं, जबकि LBW और उच्च रक्तचाप के साथ संबंध अपेक्षाकृत कमजोर तथा प्रदूषण स्तर के अनुसार असंगत हैं। यह अध्ययन जनस्वास्थ्य सुदृढ़ीकरण और पर्यावरणीय जोखिमों में कमी के लिए हरित क्षेत्रों की दोहरी भूमिका को उजागर करता है तथा इस बात पर बल देता है कि भारत में सतत शहरी विकास, पर्यावरणीय न्याय और स्वास्थ्य असमानता में कमी के लिए हरित क्षेत्र विकास को वायु गुणवत्ता प्रबंधन के साथ एकीकृत करना आवश्यक है। भविष्य के शोधों में अनुदैर्ध्य अध्ययन तथा जैविक एवं पर्यावरणीय मार्गों की गहन जांच शामिल होनी चाहिए, जिससे हरित-क्षेत्र-आधारित प्रभावी स्वास्थ्य हस्तक्षेपों की दिशा निर्धारित की जा सके।

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

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Publications included in this thesis

1) Saw, G., Van Buskirk, J., Dey, S., Singh, N., & Knibbs, L. D. (2025). Association between residential greenspace and anaemia prevalence among Indian women of reproductive age. *Environmental Research*, 121985.

2) Saw, G. K., Van Buskirk, J., Dey, S., & Knibbs, L. D. (2025). Higher in-utero exposure to greenspace can reduce the prevalence of low birth weight in India. *Environmental Research Letters*.

Unpublished manuscripts included in this thesis

Association Between Residential Greenspace Exposure and Hypertension Among Indian Adults.

Conference abstracts:

Saw, G., Dey, S., and Knibbs, L. (2022, December). Association between Residential Greenness and Heart Disease Risk in Indian Women. In AGU Fall Meeting Abstracts (Vol. 2022, pp. GH52A-01).

Saw, G., Dey, S., and Knibbs, L. (2023, December). Benefits of residential green spaces in mitigating diabetes risk in Indian adults. The University of Queensland SPH, Poche and CHSR 2023 Higher Degree Research Conference.

Statement of Contribution

1) Saw, G., Van Buskirk, J., Dey, S., Singh, N., & Knibbs, L. D. (2025). Association between residential greenspace and anaemia prevalence among Indian women of reproductive age. *Environmental Research*, 121985. (presented in Chapter 3)

CRediT authorship contribution statement

Gautam Saw: Conceptualisation, Methodology, Formal analysis, Data curation, Statistical analysis, Interpretation of data, Writing – original draft. **Joe Van Buskirk**: Conceptualisation, Methodology, Formal analysis, Statistical analysis, Interpretation of data, Writing – review and editing. **Sagnik Dey**: Conceptualisation, Methodology, Funding acquisition, Formal analysis, Writing – review and editing, Supervision. **Neha Singh**: NO_2 data curation, Writing – review and editing. **Luke D. Knibbs**: Conceptualisation, Methodology, Funding acquisition, Formal analysis, Writing – review and editing, Supervision.

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Contributions by others to the thesis

My supervisors, Professor Sagnik Dey and Professor Luke D Knibbs, provided substantial input into the conception and design of the research questions, as well as the analysis and interpretation of results. The contributions of co-authors for the published and under review paper are detailed under the 'Statement of Contribution' section.

All chapters

Editorial suggestions were provided by Professor Sagnik Dey (IITD Supervisor), Associate Professor Luke Knibbs (UQ supervisor), Professor Somnath Baidya Roy (ASMC chair), Professor Gazala Habib (ASMC IITD Expert), and Professor Paul Jagals (ASMC UQ expert).

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

This project primarily utilises satellite and atmospheric reanalysis data to assess exposure to greenspace and air pollutants, calculate pixel-wise particulate matter ($PM_{2.5}$) dry deposition on vegetation, and evaluate the potential health benefits of residential greenspace. These datasets provide high-resolution spatial and temporal information on greenspace, atmospheric conditions, and $PM_{2.5}$ levels, enabling a detailed analysis. It examines the health impacts of residential greenspace and air pollution exposure using data from India's Demographic and Health Survey (DHS). The DHS is a publicly available dataset, accessible upon formal request. All DHS surveys are approved by the ORC Macro Institutional Review Board and relevant ethical review boards in each participating country. While the dataset excludes any information that could identify specific clusters, households, or individuals, it provides sufficient details for population-level analysis. For this research, I obtained official permission from the ICF-DHS program to access and use the DHS data.

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Keywords

Greenspace, air pollution, particulate matter, anaemia, haemoglobin levels, low birth weight, dry deposition, National Family Health Survey, socio-economic exposure, Enhanced Vegetation Index

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Fields of research classification

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FoR code: 3701, Atmospheric Sciences, 30%

FoR code: 3704, Geoinformatics, 10%

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NDVI	Normalised Difference Vegetation Index
EVI	Enhanced Vegetation Index
OR	Odds Ratio
CI	Confidence Interval
$PM_{2.5}$	Particulate matter with an aerodynamic diameter $\leq$ 2.5 μm
SD	Standard Deviation
MODIS	Moderate Resolution Imaging Spectroradiometer
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Atmospheric Reanalysis 5th Generation
NO_2	Nitrogen dioxide
WHO	World Health Organisation
GIS	Geographic Information System
DHS	Demographic Health Survey
NFHS	National Family Health Survey
LBW	Low Birth Weight
LMICs	Low and Middle Income Countries
WRA	Women of Reproductive Age
NCAP	National Clean Air Programme
CVD	Cardiovascular Disease
NASA	National Aeronautics and Space Administration
CPCB	Central Pollution Control Board
Hb	Haemoglobin
NCD	Non-Communicable Disease
SES	Socioeconomic Status