

ENVIRONMENTAL HEAT STRESS VULNERABILITY IN INDIA

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**CENTRE FOR ATMOSPHERIC SCIENCES
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by

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माँ, पिताजी
एवं
मेरे गुरुजनों को
समर्पित

**Dedicated to
My Parents
and
Teachers**

Certificate

This is to certify that the thesis entitled, “**Environmental Heat Stress Vulnerability in India,**” submitted by Mr. Rohit Kumar Choudhary for the award of the degree of Doctor of Philosophy, is a record of the original bonafide research work he carried out. He has worked under our 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.

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Date:

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Abstract

India, with its diverse geography and climate, experiences significant temperature variations. The National Crime Records Bureau (NCRB) reports that heat is a leading cause of mortality due to natural causes, contributing to 15%-18% of annual deaths, second only to lightning. One-third of these deaths occur in cities. Currently, 35% of the population lives in urban areas, which is expected to exceed 50% by 2050 due to rapid urbanization. Global temperatures have risen by 0.85°C since 1880, with further increases anticipated, particularly affecting human health in developing countries' cities. Heat waves pose higher stress risks, especially for vulnerable populations lacking adaptation resources.

Studies on heat in India primarily focus on heat waves, but other factors like humidity, wind, solar radiation, and livelihood also affect human physiology. Heat stress occurs when the body cannot dissipate heat, leading to heat strain. While studies highlight rising heat wave frequencies, limited research has examined heat-stress vulnerability in specific cities and workplaces, often considering only temperature and humidity. However, wind and solar radiation are crucial and should not be overlooked.

India's diverse climates and rising temperatures, coupled with more frequent heat waves, pose environmental challenges. Heat stress affects ecosystems and human health, impacting agriculture, crop yields, and livestock. Vulnerable populations, such as the elderly and those with pre-existing health conditions, are particularly at risk from prolonged high temperatures. Recognizing heat-related incidents as a leading cause of mortality underscores the urgent need for comprehensive public health strategies. Existing heat stress indices, developed in temperate

zones, are inadequate for India's diverse climates. There is a need for an India-specific index to assess heat-stress conditions accurately. Additionally, there is a lack of comprehensive assessments of heat-stress burden and vulnerability at the regional level, essential for effective policymaking.

This study used ERA-5 atmospheric reanalysis data from 1979 to 2020 to propose an India-specific heat index (IHI) and comfort thresholds, incorporating air temperature, relative humidity, wind speed, and solar radiation. The IHI and threshold values were applied to a climatological study of heat stress, assessing the burden and vulnerability across India at district and city levels. These thresholds were tested using a semi-parametric quasi-Poisson generalized additive regression model on mortality data from Delhi, Varanasi, and Chennai, representing semi-arid, humid subtropical, and tropical wet and dry climates, respectively. These zones cover over 75% of India's area and are home to about 88% of its population. The study estimated the relative risk of mortality due to heat stress on both heatwave and non-heatwave days.

Additionally, the study examined heat stress in 2010 and projected conditions for 2030 under different climate change scenarios (RCP 4.5 and RCP 8.5), accounting for aerosol direct radiative feedback. Another chapter focuses on urbanization's impact on heat stress, examining over a hundred cities. Urbanization was assessed using land use and land cover (LULC) data from the European Space Agency Climate Change Initiative (ESA CCI), land surface temperature (LST) data from MODIS Aqua, and the IHI for heat stress conditions. Global urban population data from LandScan Global were used to analyze population changes.

The study found increasing vulnerability to heat stress across India, with humid subtropical, semi-arid, and tropical wet and dry regions most affected. Districts are becoming

more vulnerable, with extreme class exposures increasing almost threefold in the last four decades. Heat stress has risen by 2 to 2.4°C in India under climate change scenarios over the last 40 years. With pollution mitigation, heat stress is predicted to increase. As temperatures and heat stress rise, the diurnal temperature range (DTR) decreases, reducing heat dissipation and leading to more health issues. Mortality risks increase by 6%-8% with each unit rise in extreme comfort classes. Aerosols modulate temperature and heat stress, suggesting that pollution mitigation efforts might inadvertently intensify future heat stress, while higher aerosol concentrations could have a cooling effect.

This study aims to assist administrators in mitigating heat stress impacts, particularly in rapidly growing urban areas. Additionally, it projects future heat stress under anticipated climate change scenarios, providing insights for long-term planning and adaptation strategies.

सारांश

भारत, अपने विविध भौगोलिक स्थिति और जलवायु के साथ, महत्वपूर्ण तापमान भिन्नताओं का अनुभव करता है। नेशनल क्राइम रिकॉर्ड ब्यूरो, (NCRB) की वार्षिक रिपोर्टों से यह पता चलता है कि गर्मी प्राकृतिक कारणों से होने वाली मृत्यु का एक प्रमुख कारण है, जो की वार्षिक 15% -18% मौतें केवल गर्मी के अत्यधिक प्रकोप के कारण होती हैं। यह संख्या, बिजली गिरने से होने वाली मृत्यु संख्या के बाद दूसरे स्थान पर है। गर्मी के कारण होने वाली कुल मौतों की संख्या में से एक तिहाई मौतें केवल शहरों में होती हैं। वर्तमान में, भारत की कुल आबादी का 35% हिस्सा शहरी क्षेत्रों में रहता है, जो तेजी से बढ़ती शहरीकरण के कारण 2050 तक 50% से अधिक होने की उम्मीद है। 1880 के बाद से वैश्विक तापमान में 0.85 °C की वृद्धि हुई है, तथा आगे भी वृद्धि की संभावना है। इन कारणों से विशेष रूप से विकासशील देशों के शहरों में मानव स्वास्थ्य अधिक प्रभावित हो रहा है। गर्मी की लहरें अत्यधिक तनाव और जोखिम पैदा करती हैं, विशेष रूप से उन जनसंख्या को जो गर्मी से निपटने के लिए आवश्यक अनुकूल संसाधनों की कमी से जूझ रहे हैं।

भारत में गर्मी पर अध्ययन मुख्य रूप से गर्मी की लहरों (लू) पर केंद्रित है, लेकिन आर्द्रता, हवा, सौर विकिरण, साथ ही आजीविका तथा वेशभूषा आदि जैसे अन्य कारक भी मानव शरीर विज्ञान को प्रभावित करते हैं। जब शरीर अपने अनावश्यक गर्मी को, प्राकृतिक तरीकों से निष्कासित नहीं कर पाता, तब वह शरीर पर नकारात्मक प्रभाव डालता है। ऐसी पर्यावरणीय स्थिति के कारण से गर्मी का तनाव या फिर गर्मी-तनाव (हिट स्ट्रेस) होता है। जबकि ज्यादातर अध्ययन गर्मी की लहरों की बढ़ती आवृत्तियों पर प्रकाश डालती हैं, कुछ सीमित शोधों ने कुछ विशेष शहरों और कार्यस्थलों में होने वाली गर्मी-तनाव की संवेदनशीलता की भी जांच की है। परन्तु वह एक छोटे स्थान या कार्यक्षेत्र पर ही किया गया है। सामान्यतः, केवल तापमान और आर्द्रता पर विचार किया जाता है, जबकि हवा और सौर विकिरण भी महत्वपूर्ण हैं, और इन्हें नज़रअंदाज़ नहीं किया जाना चाहिए।

भारत की विविध जलवायु और बढ़ते तापमान के साथ-साथ अधिक बार होने वाली गर्मी की लहरों के कारण पर्यावरणीय चुनौतियाँ पैदा करती हैं। हिट-स्ट्रेस पारिस्थितिक तंत्र और मानव स्वास्थ्य को प्रभावित करता है, जिससे कृषि, फसल की पैदावार और पशुधन भी प्रभावित होता है। शारीरिक रूप से कमजोर वर्ग, विशेष रूप से, वृद्ध और पहले से स्वास्थ्य समस्याओं से पीड़ित लोग, उच्च तापमान से अधिक जोखिम में होते हैं। गर्मी से संबंधित घटनाओं को मृत्यु दर के प्रमुख कारण के रूप में पहचानना, व्यापक सार्वजनिक स्वास्थ्य रणनीतियों की तत्काल आवश्यकता को रेखांकित करता है। समशीतोष्ण क्षेत्रों में विकसित मौजूदा ताप तनाव सूचकांक (हिट-स्ट्रेस इंडेक्स), भारत की विविध जलवायु क्षेत्र के लिए अपर्याप्त प्रतीत होता है। इस कारण, हिट-स्ट्रेस की स्थिति का सटीक आकलन करने के लिए एक भारत-विशिष्ट सूचकांक की आवश्यकता है। इसके अतिरिक्त, भिन्न जलवायु वाले क्षेत्रीय स्तर पर हिट-स्ट्रेस के बोझ और संवेदनशीलता के व्यापक आकलन का भी अभाव है, जो की एक प्रभावी नीति निर्धारण के लिए अति आवश्यक है।

इस अध्ययन में हवा के तापमान (temperature), सापेक्ष आर्द्रता (relative humidity), हवा की गति (wind) और सौर विकिरण (solar radiation) को शामिल करते हुए भारत-विशिष्ट ताप सूचकांक, इंडिया हीट इंडेक्स (IHI) और मनुष्य शरीर पर तापमान के विभिन्न स्तर पर प्रभावों को आकलन करने हेतु पांच कम्फर्ट क्लास थ्रेसहोल्ड प्रस्तावित किया गया है। इस अध्ययन के लिए 1979 से 2020 तक की, पांचवीं पीढ़ी की यूरोपियन सेंटर फॉर मीडियम रेंज वेदर फोरकास्ट के वायुमंडलीय पुनर्विश्लेषण डेटा (ECMWF Re-Analysis, ERA5) का उपयोग किया गया है। IHI और थ्रेशोल्ड मानों को पूरे भारत में जिला और विभिन्न स्मार्ट शहरों में बढ़ते शहरीकरण के अंतर्गत गर्मी से होने वाले तनाव के बोझ का आकलन करने हेतु इस अध्ययन को किया गया है, साथ ही हिट-स्ट्रेस पर जलवायु परिवर्तन संबंधी अध्ययन के लिए भी इनका प्रयोग किया गया है। यही गर्मी सूचकांक तथा कम्फर्ट क्लास थ्रेशोल्ड का परीक्षण दिल्ली, वाराणसी और चेन्नई के मृत्यु संख्या पर, सेमी पैरामीट्रिक कुअसी-पॉइसन जेनेरलाइज़्ड एडिटिव रिग्रेशन मॉडल का उपयोग करके किया गया है, जो क्रमशः अर्ध-शुष्क, आर्द्र उपोष्णकटिबंधीय और उष्णकटिबंधीय गीले और शुष्क जलवायु का प्रतिनिधित्व करते हैं। यह तीन जलवायु क्षेत्र भारत का लगभग 75% से अधिक भौगोलिक क्षेत्र में फैले हुए हैं और भारत की लगभग

88% आबादी इन्हीं क्षेत्रों में रहती हैं। अध्ययन में लू और बिना लू वाले दिनों में गर्मी के तनाव के कारण मृत्यु के सापेक्ष जोखिम (रिलेटिव रिस्क) का अनुमान लगाया गया है।

इसके अतिरिक्त, इस अध्ययन में साल 2010 तथा 2030 में वायु प्रदूषण, विशेष कर एयरोसोल का प्रभाव आने वाले दिनों के जलवायु पर किस प्रकार होगा तथा, हिट-स्ट्रेस पर इसका क्या प्रभाव पड़ेगा, इसका अध्ययन किया गया है। हिट-स्ट्रेस की जांच की गयी है और एयरोसोल प्रत्यक्ष विकिरण प्रतिक्रिया को समझते हुए, विभिन्न जलवायु परिवर्तन परिदृश्यों (RCP 4.5 और RCP 8.5) के तहत 2030 के लिए अनुमानित स्थितियों का भी आकलन किया गया है।

एक अध्याय जिसमें की, हिट-स्ट्रेस पर बढ़ते शहरीकरण के प्रभाव को देखा गया है, जिसमें सौ से अधिक शहरों की जांच की गई है। शहरीकरण के बढ़ते स्तर का मूल्यांकन, यूरोपीय स्पेस एजेंसी क्लाइमेट चेंज इनिशिएटिव (ESA CCI) से लैंड युज लैंड कवर (LULC) डेटा, लैंड सरफेस टेम्परेचर (LST) डेटा और गर्मी तनाव स्थितियों के लिए IHI का उपयोग करके किया गया है। जनसंख्या परिवर्तन का विश्लेषण करने के लिए लैंडस्कैन ग्लोबल के वैश्विक शहरी जनसंख्या डेटा का उपयोग किया गया।

अध्ययन में पाया गया कि पूरे भारत में गर्मी के तनाव के प्रति संवेदनशीलता बढ़ रही है, जिसमें आर्द्र उपोष्णकटिबंधीय, अर्ध-शुष्क और उष्णकटिबंधीय गीले और शुष्क क्षेत्र सबसे अधिक प्रभावित हैं। जिले अधिक असुरक्षित होते जा रहे हैं। पिछले चार दशकों में अत्यधिक जोखिम वाले गर्मी के प्रभाव, कम्फर्ट क्लास के सबसे अधिक जोखिम वाले स्तर (वैरी हॉट और स्वेल्टरिंग) से ग्रसित जिलों की संख्या तीन गुना तक बढ़ गयी है। पिछले 40 वर्षों में जलवायु परिवर्तन परिदृश्यों के तहत भारत में गर्मी का तनाव 2°C से 2.4 °C तक बढ़ गया है। प्रदूषण कम होने से गर्मी का तनाव अधिक बढ़ने का अनुमान है। जैसे-जैसे तापमान और गर्मी का तनाव बढ़ता है, दिन रात के तापमान का अंतर, (डाइयुर्नल टेम्परेचर रेंज, DTR), कम हो जाती है, जिस कारण शरीर से गर्मी के प्राकृतिक रूप से घटने की क्षमता कम हो जाती है, और अधिक स्वास्थ्य समस्याएं पैदा होती हैं। IHI के पांच स्तर के मानक (कम्फर्ट क्लास थ्रेसहोल्ड्स) बनाये गए हैं, जिसमें अत्यधिक प्रभावी स्वेल्टरिंग क्लास में प्रति इकाई की वृद्धि के साथ मृत्यु दर का जोखिम 6%-8% बढ़ जाता है। एयरोसोल तापमान और गर्मी के तनाव को प्रभावित करते

हैं, एयरोसोल की कमी के कारण पर्यावरणीय तापमान अधिक बढ़ सकता है, जिससे पता चलता है कि प्रदूषण शमन के प्रयास अनजाने में भविष्य में गर्मी के तनाव को बढ़ा सकते हैं, जबकि उच्च एयरोसोल का शीतलन प्रभाव हो सकता है ।

इस अध्ययन का उद्देश्य विशेष रूप से तेजी से बढ़ते शहरी क्षेत्रों में हिट-स्ट्रेस के प्रभावों को कम करने में प्रशासकों की सहायता करना है। इसके अतिरिक्त, यह प्रत्याशित जलवायु परिवर्तन परिदृश्यों के तहत भविष्य में हिट-स्ट्रेस को दर्शाता है, तथा दीर्घकालिक योजना और अनुकूलन रणनीतियों के लिए अंतर्दृष्टि प्रदान करता है ।

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List of Abbreviations

#	Abbreviation	Expansion
1	AR6	The Sixth Assessment Report (of IPCC)
2	AT	Apparent Temperature
3	Avg	Average
4	BC	Black Carbon
5	Climate AR	Arid Climate
6	Climate HS	Humid Subtropical Climate
7	Climate MO	Montane Climate
8	Climate SA	Semi-Arid Climate
9	Climate TW	Tropical Wet Climate
10	Climate TWD	Tropical Wet and Dry Climate
11	CPCB	Central Pollution Control Board
12	D1	Decade 1 (1981-1990)
13	D2	Decade 2 (1991-2000)
14	D3	Decade 3 (2001-2010)
15	D4	Decade 4 (2011-2020)
16	DTR	Diurnal Temperature Range
17	ECLIPSE	Climate and Air Quality Impact of Short-Lived Pollutant Emission
18	ECMWF	European Centre for Medium-Range Weather Forecasts
19	ERA	ECMWF Re-Analysis
20	ESACCI	European Space Agency Climate Change Initiative
21	GHG	Greenhouse Gases
22	GOCART	Goddard Chemistry Aerosol Radiation and Transport
23	GoI	Government of India
24	HI	Heat Index
25	HSI	Heat Stress Index
26	HW	Heat Wave
27	IHI	India Heat Index
28	IMD	India Meteorological Department
29	IPCC	Intergovernmental Panel on Climate Change
30	IPCC WG-II	Intergovernmental Panel on Climate Change Working Group II
31	LP DAAC	Land Processes Distributed Active Archive Center
32	LMICs	Low And Middle-Income Countries
33	LST	Land Surface Temperature
34	LULC	Land Use Land Cover
35	MHA	Ministry of Home Affairs
36	MODIS	Moderate Resolution Imaging Spectroradiometer

37	NASA	National Aeronautics and Space Administration
38	NCRB	National Crime Records Bureau
39	NHW	Non- Heat Wave
40	NOAA	The National Oceanic and Atmospheric Administration
41	NRMSE	Normalized Root Mean Square Error
42	OC	Organic Carbon
43	PM _{2.5}	Particulate Matter of size 2.5 micron
44	PSI	Physiological Strain Index
45	RCP	Representative Concentration Pathway
46	RH	Relative Humidity
47	SLCPs	Short-Lived Climate Pollutants
48	SR	Solar Radiation
49	SUHI	Surface Urban Heat Island
50	T _a	Temperature
51	T _g	Globe Temperature
52	T _{nwb}	Natural Wet Bulb Temperature
53	UHI	Urban Heat Island
54	UN	United Nations
55	UNFCCC	United Nations Framework Convention on Climate Change
56	US-NWS	National Weather Service of The United States
57	UTCI	Universal Thermal Climate Index
58	WBGT	Wet-Bulb Globe Temperature
59	WRF-Chem	Weather Research Forecasting Model Coupled with Chemistry
60	WS	Wind Speed