MITIGATING AIR POLLUTION AND URBAN HEAT THROUGH CLIMATE-SENSITIVE HEALTH INTERVENTION

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ABSTRACT

Urbanization-driven Urban Pollution Island (UPI) and Urban Heat Island (UHI) effects intensify air pollution and heat, severely threatening public health and urban sustainability. Earlier, both phenomena were addressed separately, primarily through quantitative research approaches. This study investigates the spatio-temporal quantitative dynamics of UPI and UHI driven by urbanization in Lahore and Faisalabad, Pakistan, while proposing qualitative, climate-sensitive interventions through the Thermal Haze Adversity Index (THAI) scale development to mitigate their combined impacts. Although instruments record increasing temperatures and air pollution, the study emphasizes human perception, individual health resilience, and psychological well-being, introducing practical human-centred coping strategies until permanent solutions are implemented. Using a geospatial approach, this study analyses three critical temporal time periods, including annual, heatwave, and smog periods (2015–2024) in Lahore and Faisalabad. Google Earth Engine (GEE) was employed to process multi-source satellite datasets, including Landsat-8 for Land Surface Temperature (LST) to compute UHI and land use characteristics, and Sentinel-5P for air pollutants (NO_2, SO_2, O_3, and CO) concentrations and to compute UPI & pollution risk zones. Additionally, the role of Urban Green Spaces (UGS) was evaluated in mitigating air pollution and urban heat, and to identify optimal sites for their establishment through site suitability analysis. Finally, public awareness, perception and behaviour were assessed through developing the THAI, integrating three key factors: the level of heat exposure experienced, the severity of air pollution, and the community's capacity to cope and adapt to heat and air pollution risk. The results revealed a pronounced increase in annual mean LST over the decade, with a 4 °C and 5°C rise in Lahore and Faisalabad, respectively. During the heatwave period, surface temperature increased 0.72 °C in Lahore and 1.4 °C in Faisalabad and in smog months, 4 °C in Lahore and 2 °C in Faisalabad, indicating a substantial increase in UHI intensity. Overall, air quality worsened. Annually, Lahore experienced rising O_3 and CO with declining NO_2 and SO_2 (2018–2024), due to partial policy interventions. Conversely, Faisalabad recorded an increase in all pollutants and expanding medium-risk zones. Urban green spaces proved that dense, healthy vegetation kept ground temperatures below 30°C. Large, connected parks lowered LST by 1.5–2°C and reduced pollutants, with a cooling effect extending up to 300 m, whereas fragmented patches offered limited benefits. The study proposed practical solutions by: (a) finding optimal locations for new green spaces through site suitability analysis, and (b) identifying priority areas for tree cover and green spaces. Finally, THAI findings indicated that public awareness and the government's environmental policies shape adaptive perception and enhance community resilience. The study demonstrated the importance of integrating urban green infrastructure, pollution mitigation, and heat management into city planning as effective interventions. The findings offer guidance for policymakers and urban planners to promote climate-resilient, healthy, and sustainable cities.

Keywords: Urban Heat, Air Pollution, Green Spaces, Thermal Comfort, Climate-Sensitive, Health Intervention, THAI, Lahore, Faisalabad.

PREFACE

Large Pakistani cities are facing an increasing environmental and public health crisis driven by deteriorating air quality and intensifying summer heat. Higher concentrations of fine particulate matter ($PM_{2.5}$) and key pollutant gases, i.e. carbon monoxide (CO), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) have emerged as critical risk factors for citizens' health. These challenges are further amplified by the local climate crisis. Lahore consistently ranks among the world's most polluted cities, with daily $PM_{2.5}$ levels during peak smog episodes frequently reaching over 50–60 times the WHO's annual guideline value of 5 $\mu g/m^3$. In 2025, severe heatwaves and daytime temperatures frequently exceeded 45 °C in Punjab during the summer.

Rapid urbanization, declining green spaces, increased emissions, industrial activity, and poorly regulated construction have collectively driven the emergence of the phenomenon of Urban Heat Island (UHI) and Urban Pollution Island (UPI) effects. Despite growing recognition of these threats, the effects of extreme heat and poor air quality on public health remain insufficiently studied in Pakistani urban contexts. This study aims to address this critical gap by integrating quantitative and qualitative approaches within a geospatial framework to assess the compounded effects of urban heat and air pollution. A key innovation is the Thermal Haze Adversity Index (THAI), a novel composite metric based on public awareness, perception, behaviour, and adaptive capacity to assess citizens' resilience to UHI and UPI impacts. Using a geospatial analytical framework alongside the THAI behavioral and governance tool, the study supports evidence-based, climate-resilient urban planning.

The authors extend their sincere appreciation to Ms. Masooma Zanib for her dedicated support as a Research Associate on this project. Her valuable technical assistance in spatial analysis, literature management, and research coordination greatly facilitated the successful completion of this work. Her commitment and diligence were instrumental in the compilation and finalization of the project report. The authors extend heartfelt gratitude to their mentors, Dr. Nasir Javed (Former CEO, Urban Unit, Government of Punjab) and Dr. Muhammad Aman Ullah (Senior Advisor, Punjab SDGs, UNDP, Lahore), whose expert guidance and constructive feedback greatly enriched this research. We highly appreciate the valuable comments of the anonymous reviewers, participants of the mid-term review workshop, the Research Advisory Committee (RAC), and the Project Management Team (PMT). We are also thankful to the Pakistan Institute of Development Economics (PIDE), Islamabad, for the institutional support and resources that made this work possible. It is our sincere hope that the findings and recommendations will contribute to academic discourse and provide useful insights for policymakers, urban planners, and public health practitioners in developing effective strategies for a resilient and healthier urban future.

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ABBREVIATIONS

AC	Adaptive Capacity
AHP	Analytical Hierarchy Process
CFA	Confirmatory Factor Analysis
CPI	Composite Priority Index
EEI	Ecological Evaluation Index
EFA	Exploratory Factor Analysis
EPA	Environmental Protection Authority
GHSL	Global Human Settlement Layer
GIS	Geographical Information System
GP	Government Policies
HBM	Health Belief Model
IPCC	Intergovernmental Panel on Climate Change
LDA	Lahore Development Authority
LST	Land Surface Temperature
LULC	Land Use Land Cover
MCA	Multi-Criteria Analysis
MCDA	Multi-Criteria Decision Analysis
NDBaI	Normalized Difference Bareness Index
NDBI	Normalized Difference Built-Up Index
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
PCA	Principal Component Analysis
PP	Public Perception
PHA	Parks and Horticulture Authorities
PMD	Pakistan Meteorological Department
RAP	Reduction in Air Pollution
SDGs	Sustainable Development Goals
SUHI	Surface Urban Heat Island
UGS	Urban Green Spaces
UHI	Urban Heat Island
UHII	Urban Heat Island Intensity
UPI	Urban Pollution Island
UTFVI	Urban Thermal Field Variance Index
THAI	Thermal-Haze Adversity Index
WHO	World Health Organization

INTRODUCTION

Urbanization and economic development have intensified environmental and ecological challenges, including air pollution, urban heat and biodiversity loss (Kalhor & Mahdisoltani, 2015; Zhu et al., 2020). These challenges are particularly prevalent in developing countries such as Pakistan, where cities, despite their socio-economic importance, often face environmental degradation, poor living conditions, and inadequate green spaces (Lapitan et al., 2011). Urbanization and climate change give rise to two major urban climate phenomena in urban landscapes: the Urban Heat Island (UHI) and the Urban Pollution Island (UPI). UHI describes higher air temperatures in urban areas compared to nearby rural areas, driven primarily by dense built-up surfaces and human activities (Ulpiani, 2021), whereas UPI refers to higher concentrations of pollutants in urban atmospheres relative to surrounding rural areas (Crutzen, 2004). These phenomena are closely interconnected, largely driven by combustion from transport, industries, and anthropogenic activities (Li et al., 2007) and interact through complex feedback mechanisms at local and regional scales (Oke, 1982; Baklanov et al., 2016).

Air pollution is a major environmental health risk, contributing significantly to cardiovascular disease and premature deaths (WHO, 2024a). Industrialization, vehicular emissions, and energy consumption have compounded air quality issues in both developed and developing countries (Kamruzzaman et al., 2018). Pollutants (NO_2, SO_2, CO, $PM_{2.5}$, and O_3), primarily from factories, brick kilns, fossil fuel combustion, and transport, contribute to smog formation and deteriorating health (Wielgosiński & Czerwińska, 2020; Raza et al., 2021; Naureen et al., 2022). Increasing air pollution has been observed globally, including in Ningbo (Yang & Shi, 2017), Delhi (Sharma & Masiwal, 2022), Hazaribagh (Hashem et al., 2015), and Lahore (Riaz & Hamid, 2018). Pakistan ranks among the top ten most polluted countries, with an annual mean of 44.21 $\mu g/m^3$ $PM_{2.5}$, exceeding the WHO guideline of 5 $\mu g/m^3$ (WHO, 2024b; Owusu & Sarkodie, 2020).

Air pollutants also cause changes in local climate and environmental degradation (Anbazu & Antwi, 2023). The IPCC estimates that between 1800 and 2012, global temperatures increased by 0.85°C, and by 2065, temperatures are predicted to rise by 2.6°C (IPCC, 2014). As urban expansion replaces vegetation with impervious surfaces, heat absorption increases, leading to thermal discomfort (Menon & Sharma, 2021). UHI worsens heat-related mortality and health conditions, while also increasing energy demand (Oke, 1982; Hondula et al., 2014). The UHI effect significantly increases pollutant concentration, stimulating air pollution (Swamy et al., 2017). There is a strong paradox between air pollution and urban heat, and its impact on public health, with climate change overall worsening UHI and UPI effects, such as increased heat waves and smog exposure (Fang et al., 2020) and impacting health, leading to mortality. Air pollution led to 8.1 million deaths in 2021, and health impacts are expected to aggravate due to inadequate mitigation of climate change (Esposito et al., 2025).

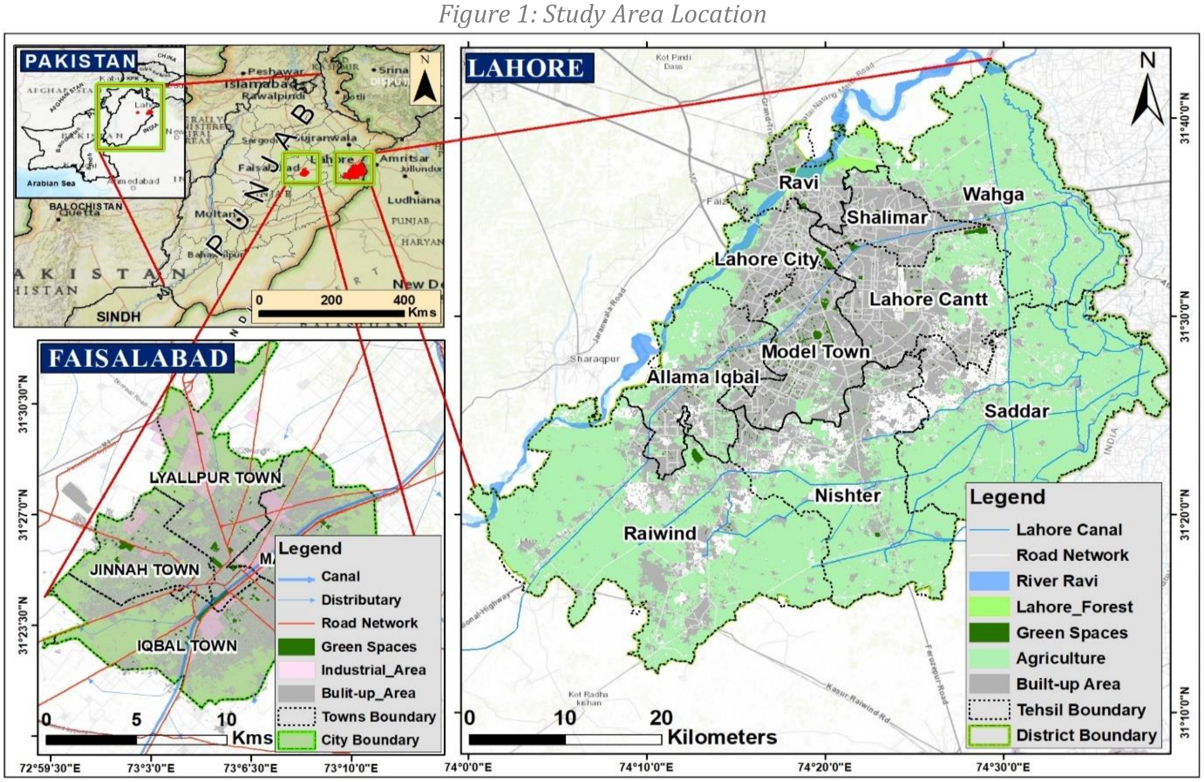
This study emphasizes understanding the effects of air pollution and urban heat and provides a framework for taking action to reduce their negative effects on the environment and health. It seeks to systematically assess UHI and UPI, which are essential for policymakers and public health experts to develop adequate strategies. Integrating quantitative and qualitative research approaches allows for a more accurate and comprehensive understanding of UHI and UPI formation in Lahore and Faisalabad, strengthening the evidence-based interventions for resilient urban planning. This research also supports SDGs 3 (Good Health and Well-Being) 3.9, minimizing air-pollution-related illness, 11 (Sustainable Cities and Communities) 11.6, improving air quality, and 13 (Climate Action), advancing environmental sustainability and public well-being.

1.1. Purpose and Scope of the Research

This study focuses on Lahore and Faisalabad (Figure 1), two rapidly urbanizing cities in Punjab, Pakistan. In 2023, Lahore, the second-largest city, had a population of about 13 million and Faisalabad, the third most populous city, had 3.69 million residents (GOP, 2024). Lahore, the provincial capital, has a denser population, heavy traffic movement, and a mixed land use pattern. Faisalabad is the major industrial hub dominated by the textile industry and energy-intensive sectors. These differences in urban function and size enable investigation of the variability of urban heat and air pollution dynamics.

In terms of governance, Lahore benefits from relatively stronger institutional capacity, including environmental and developmental institutes, and ongoing climate and heat management initiatives. Faisalabad, although governed under similar provincial frameworks, faces weaker environmental monitoring and regulatory implementation. Both cities experience a semi-arid to sub-humid climate, though with distinct microclimatic conditions. Together, these case studies emphasize varying contributors of UPI and UHI, enhancing the comparative analysis and supporting the transferability of findings to other rapidly urbanizing cities with similar geographical contexts.

Figure 1: Study Area Location



Source: Author's work.

1.1.1. Objectives of the Study

1. To analyze spatial and temporal patterns of UPI and UHI effects.
2. To identify the role of Urban Green Spaces (UGS) in combating the effects of UPI and UHI.
3. To recommend suitable sites for the establishment of UGS that serve as carbon sinks through strategic urban planning and green initiatives.
4. To develop a qualitative THAI scale that evaluates community resilience against rising temperature and air pollution.
5. To inform long-term air quality and heat-related management strategies and recommendations for implementing scalable interventions.

1.1.2. Research Questions

1. How do UPI and the UHI effects vary spatially and temporally in both cities?
2. What role do UGS play in mitigating the impacts of UPI and the UHI?
3. Which suitable sites for UGS development can help mitigate air pollution and urban heat to support a healthy urban environment?
4. What public perception and behavior matter in mitigating air pollution and heat to improve the environment and health?
5. How can long-term air quality and heat-related strategies be developed to support scalable interventions?

1.1.3. Research Hypothesis

1. If we adopt climate-sensitive health interventions, then we can efficiently combat heat and air pollution-related health illnesses.
2. If public awareness, perception, and behaviour about the increasing health problems due to heat and air pollution are incorporated, then it will improve air quality, public health, and reduce urban heat.
3. If interventions are combined with environmental policies, then they will prove to have a greater effect on improving public health in air pollution and heat-prone cities.

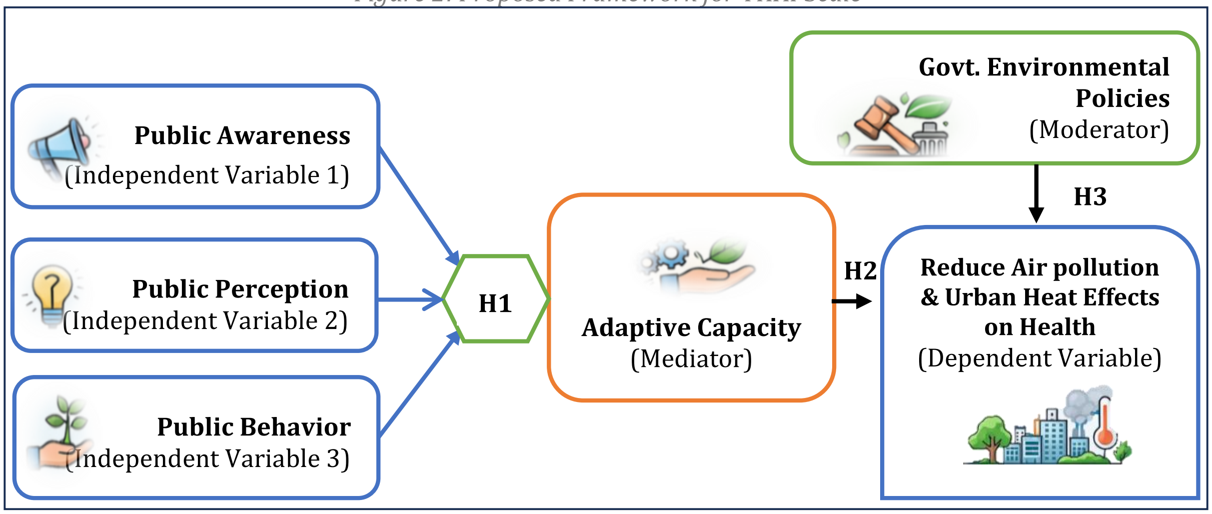
Thus, the specific hypotheses to be tested in this study are outlined below (Figure 2):

H1: Public Awareness, Perception, and Behavior positively influence Adaptive Capacity to understand the risk of urban heat and air pollution.

H2: Adaptive Capacity positively affects the reduction of air pollution and UHI effects on an individual's health.

H3: Understanding of Governmental Environmental Policies moderates the relationship between adaptive capacity and the reduction of air pollution and urban heat effects on health.

Figure 2: Proposed Framework for THAI Scale



Source: Authors' illustration.

LITERATURE REVIEW

The WHO estimates that 99% of the global population is exposed to poor air quality containing high levels of pollutants, contributing to approximately 4.2 million deaths annually (WHO, 2021a). Short-term and long-term exposure to smog is associated with a wide range of health risks, including respiratory diseases i.e. asthma, coughing, and bronchiolitis (Naureen et al., 2022), cardiovascular disease (Yang et al., 2019), neurological disorders, cancer (Maher et al., 2017), lung diseases (Cao et al., 2020), allergies (Sughis et al., 2012), infant health issues, low birth weight, and eye irritation and breathing difficulties (Altindag et al., 2017; Ontawong et al., 2020). $PM_{2.5}$ affects the upper respiratory tract, while PM_{10} impacts the lower respiratory tract, causing allergies and irritations, reducing life expectancy (Zeeshan & Malik, 2025).

Slovic et al. (2016) evaluated vehicular emissions control strategies in urban areas and their effectiveness in mitigating air pollution and urban heat. Beyond legal and governmental strategies, economic and technological innovations, though less studied, were identified as highly relevant for heat & air pollution control. Mohammadi et al. (2012) examined air pollution caused by smog and its relationship with climatic factors, including temperature, air pressure, humidity, wind speed, and atmospheric inversion layers in Tehran. Their findings indicate higher smog concentrations in winter due to the combined effects of these factors, with levels declining in spring and summer as increased atmospheric instability enhances pollution dispersion. Grzywa-Celińska et al. (2020) reviewed health impacts of air pollution, emphasizing respiratory illnesses and toxic effects of particulate matter and gaseous pollutants. Correspondingly, nitrogen dioxide, sulphates, and dust have been linked as the primary causes of lung cancer (Naureen et al., 2022).

Mir et al. (2022) examined air quality trends and impacts of pollution control strategies on health up to 2050, underlining existing legislation and socioeconomic development dynamics. Punjab, Pakistan, was most affected by $PM_{2.5}$ exposure, leading to 81,565 premature deaths in 2015. Lahore's poor air quality causes thousands of premature deaths annually, increasing respiratory and cardiovascular diseases, asthma, and reduced lung function among vulnerable groups (DGHS Punjab, n.d.; EPA, 2025). These trends mirror other polluted megacities, i.e. Bangkok, Jakarta, and Delhi (Molina & Molina, 2004). Smog also strains healthcare systems, reduces productivity, raises economic costs, and has been linked to diseases related (DGHS Punjab, n.d.). Mumtaz (2024) introduced the adaptation and implementation of Green Infrastructure (GI) initiatives and the Clean Green Movement (CGM) in Lahore to mitigate the effects of climate change. Zhu et al. (2020) explained smog reduction behaviour using the Theory of Planned Behavior (TPB), highlighting strong links between attitudes and social pressure, perceived control and pro-environmental behaviour.

Exposure to heat-related health risks is significantly higher in cities. Dense urban residents face pollution-heat-related stress, while nearby green spaces reduce exposure (Arifwidodo & Chandrasiri, 2020). Heat-related mortality, including deaths from heat waves and strokes, is strongly correlated with UHI intensity (Heaviside et al., 2017), and nearly a quarter of the world's population is affected by extreme heat waves (Tuholske et al., 2021). UHI health risks were also investigated, with a focus on respiratory and cardiovascular diseases, among residents in Beijing and Tianjin by Huang et al. (2020). Results showed a 1°C rise above 31°C increased respiratory disease mortality by 25.3%, while cardiovascular mortality rose by 7.2% above 28°C. Questionnaire data highlighted a 28°C threshold for negative mental health impacts. Urban heat intensifies physiological stress through elevated temperatures and reduced thermal comfort (Silva et al., 2025). Increasing UHI intensity harms residents' social, physical, and mental health, causing heat exhaustion, respiratory illness, and psychological impacts such as anxiety, depression, and aggression (Wong et al., 2018).

MATERIAL AND METHODS

3.1. Geospatial Data

This research utilized multi-source geospatial datasets with meteorological and population data to analyze urban heat and air pollution. Three temporal periods were selected: annual, heatwave-prone months (Apr–Jun), and smog-prone months (Oct–Feb). Composite images were generated for 2015 (UHI baseline), 2018 (UPI baseline), 2021, and 2024 to observe spatio-temporal variations. Land surface indices (NDVI, NDBI, NDBal, and NDWI) evaluate LULC characteristics (Table 1). Landsat 8 TIRs were used for LST, UHI and UTFVI retrieval.

Table 1: Metadata of Satellite Landsat-8

Year	Period	Satellite & Sensor	Band	Spatial Resolution		Cloud Cover
				MS bands	Thermal bands	
2015 to 2025	i. Annual (Jan-Dec) ii. Heatwave (Apr-Jun) iii. SMOG (Oct-Feb)	Landsat 8 OLI	1-8	30m	-	0%
			Pan 9	15m	-	
		Landsat 8 TIRs	10 & 11	-	30m (resampled from 100)	

Source: GOUS (n.d.).

This study extracted tropospheric NO_2, SO_2, CO, and O_3 concentrations from Sentinel-5P TROPOMI data (Table 2) to assess UPI, emphasizing seasonal variations during smog-prone months.

Table 2: Metadata of Satellite Sentinel-5P

Year	Period	Trace Gases	Band	Unit
2018 to 2025	i. Annual (Jan-Dec) ii. Heatwave (Apr-Jun) iii. SMOG (Oct-Feb)	NO_2	tropospheric_NO_2_column_number_density	μmol/m^2
		SO_2	SO_2_column_number_density_15km	μmol/m^2
		CO	CO_column_number_density	mol/m^2
		O_3	O_3_column_number_density	mol/m^2

Source: GOUS (n.d.).

Meteorological data (air temperature, humidity, wind speed) from PMD (2015–2025) and population census data 2023 from PBS and GHSL data 2025 and EPA pollutants data supported validation and exposure analysis. Integrating satellite, meteorological, and demographic data enabled a robust assessment of UHI and UPI.

3.2. Qualitative Data Collection and Sampling

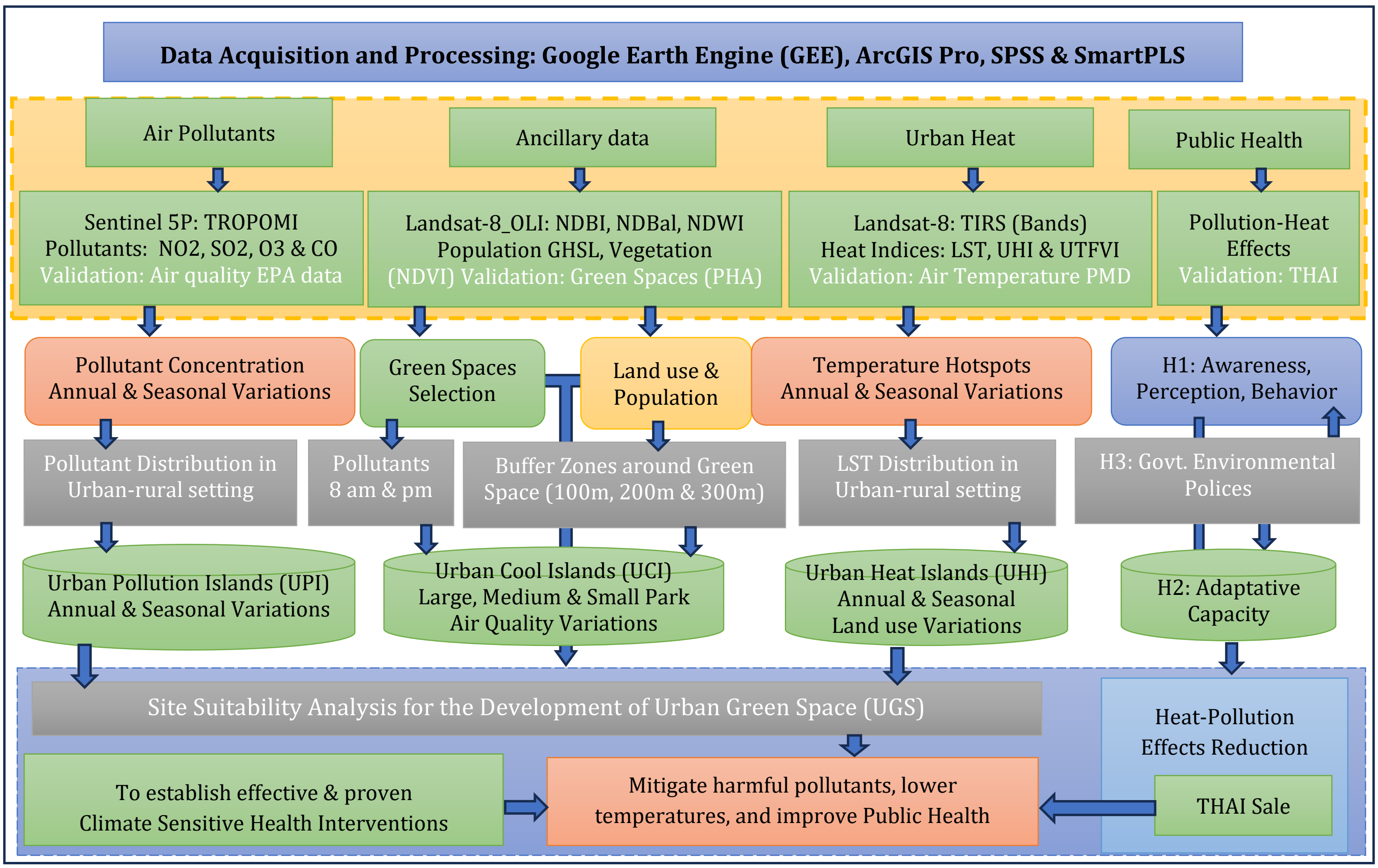
This study employed a structured questionnaire to collect data on Public Awareness, Perception, and Behaviour for developing the THAI scale. The model included public awareness, perception, and behaviour as independent variables; adaptive capacity as a mediator; health effects of air pollution and urban heat as the dependent variable; and government environmental policies as a moderator. Each construct initially comprised 15–19 items. Of 1000 questionnaires distributed between 15 September and 30 October 2025, 550 responses were received, of which 376 valid questionnaires were retained for analysis.

A goal-directed convenience sampling strategy was employed to target adults aged 18 and above. Data was collected online via social media platforms and community groups to capture a diverse demographic profile across age, gender, education, and income levels. A minimum sample size of 300-500 valid responses was aimed to ensure adequate reliability and generalizability for Structural Equation Modelling (SEM) in SmartPLS. Measurement items were adapted from established frameworks, including the IPCC Adaptive Capacity Framework and environmental psychology literature, and contextualized to reflect thermal haze conditions in Punjab, Pakistan. The final questionnaire items were grouped as shown in Annexure 1.

3.3. Research Methodology

A multi-level and mixed-method research approach was used, as shown in Figure 3 and explicitly described in relevant subsections.

Figure 3: The Flowchart of the Research Process



Source: Authors' illustrations.

3.3.1. Land Surface Indices

Land indices, as LULC representatives, are widely used in urban studies to exploit surface reflectance properties for evaluating their spatial relationship with LST, UHI, UTFVI and UPI. NDVI is widely used for assessing vegetation health and density (Chen et al., 2004) and is calculated through equation 1.

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED}) \quad \text{......} 1$$

NDBI, used to delineate built-up areas (Zha et al., 2003), and calculated through equation 2.

$$\textbf{NDBI} = (\textbf{SWIR} - \textbf{NIR}) / (\textbf{SWIR} + \textbf{NIR}) \quad \ldots\ldots 2$$

NDBaI, a bareness index, was proposed by Zhao & Chen (2005) and computed through eq. 3.

$$\textbf{NDBaI} = (\textbf{SWIR} - \textbf{TIR}) / (\textbf{SWIR} + \textbf{TIR}) \quad \ldots\ldots 3$$

NDWI, proposed by Xu (2006), enhances water feature detection and is computed through eq. 4.

$$\textbf{NDWI} = (\textbf{Green} - \textbf{SWIR}) / (\textbf{Green} + \textbf{SWIR}) \quad \ldots\ldots 4$$

3.3.2. LST Retrieval

LST was computed using Landsat 8 TIRS band 10 through radiance conversion and brightness temperature estimation following established methods (Sobrino et al., 2004). Land Surface Emissivity (ε) was estimated to use Proportional Vegetation (Pv) cover derived from NDVI, following Carlson & Ripley (1997) through equation 5.

$$\boldsymbol{PV} = (\boldsymbol{NDVImax} - \boldsymbol{NDVImin} / \boldsymbol{NDVImax} + \boldsymbol{NDVImin}) \wedge \mathbf{2} \quad \ldots\ldots 5$$

Emissive (ε) was calculated using the linear equation 6 proposed by Sobrino et al. (2004).

$$\varepsilon = 0.004 \times Pv + 0.986 \quad \ldots\ldots 6$$

LST was derived from brightness temperature T_b using the radiative transfer equation (Weng et al. 2004) and corrected using emissivity (ε), through equation 7 proposed by Faridatul (2017).

$$\textbf{LST} = \left(\textbf{Tb}/\mathbf{1} + \boldsymbol{\lambda} * (\textbf{Tb}/\boldsymbol{\rho}) * \textbf{ln}\,(\boldsymbol{\varepsilon})\right) - \mathbf{273.15} \quad \ldots\ldots 7$$

3.3.3. UHI Intensity

To ensure trustworthy comparison across different years, LST were normalized using the technique proposed by Zhang et al. (2006) and calculated using formula 8.

$$\textbf{UHI} = (\textbf{Ts} - \textbf{Tm}) / \textbf{SD} \quad \ldots\ldots 8$$

3.3.4. UTFVI-Based Comfort Analysis

UTFVI, proposed by Zhang et al. (2006), to gauge urban thermal stress and ecological vulnerability by normalizing LST deviations and determining using equation 9:

$$\textbf{UTFVI} = (\textbf{Ts} - \textbf{Tmean}) / \textbf{Tmean} \quad \ldots\ldots 9$$

Higher values of UTFVI indicate extreme ecological stress and lower thermal comfort (Guha et al., 2018).

3.3.5. Urban Pollution Islands (UPI)

The UPIs were recognized through two phases. The first phase assessed the spatial concentrations of four major air pollutants: SO_2, NO_2, CO, and O_3, because of their significance to air quality and public health effects. The second phase converted pollutant concentration maps to health risk maps based on Relative Risk (RR) to explain the UPI for targeted interventions. The analytical hierarchy process (AHP) was used to assign weights to each of the pollutants based on their health effect severity (Saaty, 2013). These assumptions are supported by epidemiological evidence indicating NO_2's stronger respiratory impacts and CO's relatively lower chronic risk (WHO, 2021b). Final pollutant weights (Table 3) were derived from the normalized matrix, and the details of the AHP process are given in Annexure 2.

Table 3: Assigned Weights

Pollutant	Weights Assigned
NO_2	51.93%
O_3	20.09%
SO_2	20.09%
CO	7.89%

Source: Author's computation.

3.3.6. Green Spaces Cooling Effect and Buffer Analysis

The LST of the study area was compared to the vegetated areas to estimate the cooling effect of UGS (Hulley et al., 2019). Buffer zone analysis was used to measure the effect of UGS on the surrounding developed areas (Yu et al., 2020). In Lahore and Faisalabad, 15 parks for both cities were categorized as large, medium, and small parks (Jamali et al., 2021). Buffer zones of 100 to 300 m radius were developed based on the 300 m accessibility criteria (Konijnendijk, 2023), and LST values were interpolated to produce cooling effect and cooling profiles (Spronken-Smith & Oke, 1998).

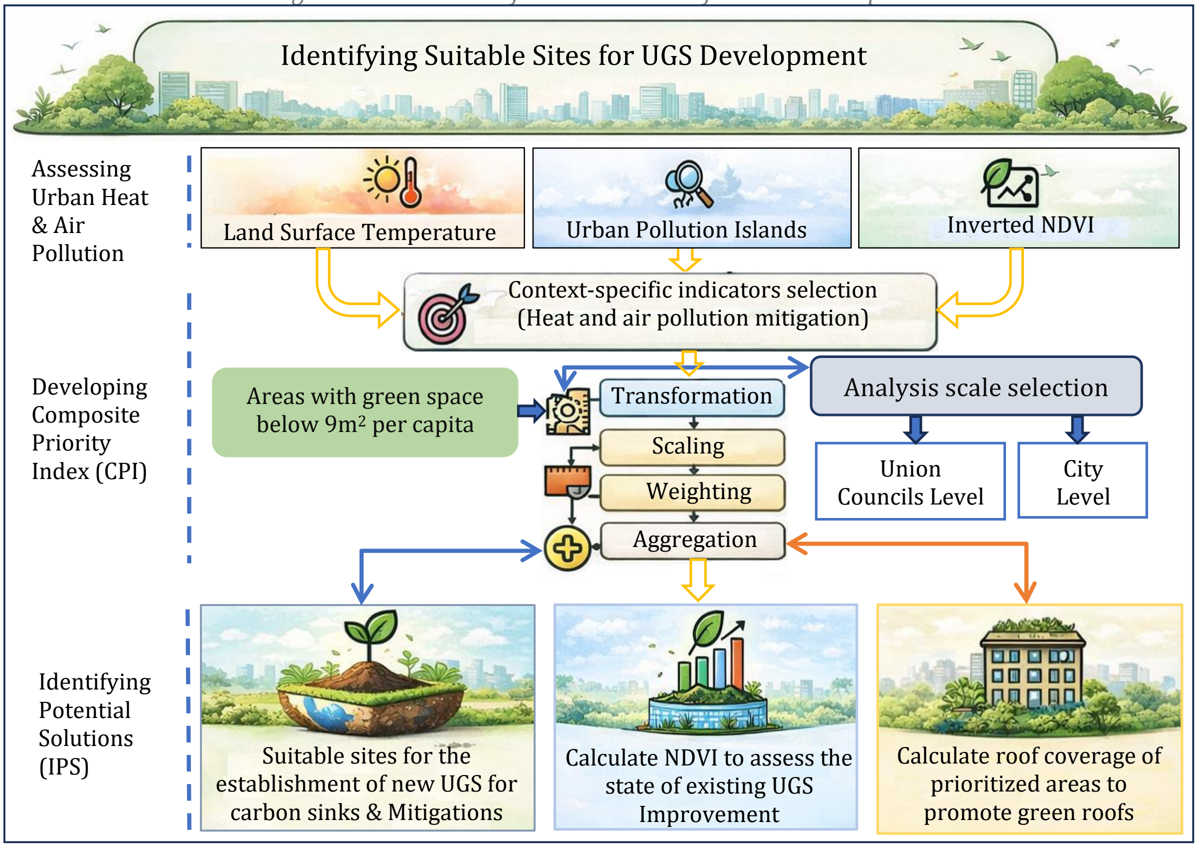
3.3.7. Impact of Urban Green Spaces on Air Quality

To examine the impact of UGS on mitigating air pollution, some data sets about air pollutants are required. These parameters, such as NO_2, CO, SO_2, and O_3, needed to be measured at 8 am and 8 pm, both in and around selected parks, through Windy App data, as recommended by Liu et al. (2024). Through selected park boundaries as references, average values were figured. These values, recorded at two occasions, morning values reflected commuter traffic, overnight accumulation, and temperature inversion (Zhang & Rao, 1999), while evening values corresponded to weak mixing, low wind, and surface accumulation (Dobson et al., 2021).

3.4. Site-Suitability Analysis

UGS play critical roles in climate control, improving air quality, reducing urban heat, and providing health benefits. The research seeks to explore and recommend locations for UGS development in both cities. Figure 4 illustrates the approach to satisfying objective 3, achieved through assessing LST and air pollution, formulating the Composite Priority Index (CPI), and identifying potential solutions.

Figure 4: Framework for Suitable Sites for UGS Development



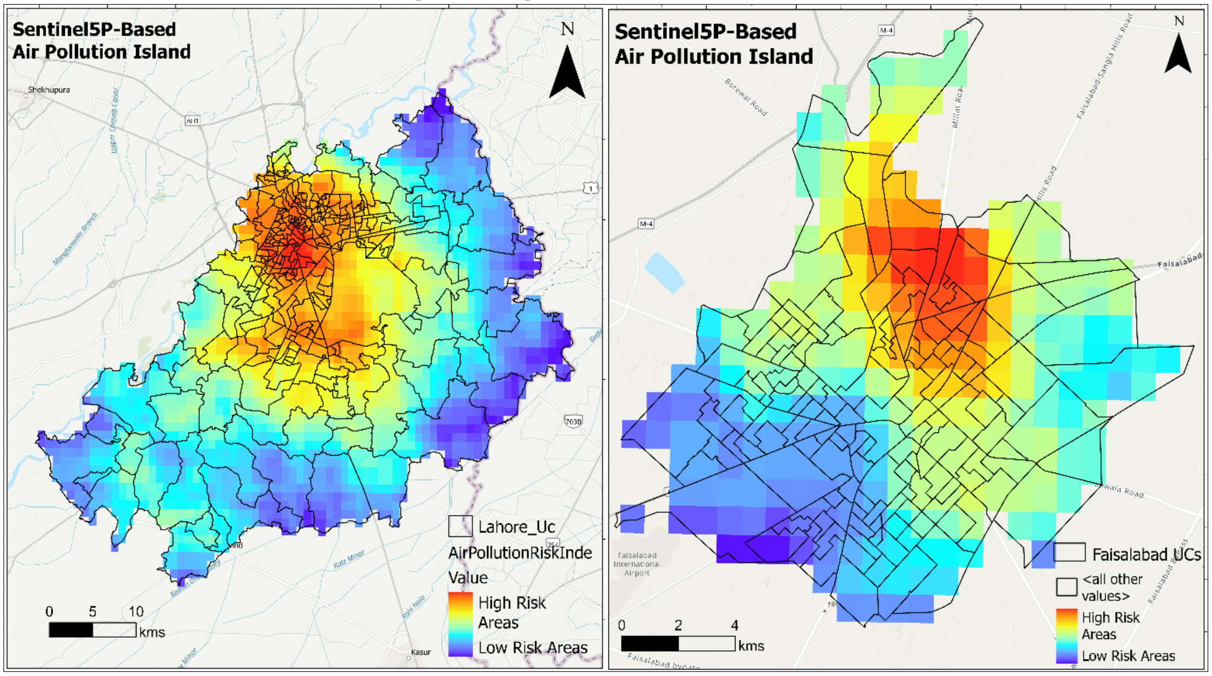
Source: Authors' illustrations

3.4.1. Analytic Hierarchy Process (AHP)

A GIS-based AHP, a popular MCDA technique, was applied to locate suitable locations for UGS establishment. The criteria ranked in order of relevance include high exposure to air pollution, high population density, minimal greenery cover, and high LST.

High Air Pollution Areas: High air pollution risk zones (Figure 5) were mapped in 2025 smog period, including NO_2, SO_2, O_3, and CO concentrations. These pollutants were integrated using a weighted overlay based on their relative health effects (Shaddick et al., 2018).

Figure 5: High-risk Air Pollution Areas

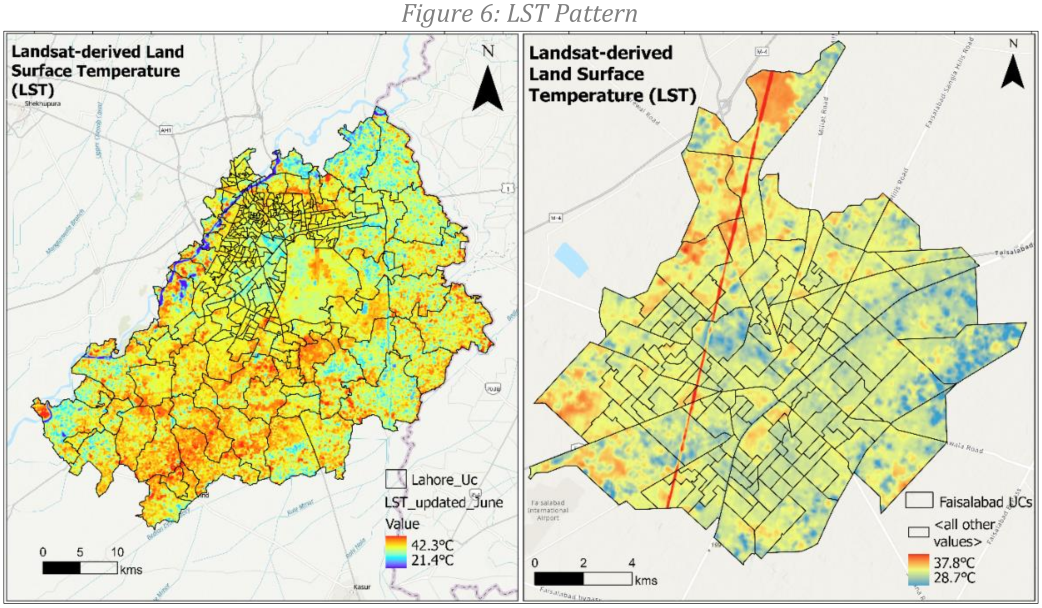


Source: Author's work

Land Surface Temperature: LST was derived corresponding to the peak temperature in 2025 heatwave period to identify urban heat hotspots (Figure 6).

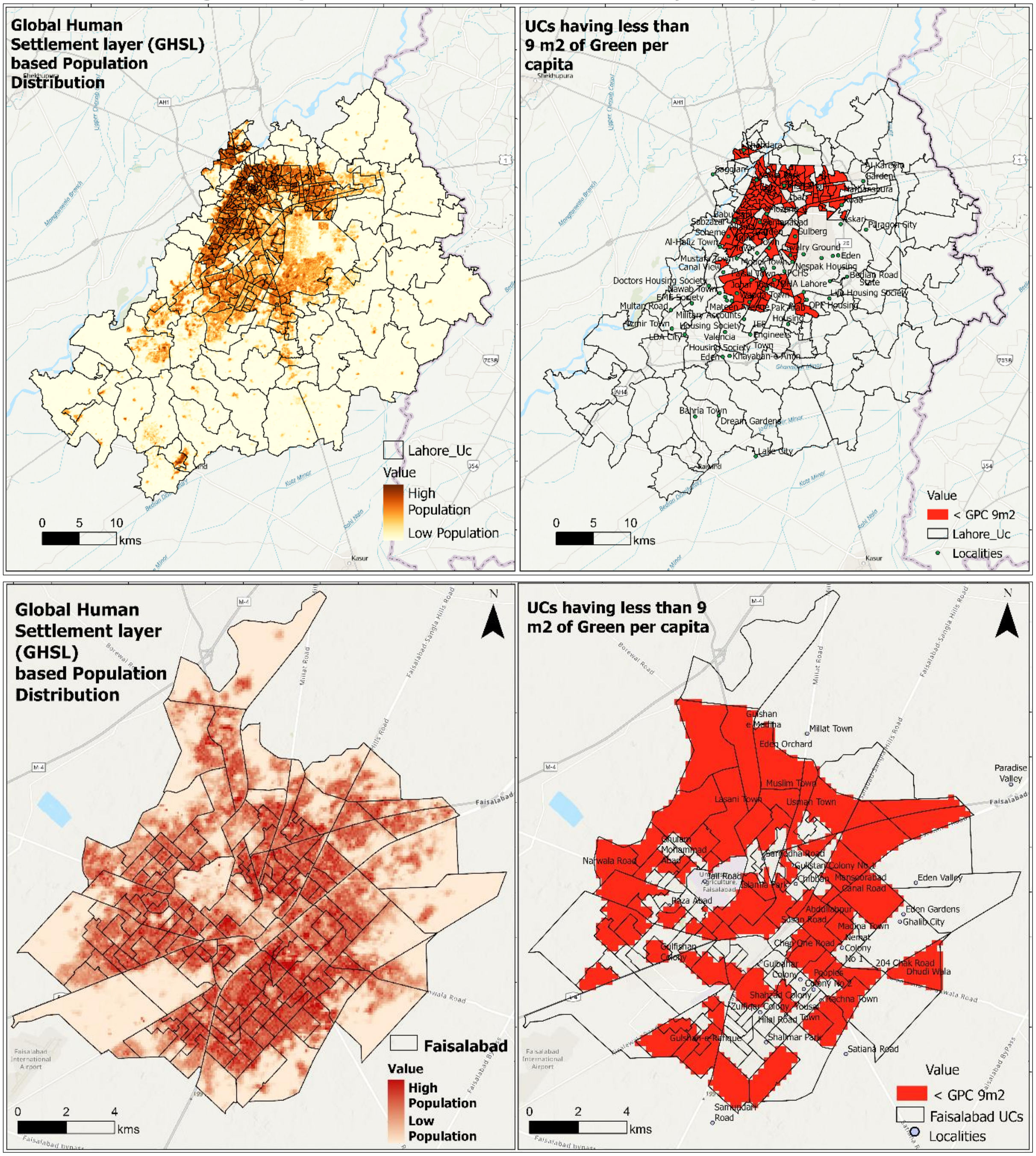
Areas with Green Space Below 9 m² per Capita (WHO Standard): Population zones failing to meet the WHO minimum standard of 9 m² green space per capita (WHO, 2017) were identified by combining population data with NDVI-derived (Konijnendijk, 2023) green space coverage (Figure 7).

Figure 6: LST Pattern



Source: Author's work.

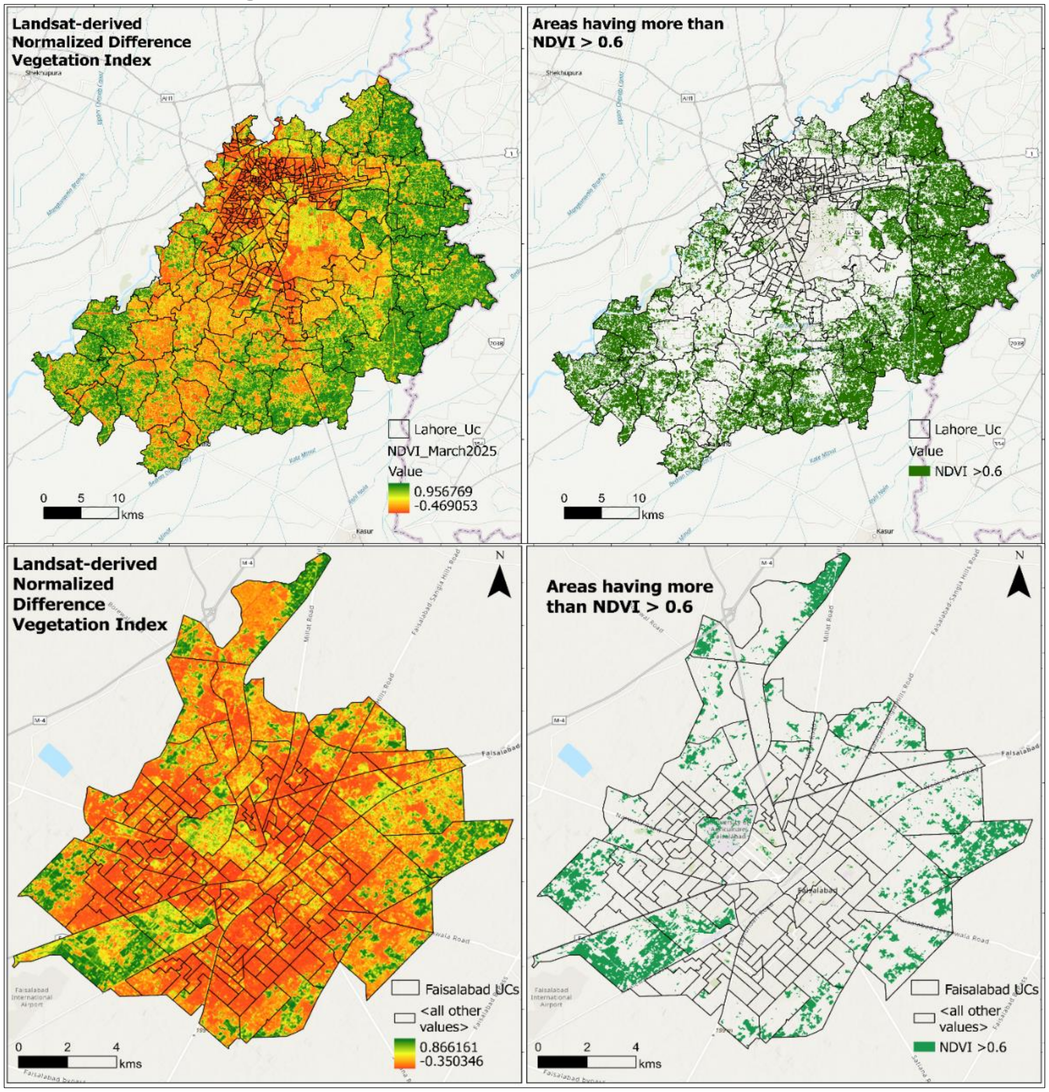
Figure 7: Population Distribution & Less than 9 m² of Green per Capita



Source: Author's work

Vegetation Cover: NDVI was used to detect low vegetation areas using February–March 2025 imagery when deciduous vegetation is minimal (Raza et al., 2025). The areas with NDVI > 0.6 were excluded. The NDVI layer was inverted to highlight vegetation-deficient zones suitable for intervention (Figure 8).

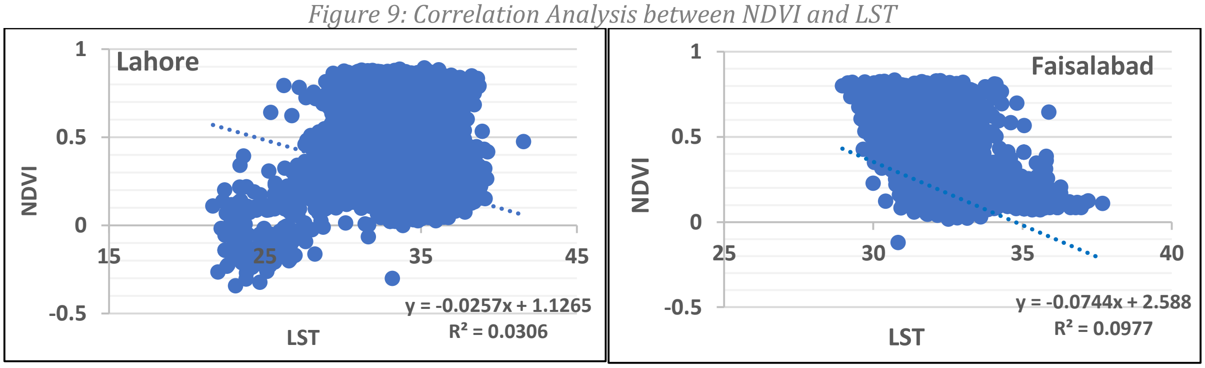
Figure 8: Lahore and Faisalabad NDVI and NDVI > 0.6



Source: Author's work

NDVI > 0.6 in Lahore & NDVI > 0.7 in Faisalabad have a temperature of less than 30° C (Figure 9).

Figure 9: Correlation Analysis between NDVI and LST



Source: Author's computations

3.4.2. Developing Composite Priority Index (CPI)

CPI involves selecting appropriate indicators. In this study, context-specific indicators were chosen to address UHI and UPI effects. All the indicators were grouped into two dimensions: i) problem indicators and ii) solution indicators, depending on their role in increasing or decreasing environmental stress (Table 4). The CPI, using a weighted linear combination, was then calculated as: **Composite Priority Index =**

Float(0.3*Float("AirPollutionRiskIndex")+0.3*Float("NDVI_invert")+0.4* Float("LST"))

Weights were assigned to each criterion in relation to their relative importance (Li et al., 2018; Ahmadi et al., 2023), with more emphasis given to LST. This means that LST was weighted as high as 40%, while pollution risk level and lack of greenery represented by NDVI were weighed 30% each through MCA.

Table 4: Indicators of CPI

Dimension	Indicators	Explanation	Data Sources
Problems Indicators	Population	Population zones where the population does not have a 9m^2 green per capita ratio	GHSL data 2025
	Minimal Greenery Area	Areas with less than 9 m^2 of green space per capita indicate insufficient urban greenery for healthy living.	Landsat 8 data 2025
	High Air Pollution Zones	NO_2, SO_2, O_3, CO, (weighted overlay sum)	Sentinel-5P 2025
	Land Surface Temperature	Rising LST worsens local climate, increases ground-level ozone, degrades air quality, and raises heat-related health risks.	Landsat 8 data 2025
Solutions Indicators	Existing Green Spaces	UGS helps mitigate the UHI effect and improve air quality	Urban Unit, Lahore
	NDVI	UGS with higher NDVI more effectively reduce UHI and improve air quality.	Landsat 8 data 2025

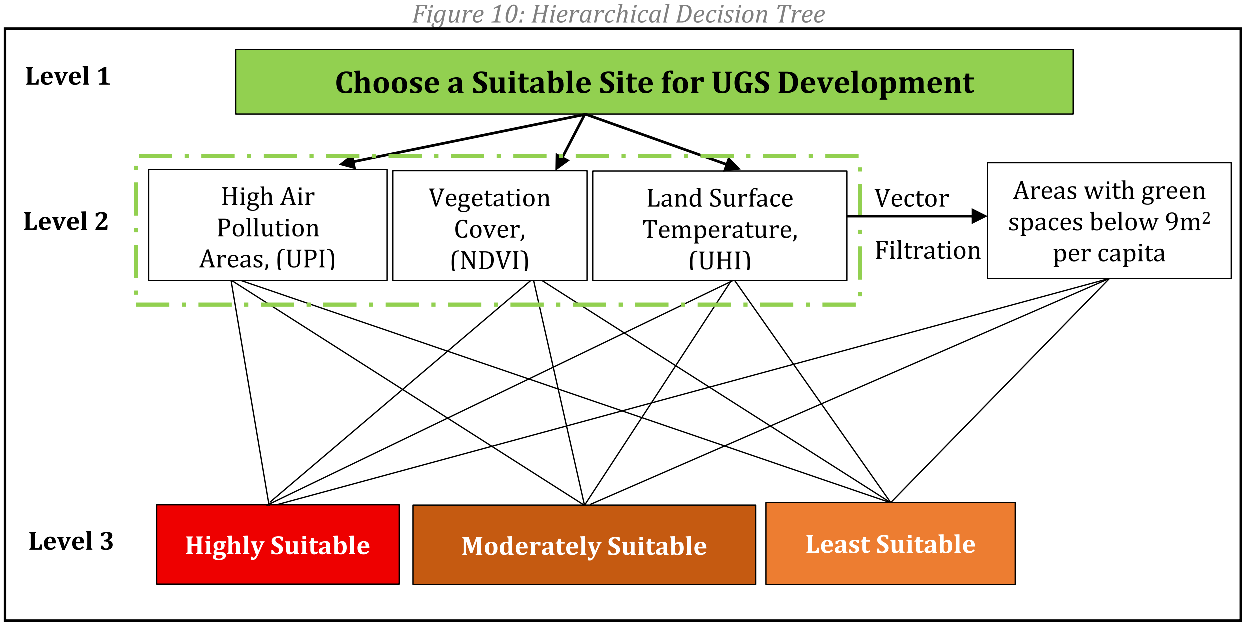
Source: Authors' compilations.

3.4.3. Identifying Potential Solutions

Suitable Sites for the Establishment of a New Green Space: Composite raster outputs from CPI were filtered using the WHO 9m^2 per capita standard to delineate priority zones for new green space development while preserving spatial accuracy. Figure 10 illustrates the systematic hierarchical decision tree that is used for the identification of the potential UGS sites.

Existing Green Space Maintenance, Rooftop and Vertical Greenery: As Lahore and Faisalabad are compact cities, the development of new UGS is limited; therefore, improving the quality of existing UGS is essential. Another alternative that can be promoted is a green roof (Baniya et al., 2018). The top surface area of buildings approximately gives the roof coverage. Therefore, calculating the percentage of roof coverage of suitable sites should be highly prioritized based on the priority index.

Figure 10: Hierarchical Decision Tree



Source: Authors' illustration.

3.5. THAI Scale Development

This section outlines the THAI scale development using equal interval methods, assuming a 5-point Likert scale from "Strongly Disagree" (1) to "Strongly Agree" (5). The methodology integrates Exploratory Factor Analysis (EFA) for item reduction and structure identification in SPSS, followed by Confirmatory Factor Analysis (CFA) for validation in SmartPLS. The THAI scale is established in the Health Belief Model (HBM), developed by Rosenstock, Hochbaum, Kegeles, and Leventhal in the 1950s (Alyafei & Easton-Carr, 2024). THAI focuses on public awareness, perception and behaviour, adaptive capacity, and government environmental policies to reduce combined air pollution and urban heat effects on health. The proposed conceptual framework (see Figure 2) hypothesizes.

3.5.1. Define the Construct

The construct is adapted from the Health Belief Model (Rosenstock, 1974; Strecher & Rosenstock, 1997; Taylor et al., 2006) and focuses on health-protective behaviours against air pollution and heat stress. Core domains include Public Awareness (PA), Public Perception and Behaviour (PP), Adaptive Capacity (AC), Reduction of air pollution and urban heat effects on health (RAP), and Government Policies (GP) as moderators (see Figure 2).

3.5.2. Generate Pool

An initial pool of 104 items was developed using a 5-point Likert scale, with balanced positive and negative wording.

3.5.3. Exploratory Factor Analysis (EFA)

Data Screening: After screening, valid responses are 376; EFA reduced the scale to 48 items (Annexure 1) across three components, explaining total variance of 66.91%. Sampling acceptability was excellent (KMO = 0.976), and Bartlett's Test of Sphericity was significant (χ^2 = 20896.107, p < 0.001), verifying appropriateness for factor analysis.

Factor Extraction: Principal Component Analysis (PCA) was applied, with all communalities ≥ 0.512 (Annexure 3), e.g., PA2 = 0.685; AC5 = 0.602; GP10 = 0.786). Eigenvalues (>1), scree plot inspection, and parallel analysis supported the extraction of three components (Annexure 4), and parallel analysis using the third-party validation by the Monte Carlo Parallel Analysis.

3.5.4. Factor Rotation and Pattern Matrix

Promax rotation with Kaiser normalization produced strong factor loadings (≥ 0.600). Component 1 represented Public Awareness/Perception/Behaviour, Component 2 Adaptive Capacity/Reduction, and Component 3 Government Policies (Annexure-5). Moderate inter-factor correlations were observed (Annexure 6). The scale showed excellent reliability (Cronbach's alpha = 0.979).

3.5.5. Confirmatory Factor Analysis (CFA)

Model Estimation: The full sample of 376 responses was used. A reflective measurement model was specified, with items assigned to their respective constructs including Public Awareness (PA1–PA9), Public Perception and Behavior (PP1–PP16, combined), Adaptive Capacity (AC1–AC6), Government Environmental Policies (GP1–GP9), and Reduction of air pollution and Urhan heat: Thermal Haze Adversity Index, (THAI) (RAP1–RAP8) as the outcome variable. Earlier, Hypothesized Proposed paths were included in the model, such as PA → AC, PP → AC, AC → Thermal Haze Index, and GP moderating the AC → Thermal Haze Adversity Index (THAI) relationship. Bootstrapping with 5,000 subsamples assessed path significance.

Validity and Reliability of the Scale: Composite reliability (0.933–0.977), Cronbach's alpha (0.918–0.977), and rho_A (0.921–0.977) exceeded recommended thresholds (Nunnally, 1978; Taber, 2018). Convergent validity was strong (AVE > 0.63), supporting discriminant validity (Fornell & Larcker, 1981) (Table 5).

Table 5: Construct Reliability and Validity of the Scales

Constructs	Cronbach's Alpha	rho_A	Composite Reliability	AVE
Adaptive Capacity	0.925	0.926	0.942	0.729
Govt Env. Policies	0.955	0.956	0.962	0.737
Public Awareness	0.949	0.951	0.957	0.711
Public Perception and Behavior	0.977	0.977	0.979	0.741
Thermal Haze Adversity Index	0.918	0.921	0.933	0.635

Source: Author's computation.

Inter-Construct Correlation: HTMT values (<0.90) and Fornell–Larcker criteria confirmed discriminant validity (Annexure 7 & 8). Overall model fit was acceptable (SRMR = 0.090; NFI = 0.857) (Annexure 9).

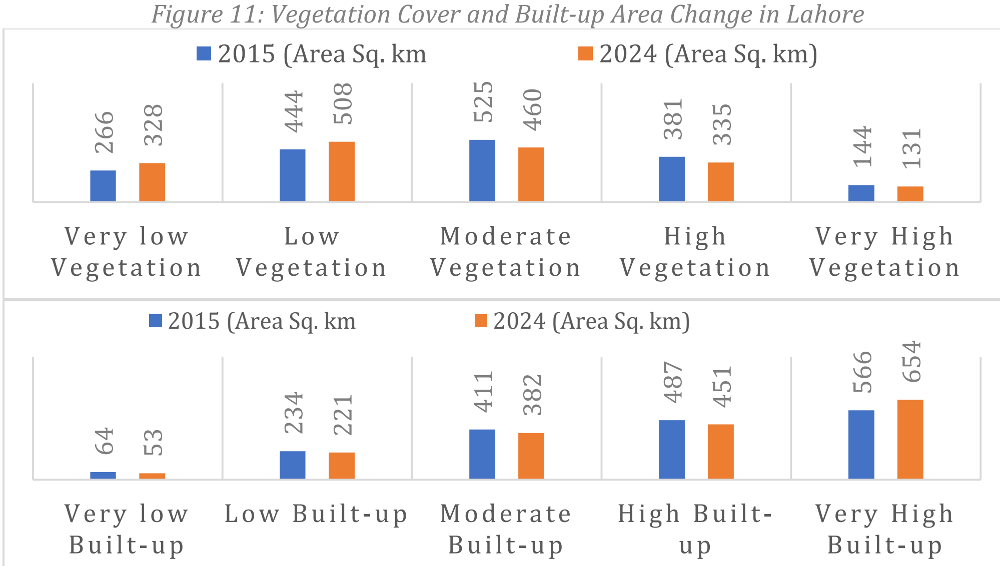
Model Fit Assessment: The measurement model shows item loadings were strong (>0.7), confirming measurement model adequacy (Annexure 10).

FINDINGS AND DISCUSSION

4.1. Dynamics of Land Surface Indices

Lahore experienced significant vegetation loss, with very high NDVI, high NDVI, and moderate NDVI categories declining from 144 km² to 131 km², 381 km² to 335 km², and 525 km² to 460 km², respectively. However, the low vegetation class expanded from 444 km² to 508 km² (Figure 11). The decline is primarily driven by rapid urbanization, infrastructural growth, and conversion of agricultural land into impervious surfaces, particularly along Ferozepur and Raiwind Road, GT Road, and Saggian Bypass (Figure 12). Though the very low vegetation class expanded by 62 km², immediate initiatives for greening, as well as emphasis on sound environmental planning, are imperative for slowing down impending natural resource deterioration and combating urban heat and air pollution effects.

Figure 11: Vegetation Cover and Built-up Area Change in Lahore

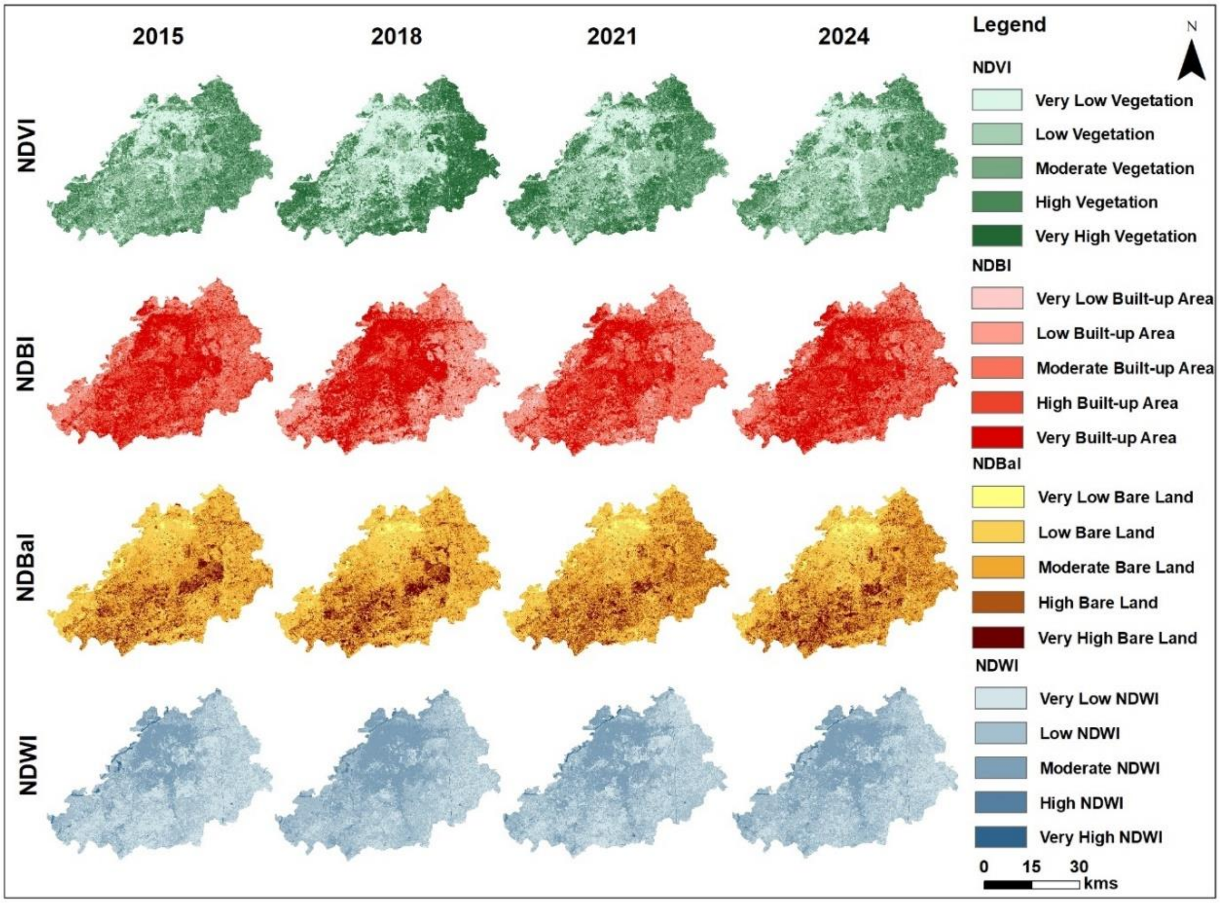


Source: Author's computations.

Built-up area has extended at the expense of vegetation cover, subsequent in a decrease in local carbon sinks (Ibrahim et al., 2012; Hussain et al., 2022). The very low (64 km²→53 km²), low (234 km² → 221 km²), moderate (411 km² → 382 km²), and high NDBI (487 km² → 451 km²) categories declined, but the very high NDBI class extended (566 km² → 654 km²). Such built-up area expansion patterns have led to green cover decreases, subsequently in increased LST and enhanced emissions (Rahaman et al., 2022). Barren land significantly increased, especially evident by enhanced NDBaI (-0.96 to -0.25), along with a decrease in NDWI (0.58 to -0.53) (Figure 12).

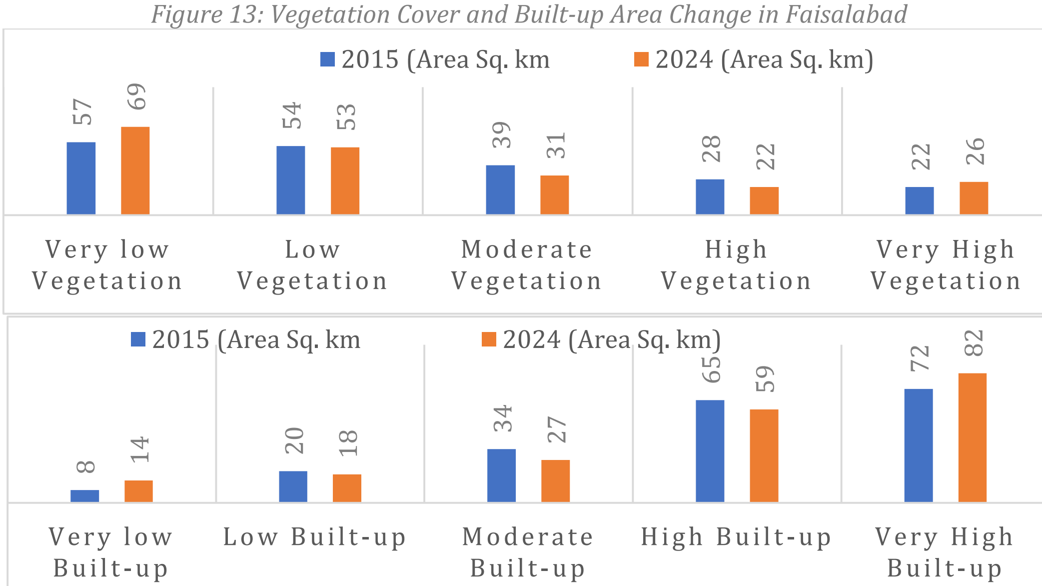
Vegetation cover in Faisalabad has declined due to natural land conversion, as the low, moderate, and high vegetation categories have shrunk from 54→53 km², 39→31 km², and 28→22 km², respectively (Figure 13). This reduction has increased UHI effects and weakened ecosystem services. However, very low vegetation increased from 57→69 km², while very high vegetation rose from 22→26 km². NDBI (-0.48 to 0.34) indicates built-up area growth, while NDBaI (-0.93 to -0.23) and NDWI (-0.59 to 0.42) reflect increasing vacant land & declining NDWI (Figure 14).

Figure 12: Spatial Pattern of Land Surface Indices of Lahore



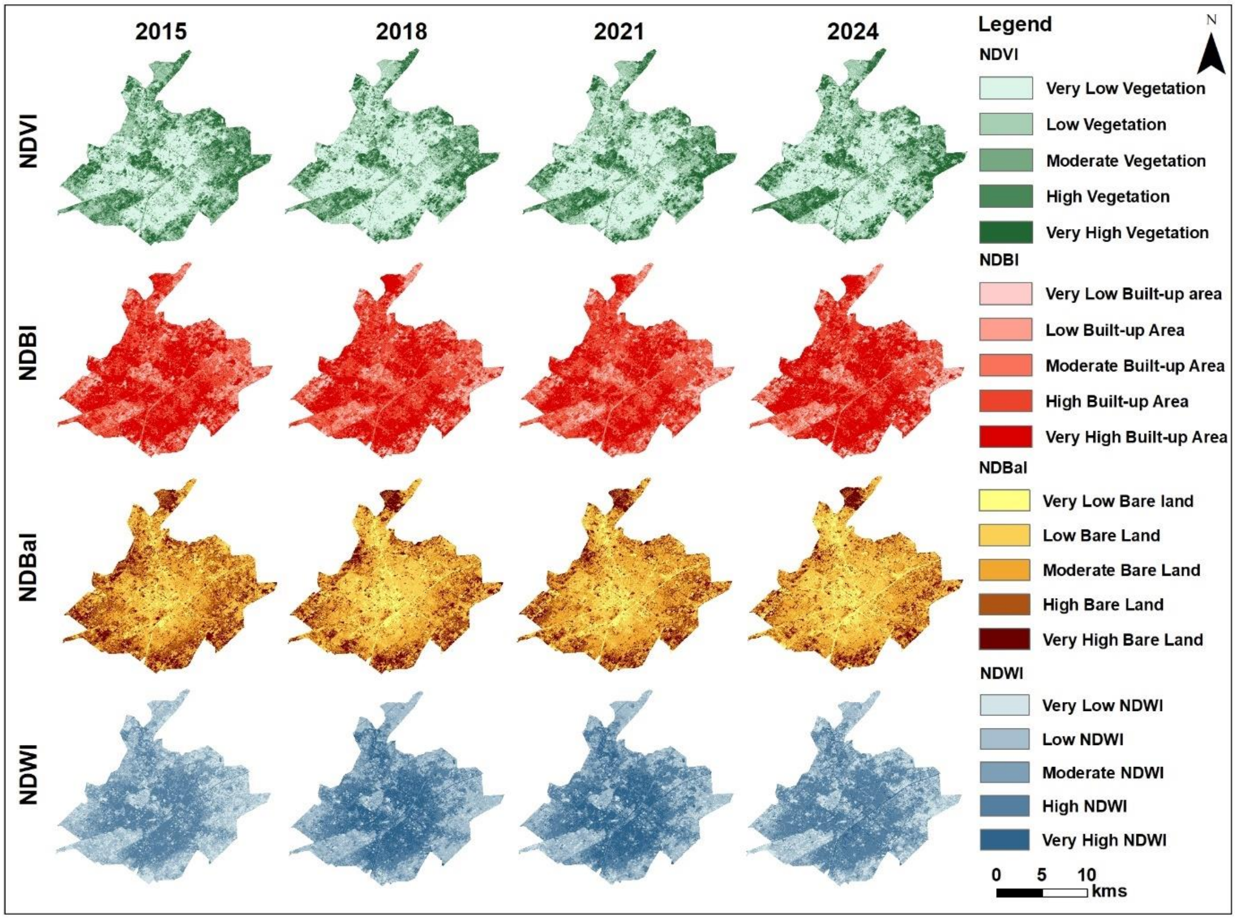
Source: Author's work.

Figure 13: Vegetation Cover and Built-up Area Change in Faisalabad



Source: Author's computations.

Figure 14: Spatial Pattern of Land Surface Indices of Faisalabad



Source: Author's work

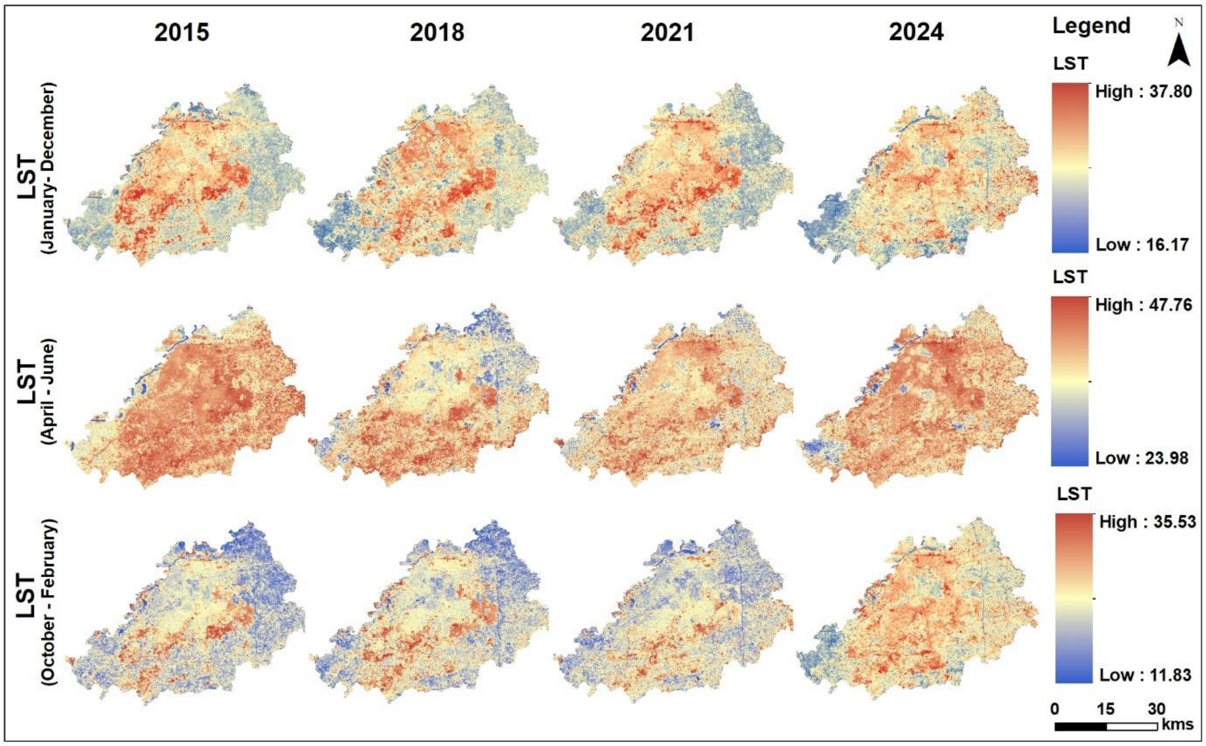
4.2. Spatio-temporal & Seasonal Patterns of LST

4.2.1. Annual & Seasonal LST of Lahore

Over the past decade, Lahore experienced rising temperatures, particularly during annual, heatwave, and smog months (Figure 15). The annual mean LST increased from 25.36 °C to 29.87 °C, reflecting a net rise of 4.51 °C. During the heatwave months, the mean LST increased by 0.73 °C from 38.75 °C to 39.47 °C, while in the smog period mean LST increased from 24.78 °C to 28.9 °C, resulting in a net rise of 4.12 °C. The widening gap between surface temperature and ground data suggests extensive conversion of vegetated land into built-up and vacant areas (Table 6).

Spatially, high LST hotspots persisted in central and southern Lahore between 2015 and 2024. High-density areas, including the Walled City, Allama Iqbal Town, Anarkali, Ferozepur Road, and Township, remained constant hotspots due to the presence of higher impervious surfaces. In contrast, vegetated cover and green spaces such as Jallo Park, Model Town Park, Punjab University and Greater Iqbal Park consistently exhibited lower LST than impervious surfaces, reflecting Urban Cool Island (UCI) effects produced by green spaces.

Figure 15: Annual and Seasonal LST of Lahore



Source: Author's work.

Table 6: LST Descriptive Statistics of Lahore

Period	Year	2015			2018			2021			2024		
		Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Annual Jan-Dec	LST	18.17	33.57	25.39	16.82	34.11	27.21	16.17	36.53	27.27	19.41	37.80	29.87
	Air Temperature	18.8	29.8	24.3	19.5	31.1	25.3	19.02	30.5	24.76	19.14	30.58	24.86
	Difference	0.63	3.77	1.09	-2.68	3.01	1.91	-2.85	6.03	2.51	0.31	7.22	5.01
Heat wave Apr-Jun	LST	22.58	46.31	38.75	23.98	41.09	34.28	23.58	43.02	34.83	23.09	47.76	39.47
	Air Temperature	24.1	36.6	26.4	25.1	37.7	31.20	24.2	36.6	30.20	24.73	38.43	31.58
	Difference	-1.52	9.71	12.34	-1.12	7.69	3.08	-0.68	6.42	4.63	-1.64	9.33	7.89
Smog Oct-Feb	LST	16.54	31.79	24.78	17.02	33.83	26.19	11.83	34.04	25.75	20.42	35.53	28.9
	Air Temperature	12.0	24.30	17.8	12.4	23.9	17.8	12.1	23.7	17.5	15.1	27.46	21.58
	Difference	4.54	7.49	6.98	5.02	9.93	8.39	-0.27	10.34	8.25	9.32	8.07	7.32

Source: Author's calculations.

During smog months, LST patterns show a marked increase associated with smog episodes and the temperature inversion phenomenon, which is persistent and traps pollutants in the near-surface atmosphere. Although green spaces such as Jallo Park, Shalimar Gardens, Jilani Park (Racecourse), Gulshan-e-Iqbal Park, and Model Town Park exhibit low LST, they provide better conditions than dense urban cores, which retain heat and, in turn, increase pollution and thermal discomfort. This pattern aligns with previous findings showing that high NO_2, CO, and SO_2 in winter contribute to the inversion-induced atmospheric stability and limit dispersion (Safarianzengir et al., 2020).

4.2.2. Annual & Seasonal LST of Faisalabad

Like Lahore, Faisalabad shows a rising and increasing trend of annual LST from 2015 to 2024. Annual mean LST increased from 26.63 °C to 32.09 °C, reflecting a noticeable warming trend of 5.46 °C. During heatwave season, the LST drastically worsened, especially after 2021. The mean LST increased from 39.74 °C to 41.16 °C, a rise of 1.42 °C, indicating the increased UHI intensity. During smog months, mean LST increased from 19.07 °C to 20.85 °C and net rose to 1.78 °C over a decade, reflecting increased night-time heat retention and persistent atmospheric inversions that trap heat and pollutants near the surface (Table 7).

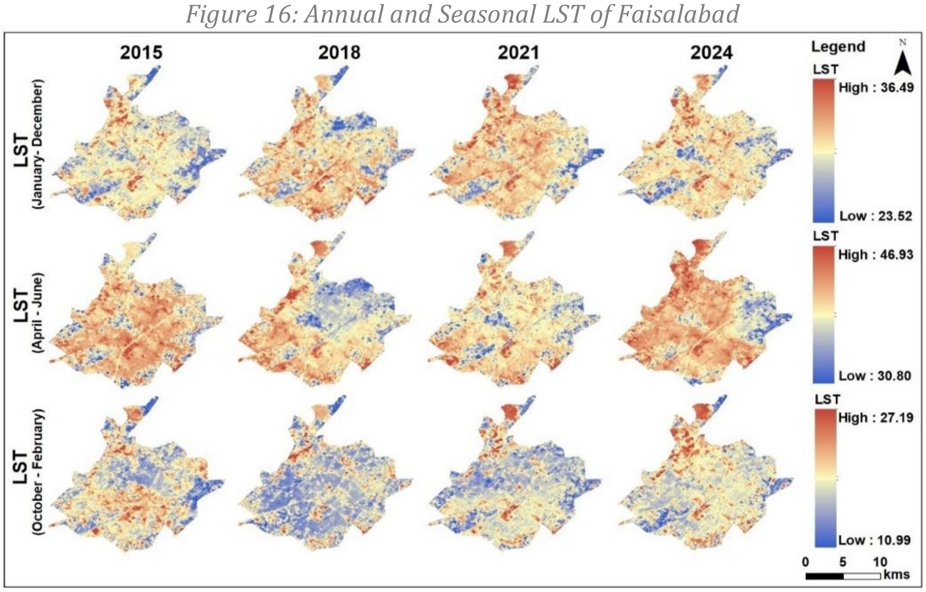
Table 7: LST descriptive Statistics of Faisalabad

Period	Year	2015			2018			2021			2024		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Annual Jan-Dec	LST	23.74	31.08	26.63	23.52	31.75	27.94	25.32	33.01	29.41	27.72	36.49	32.09
	Air Temperature	18.09	30.30	24.20	18.39	31.66	25.03	18.38	31.43	24.91	18.95	30.87	24.91
	Difference	05.65	0.79	05.23	05.11	0.09	02.91	06.94	01.58	04.50	8.77	5.62	7.18
Heat wave Apr-Jun	LST	32.70	44.79	39.74	34.15	45.15	39.74	30.80	41.27	36.11	33.55	46.93	41.16
	Air Temperature	23.53	37.13	30.33	24.47	38.07	31.27	23.26	37.27	30.27	24.4	38.76	31.58
	Difference	09.17	07.66	09.41	09.68	07.08	08.47	07.54	4.00	05.84	9.15	8.17	9.58
Smog OCT-Feb	LST	16.36	23.32	19.07	10.99	22.78	18.23	19.35	27.79	22.36	17.71	24.49	20.85
	Air Temperature	10.74	24.58	17.66	9.94	23.88	16.91	10.78	24.4	19.39	14.26	27.4	20.83
	Difference	5.62	-1.26	1.41	1.05	-1.1	1.32	8.57	3.39	2.97	2.84	-2.91	0.02

Source: Author's calculations.

Spatially, high LST concentrations were seen in the city core and along industrial areas, i.e. Sargodha, Jhang and Samundari Road, while peripheral areas and green spaces experience relatively cooler temperatures (Figure 16). In Faisalabad, LST values exceeded corresponding air temperatures, indicating faster heating of land surfaces than the overlying air. Smog-period temperatures remain below summer levels but show an upward winter-warming linked to smog.

Figure 16: Annual and Seasonal LST of Faisalabad



Source: Author's work.

4.3. Spatio-temporal Patterns of UHI

4.3.1. Annual and Seasonal UHI of Lahore

The findings showed progressive intensification and spatial expansion of the UHI effect in Faisalabad (Figure 17). Annual UHI intensity increased from 6°C in 2015 to 7 °C in 2014, with an overall increase of 1 °C, and increasing thermal stress in built-up areas. The areas included the city core, northern, and southern parts, such as Shahdara Town, Ring Road, DHA, Izmir Town, and Sundar Industrial Estate.

Table 8: UHI Phenomena Statistics of Lahore

Year	Seasons	Very Low		Low		Moderate		High		Very High	
		Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
2015	Annual	85.49	4.85	579.23	32.89	429.39	24.38	446.01	25.33	220.88	12.54
	Heatwave	30.53	1.73	250.68	14.24	448.42	25.46	717.91	40.77	313.47	17.80
	Smog	188.17	10.69	477.68	27.13	605.06	34.36	342.54	19.45	147.54	8.38
2018	Annual	118.68	6.74	472.09	26.81	477.72	27.13	455.23	25.85	237.27	13.47
	Heatwave	19.60	1.11	270.40	15.34	566.01	32.14	538.57	30.58	366.42	20.80
	Smog	194.35	11.04	453.75	25.77	617.89	35.09	340.31	19.32	154.70	8.78
2021	Annual	129.57	7.36	493.38	28.02	438.35	24.89	498.57	28.31	201.13	11.42
	Heatwave	23.32	1.84	262.38	14.90	501.95	28.50	639.96	36.34	333.40	18.93
	Smog	172.67	9.8	495.15	28.12	604.57	34.33	350.11	19.88	138.50	7.86
2024	Annual	162.67	9.24	353.92	20.10	533.82	30.31	555.66	31.55	157.93	8.97
	Heatwave	39.46	2.24	229.84	13.05	457.24	25.96	724.05	41.11	310.41	17.63
	Smog	191.78	10.89	475.40	26.99	599.71	34.06	333.33	18.93	160.78	9.1

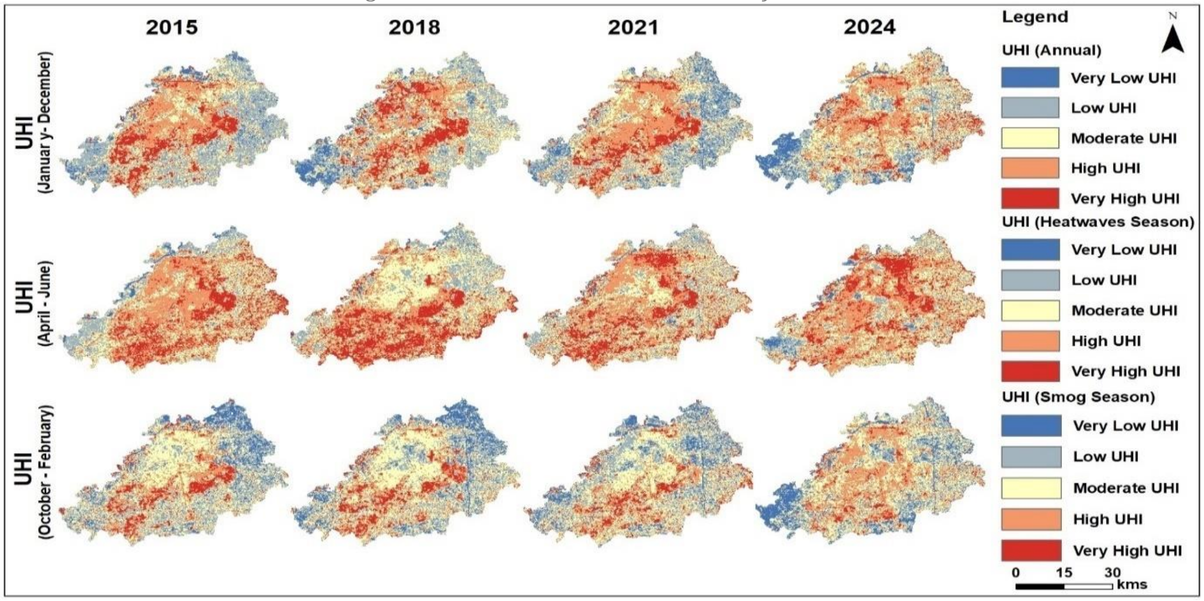
Source: Author's computation.

On the other hand, areas with vegetation and tree cover, such as the University of Punjab, Model Town Park, Bagh-e-Jinnah, and the Ravi River area, showed low UHI intensity. A slight reduction in very high UHI zones (Table 8) during 2024, as compared to 2015, may be linked to urban green initiatives, i.e. Miyawaki forests and plantation drives.

During heatwave seasons, UHI intensity increased from 3 °C to 4 °C, an increase of 1°C in intensity, reflecting increased thermal discomfort. High and very high UHI zones dominated the urban core, south-central and southeastern areas, particularly around industrial zones, the airport, Shahdara Town, and major traffic corridors. Besides, the declining extent of low-intensity UHI areas is leading to growing thermal stress.

The UHI intensity escalated to 5.33°C in 2024, indicating a 0.1°C rise in intensity from 5.23°C in 2015. Winter UHI patterns during smog months show more diffuse and generally lower intensity due to reduced solar radiation. However, persistent high UHI zones remain evident in industrial and high-traffic areas such as Sundar Industrial Estate, Gajjumata, Multan Road, Sabzazar, Kot Lakhpat, and Babu Sabu. Expansion of new housing colonies toward the periphery has shifted UHI in the outskirt areas, indicating spatial diffusion of urban warming patterns.

Figure 17: Annual and Seasonal UHI of Lahore



Source: Author's compilations

4.3.2. Annual and Seasonal UHI Patterns of Faisalabad

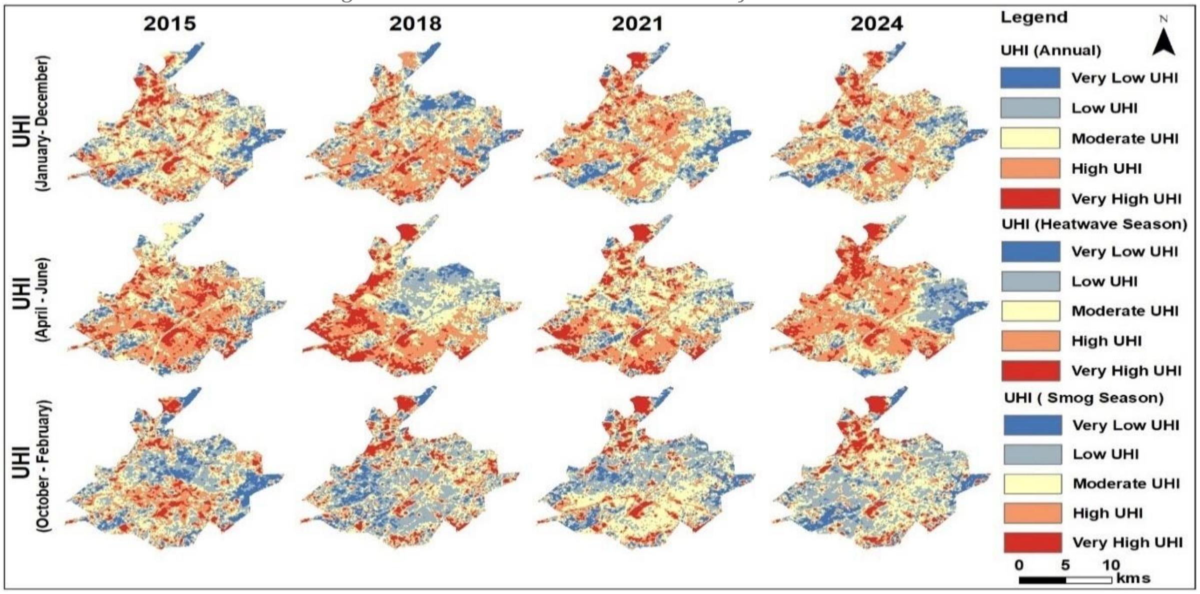
Faisalabad exhibits a UHI pattern like Lahore but with a broader spatial extent (Figure 18). High to very high UHI intensity values are concentrated in the urban core, industries, and roads such as Jhang, Samundari, Narwala and Sangla Hill Road, and the city railway station. Low vegetation areas, including People's Colony No. 2, Punjab Small Industries Estate, and Crescent Textile Mill, are thermal hotspots. In contrast, D-Ground, Jinnah Garden, and the University of Agriculture display lower UHI intensity. UHI intensity increases during heatwaves (Table 9), while during smog periods, it varies with temperature inversion, aerosol cooling, and solar radiation. Faisalabad, like Lahore, exhibits fewer extreme hotspots but an expanding area of moderate UHI.

Table 9: UHI Phenomena Statistics of Faisalabad

Year	Seasons	Very Low		Low		Moderate		High		Very High	
		Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
2015	Annual	16.76	8.31	38.50	19.08	76.06	37.70	50.37	24.97	20.06	9.94
	Heatwave	12.30	6.10	28.79	14.27	52.88	26.21	79.66	39.48	28.10	13.93
	Smog	28.20	13.98	54.92	27.22	55.95	27.73	45.60	22.60	17.07	8.46
2018	Annual	18.01	8.93	42.20	20.92	53.10	26.32	71.10	35.24	17.33	8.59
	Heatwave	7.64	3.79	41.70	20.67	55.17	27.31	61.80	30.63	35.44	17.57
	Smog	19.16	9.50	74.86	37.11	54.72	27.12	31.07	14.74	21.07	10.44
2021	Annul	18.52	9.18	34.44	17.07	62.81	31.13	69.75	34.57	16.20	8.03
	Heatwave	9.88	4.90	29.08	14.41	69.73	34.56	62.68	31.07	30.38	15.06
	Smog	22.70	11.25	59.75	29.62	70.57	34.98	29.95	14.85	18.77	9.30
2024	Annual	18.39	9.11	34.65	17.17	64.66	32.05	68.16	33.78	15.88	7.87
	Heatwave	12.18	6.04	31.15	15.44	46.29	22.94	83.94	41.60	28.94	14.34
	Smog	19.10	9.47	65.36	32.40	67.85	33.63	29.08	13.80	20.36	10.09

Source: Author's computations.

Figure 18: Annual and Seasonal UHI of Faisalabad



Source: Author's work

4.4. Ecological Evaluation Using UTFVI

4.4.1. Annual and Seasonal UTFVI of Lahore

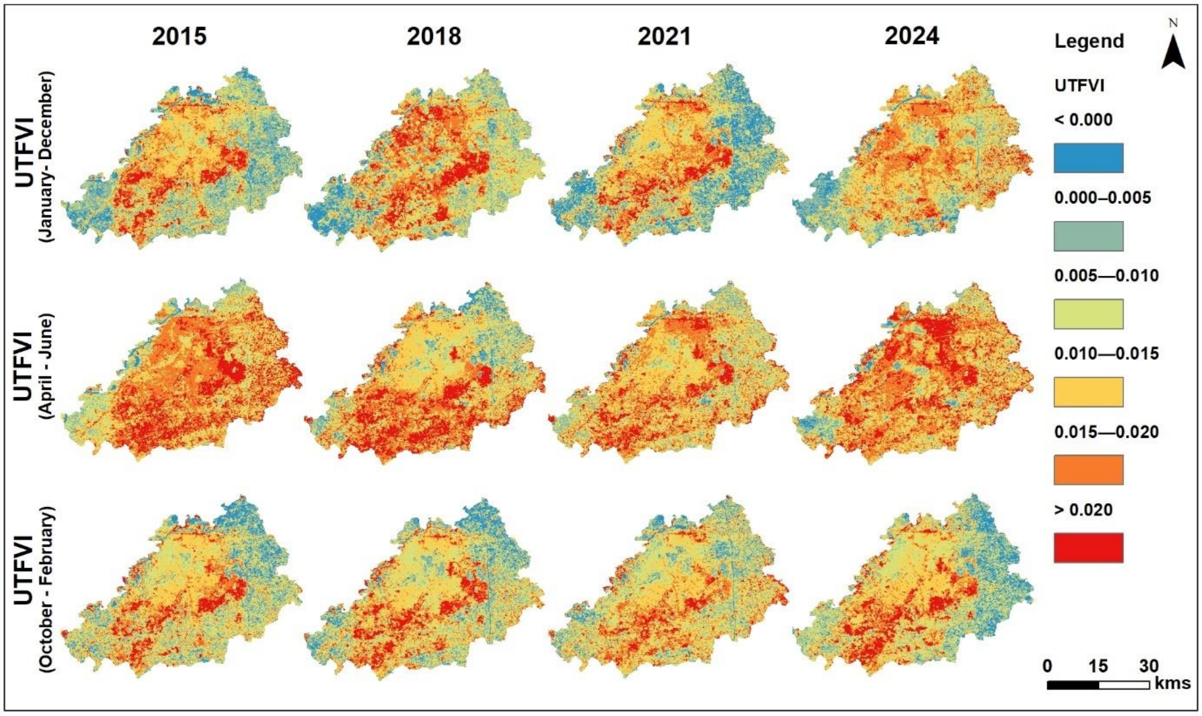
The annual UTFVI shows a rise in areas with high UTFVI values (>0.010) in the urban core and northwestern, southern, and eastern suburbs, driven by vegetation loss from urban expansion. Between 2015 & 2024, the excellent & good ecological conditions decreased from 7.4 % to 4.1 % and from 25.6 % to 15.3 %, respectively, while bad and worse conditions increased to 22.9 % to 28.2 % and 14.9 % to 24.5 %, respectively (Table 10). These trends imply impulsive urban expansion and conversion of farmland, strengthening UHI intensities and lowering ecological conditions & resilience (Figure 19).

Table 10: UTFVI Descriptive Statistics of Lahore

UTFVI		**< 0.000**		**0.000–0.005**		**0.005—0.010**		**0.010—0.015**		**0.015—0.020**		**> 0.020**	
UHI phenomenon		None		Weak		Middle		Strong		Stronger		Strongest	
Ecological Evaluation Index (EEI)		Excellent		Good		Normal		Bad		Worse		Worst	
Year	**Area**	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%
2015	Annul	130	7.4	451	25.6	387	22	404	22.9	263	14.9	126	7.2
	Heatwave	17	0.9	101	5.5	270	14.8	424	23.3	609	33.5	399	21.9
	Smog	130	7.4	327	18.6	448	25.4	471	26.7	258	14.7	127	7.2
2018	Annul	98	5.6	323	18.3	433	24.6	353	20.0	364	20.7	191	10.8
	Heatwave	60	3.4	184	10.4	333	18.9	496	28.2	411	23.3	277	15.7
	Smog	112	6.4	314	17.8	473	26.9	445	25.3	265	15.1	151	8.6
2021	Annul	239	13.6	370	21.0	355	20.2	395	22.4	274	15.6	127	7.2
	Heatwave	15	0.9	171	9.7	369	21.0	559	31.8	438	24.9	207	11.8
	Smog	69	3.9	284	16.1	493	28.0	501	28.4	302	17.1	112	6.4
2024	Annul	72	4.1	270	15.3	394	22.4	497	28.2	432	24.5	96	5.5
	Heatwave	25	1.4	117	6.6	274	15.6	451	25.6	574	32.6	319	18.1
	Smog	139	7.9	304	17.3	465	26.4	446	25.3	241	13.7	165	9.4

Source: Author's computations.

Figure 19: Ecological Conditions of Lahore



Source: Author's work

Heatwave season consistently shows strong, stronger, and strongest UTFVI conditions, drawing attention to them as the most critical periods for heat vulnerability, while smog seasons maintain predominantly middle to strong UTFVI conditions. This indicates persistent but comparatively moderate stress induced by atmospheric stagnation and urban heat retention.

4.4.2. Annual and Seasonal UTFVI of Faisalabad

The thermal discomfort in Faisalabad showed an increasing trend through the bad and worse conditions (Table 11). Bad to Worst UTFVI conditions concentrated in built-up, industrial and traffic zones, including Dare Ahsan Town, Jilani Pura, and Textile mills. Excellent ecological conditions persisted mainly in agricultural fields, green space and the University of Agriculture, reflecting vegetation's moderating effect on lowering heat stress (Figure 20).

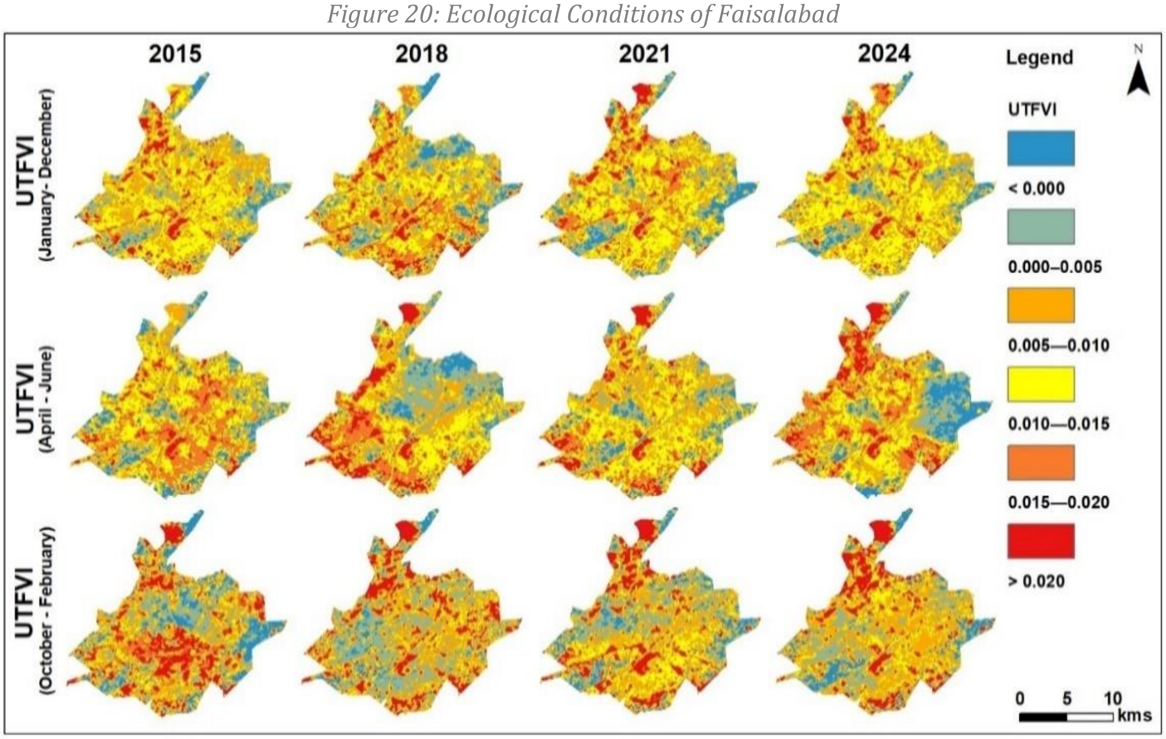
Figure 20 shows that during heatwaves, most of the dense urban cores, roads, and industrial estates, including Allama Iqbal Colony, Madinah Town, and Crescent Textile Mill, showed extreme thermal stress, while parks like Jinnah Garden and D-Ground retained comfort zones. Excellent and good EEI zones are decreasing in the smog period, while excellent and good zones show an increasing trend in annual and heatwave seasons. The bad conditions have increased annually, particularly during smog months, due to air pollution and temperature inversions (Table 11).

Table 11: UTFVI Descriptive Statistics of Faisalabad

UTFVI		< 0.000		0.000–0.005		0.005—0.010		0.010—0.015		0.015—0.020		> 0.020	
UHI phenomenon		None		Weak		Middle		Strong		Stronger		Strongest	
Ecological Evaluation Index (EEI)		Excellent		Good		Normal		Bad		Worse		Worst	
Year	**Area**	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
2015	Annual	08	3.98	25	12.43	54	26.86	71	35.32	30	14.93	13	6.47
	Heatwave	15	7.46	23	11.44	40	19.90	61	30.35	53	26.37	09	4.48
	Smog	22	10.89	37	18.32	38	18.81	34	16.83	38	18.81	33	16.34
2018	Annual	14	6.89	29	14.29	42	20.69	58	28.57	46	22.66	14	6.89
	Heatwave	13	6.44	36	17.82	42	20.79	48	23.76	42	20.79	21	10.39
	Smog	09	4.46	50	24.75	52	25.74	34	16.83	26	12.87	31	15.35
2021	Annual	14	6.93	24	11.88	40	19.80	70	34.65	41	20.29	13	6.44
	Heatwave	11	5.47	24	11.94	53	26.37	64	31.84	34	16.92	15	7.46
	Smog	16	7.92	37	18.32	51	25.25	44	21.78	26	12.87	28	13.86
2024	Annual	09	4.5	23	11.5	45	22.5	82	41	32	16	09	4.5
	Heatwave	22	10.38	35	16.51	28	13.21	52	24.52	55	25.94	20	9.43
	Smog	13	6.44	32	15.84	63	31.19	41	20.29	25	12.38	28	13.86

Source: Author's computations

Figure 20: Ecological Conditions of Faisalabad



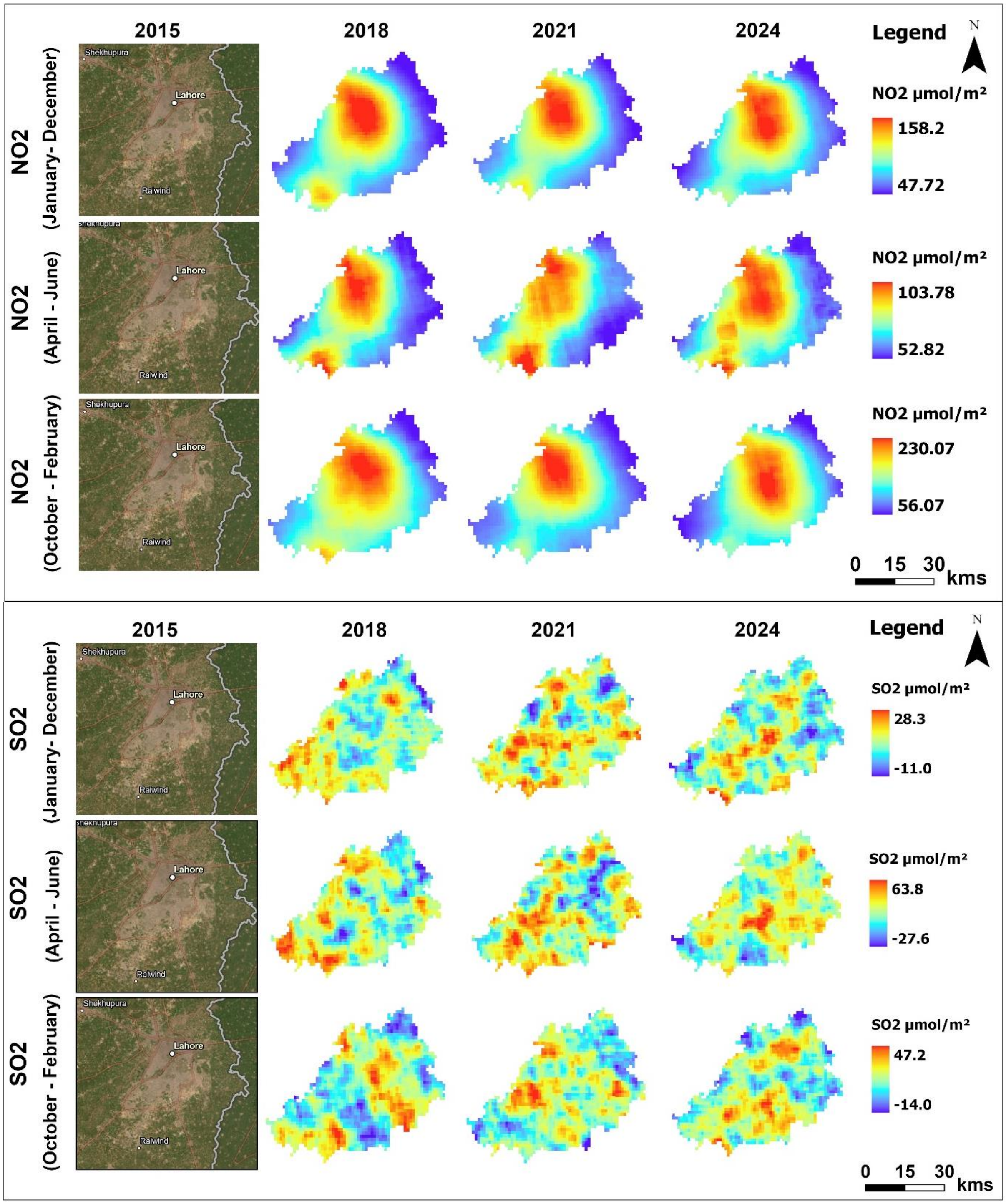
Source: Author's work.

4.5. Spatio-temporal Patterns of Air Pollution

4.5.1. NO_2 & SO_2 Concentration in Lahore

Temporally, NO_2 peaks in 2021 across all periods (annual, heatwave, smog), followed by a decline by 2024, although the concentration level remained elevated in 2018. In contrast, SO_2 increases slightly over time under high conditions annually and heatwave periods but drops sharply under smog conditions by 2024 (Figure 21).

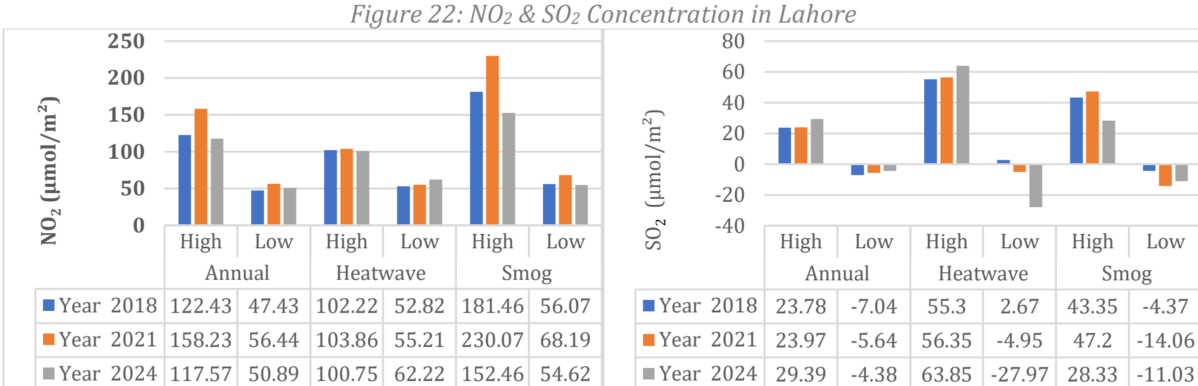
Figure 21: Spatial Distributions of NO_2 and SO_2 in Lahore



Source: Author's work.

SO_2 levels declined during the 2024 smog season, potentially reflecting the impact of control measures such as the Green Lockdown. Spatial patterns of both pollutants are not similar as NO_2 concentrated in the centre of Lahore, while SO_2 has small patches primarily over industrial zones, i.e. Sundar Industrial Estate near Raiwind Tehsil at south side, indicating several SO_2 generating sources (Figure 22).

Figure 22: NO_2 & SO_2 Concentration in Lahore



	High	Low	High	Low	High	Low
	Annual		Heatwave		Smog	
Year 2018	122.43	47.43	102.22	52.82	181.46	56.07
Year 2021	158.23	56.44	103.86	55.21	230.07	68.19
Year 2024	117.57	50.89	100.75	62.22	152.46	54.62

	High	Low	High	Low	High	Low
	Annual		Heatwave		Smog	
Year 2018	23.78	-7.04	55.3	2.67	43.35	-4.37
Year 2021	23.97	-5.64	56.35	-4.95	47.2	-14.06
Year 2024	29.39	-4.38	63.85	-27.97	28.33	-11.03

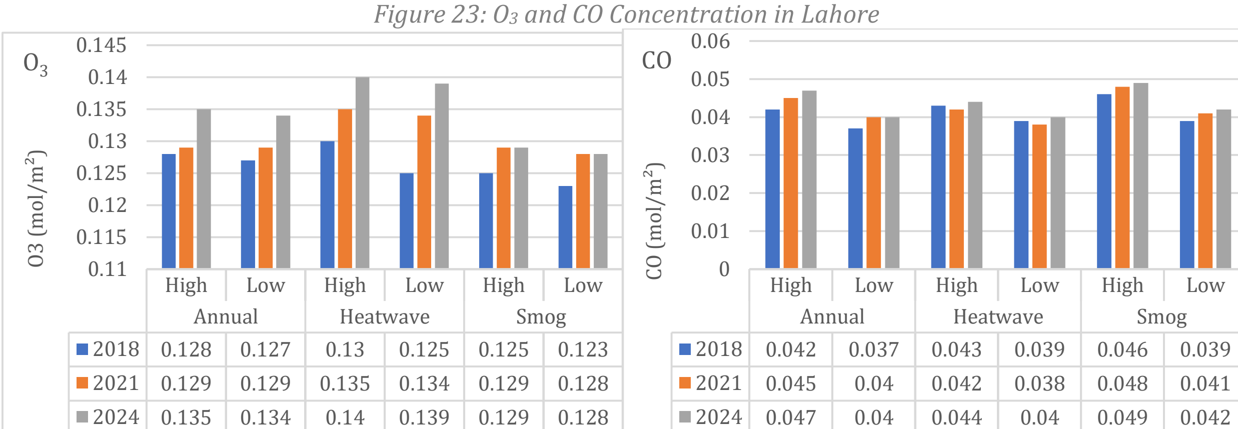
Source: Author's computations

4.5.2. O_3 & CO Concentration in Lahore

O_3 exhibits a steady upward temporal trend from 2018 to 2024, with the strongest increases during heatwave conditions, while smog-related levels remain relatively stable, indicating a limited role of O_3 in smog formation in Lahore. In contrast, CO increases gradually across all periods (Annual, Heatwave and Smog), with consistently higher concentrations in 2024, particularly under high annual and smog conditions, indicating a persistent temporal rise (Figure 23-24).

As per spatial distribution, the concentration of O_3 in Lahore exhibits a distinct north-south trend since 2018, with higher and gradually increasing levels in the northern part. In contrast, CO levels, which remain highest in the city center, particularly during October and February, are due to the influence of cold air masses and inversion phenomena. These spatial variations highlight distinct priority areas for targeted health intervention (Figure 23).

Figure 23: O_3 and CO Concentration in Lahore

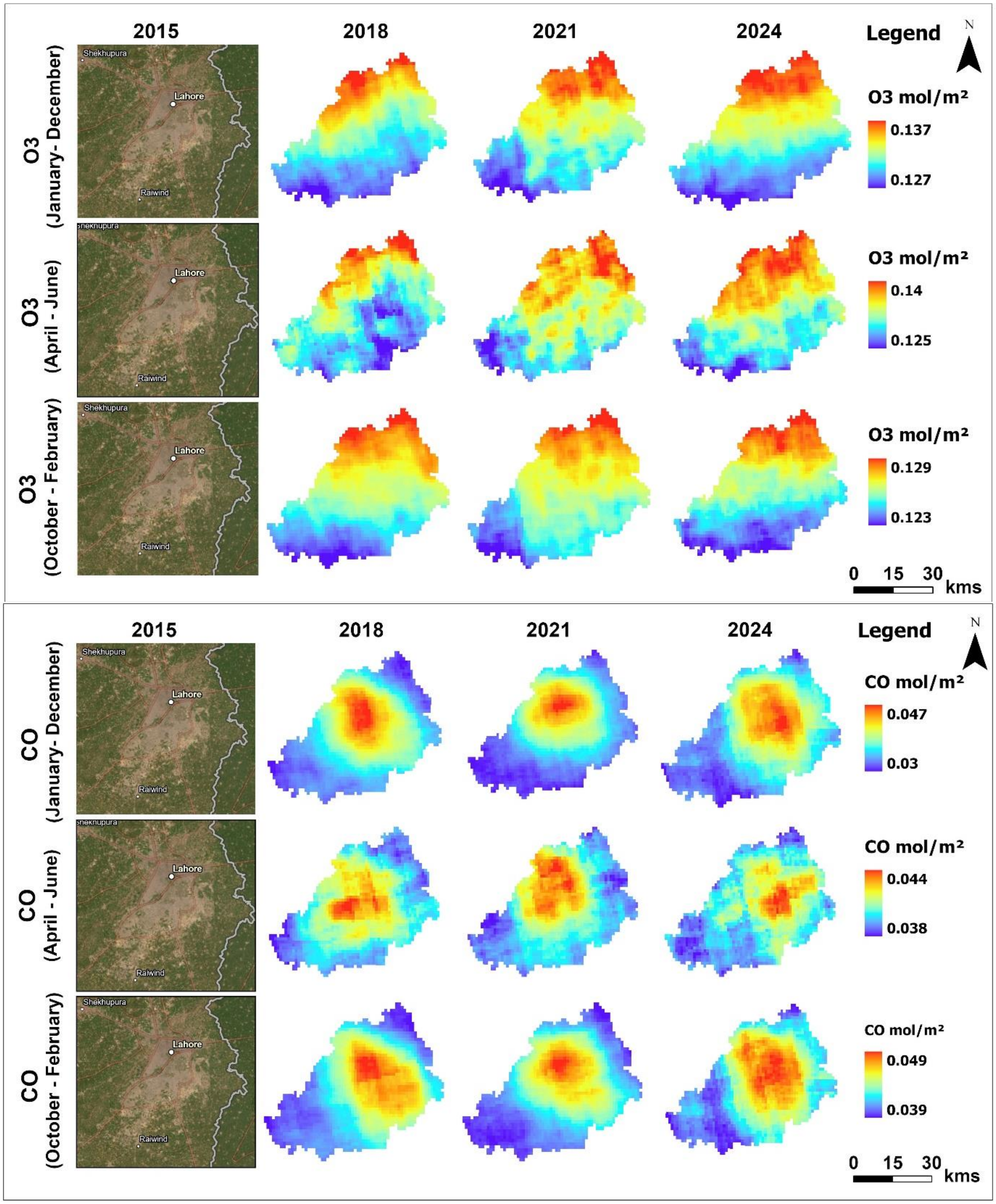


	High	Low	High	Low	High	Low
	Annual		Heatwave		Smog	
2018	0.128	0.127	0.13	0.125	0.125	0.123
2021	0.129	0.129	0.135	0.134	0.129	0.128
2024	0.135	0.134	0.14	0.139	0.129	0.128

	High	Low	High	Low	High	Low
	Annual		Heatwave		Smog	
2018	0.042	0.037	0.043	0.039	0.046	0.039
2021	0.045	0.04	0.042	0.038	0.048	0.041
2024	0.047	0.04	0.044	0.04	0.049	0.042

Source: Author's computations.

Figure 24: Spatial Distributions of O_3 & CO in Lahore

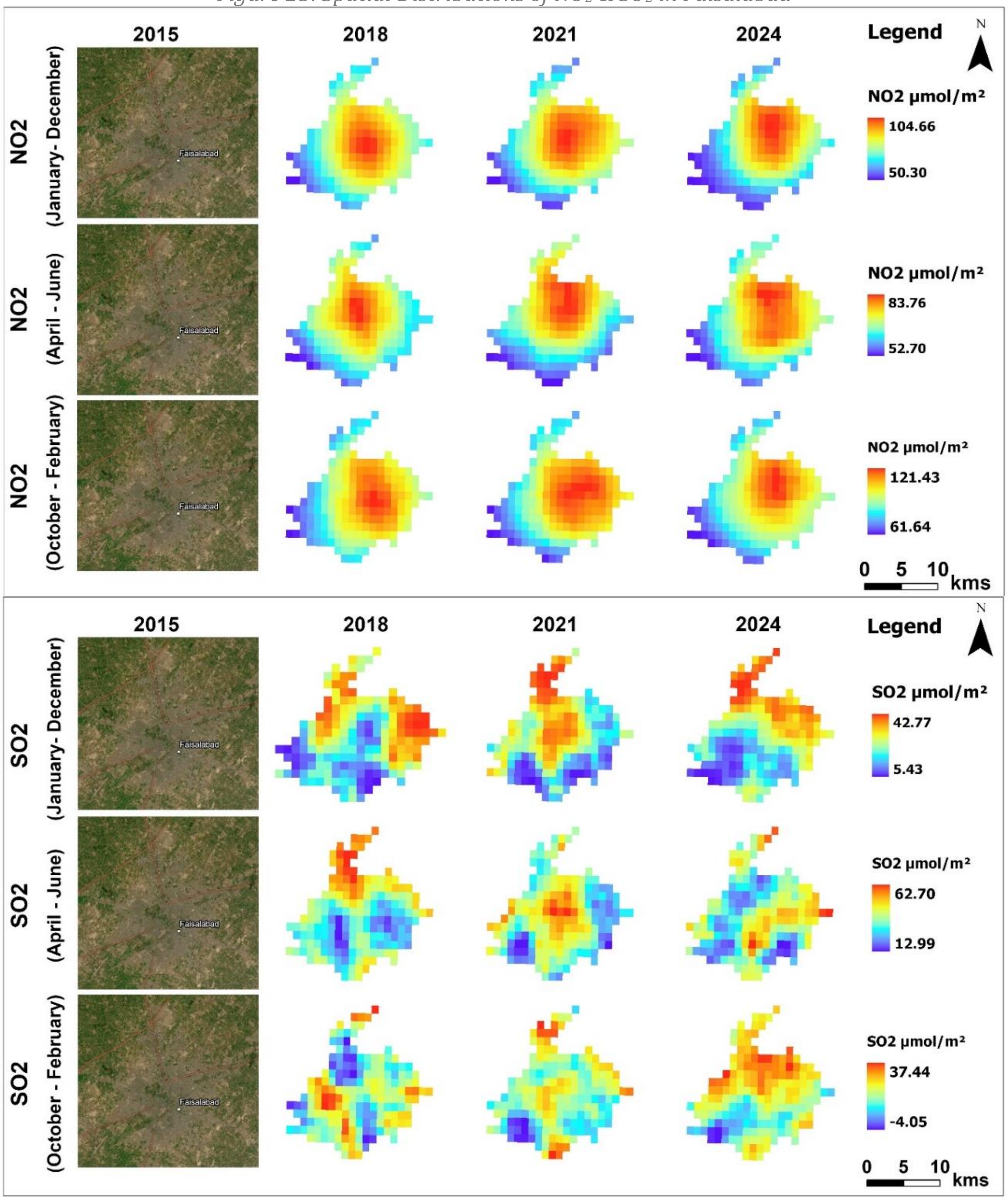


Source: Author's work

4.5.3. NO_2 & SO_2 Concentration in Faisalabad

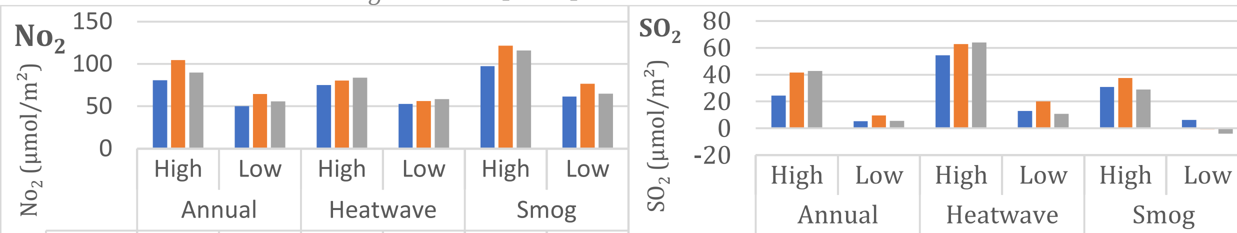
Temporally, both NO_2 and SO_2 exhibit higher concentrations (Figure 25). The NO_2 increased across all three periods from 2018 to 2024, while SO_2 rose in the annual and heatwave periods, but declined in the 2024 smog season. Central urban areas remain NO_2 pollution hotspots reflecting persistent vehicles and industrial emissions. In comparison, SO_2 levels were leading in central and eastern areas, with a seasonal peak in the north and southeastern zones. The peripheral and southwestern parts show lower levels, mainly due to weaker emission intensity (Figure 26).

Figure 25: Spatial Distributions of NO_2 & SO_2 in Faisalabad



Source: Author's work.

Figure 26: NO_2 & SO_2 Concentration in Faisalabad



	Annual High	Annual Low	Heatwave High	Heatwave Low	Smog High	Smog Low
2018	80.86	50.3	74.95	52.7	97.42	61.64
2021	104.66	64.52	80.48	56.34	121.43	76.67
2024	89.84	55.87	83.76	58.36	115.85	64.95

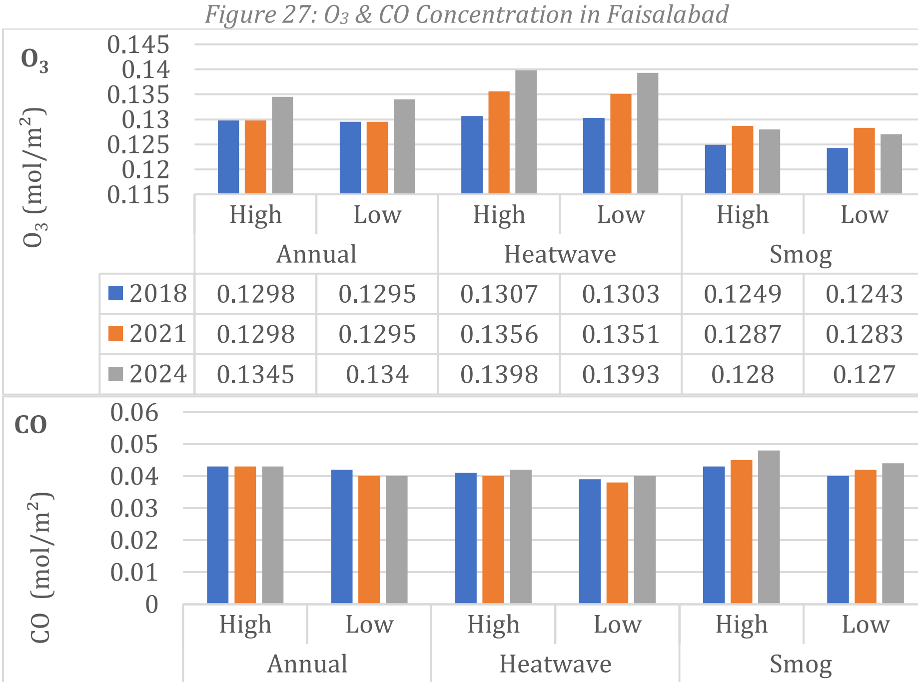
	Annual High	Annual Low	Heatwave High	Heatwave Low	Smog High	Smog Low
2018	24.39	5.43	54.43	12.99	30.75	6.27
2021	41.46	9.72	62.7	20.16	37.44	-0.66
2024	42.7	5.66	64.01	10.77	28.91	-4.05

Source: Author's computations.

4.5.4. O_3 & CO Concentrations in Faisalabad

From 2018 to 2024, O_3 shows a gradual increase, with higher concentrations during heatwaves and slightly lower levels during smog periods, indicating a limited role in smog formation. Comparatively, CO remains relatively stable over time, but increases by 2024, particularly under high smog conditions (Figure 27). In Faisalabad, ozone levels are consistently high in the northern parts, medium in central regions, and low in the southern parts of the city, with similar patterns during heatwave and smog periods. CO concentrations are highest in the central and northeastern areas (Figure 28).

Figure 27: O_3 & CO Concentration in Faisalabad

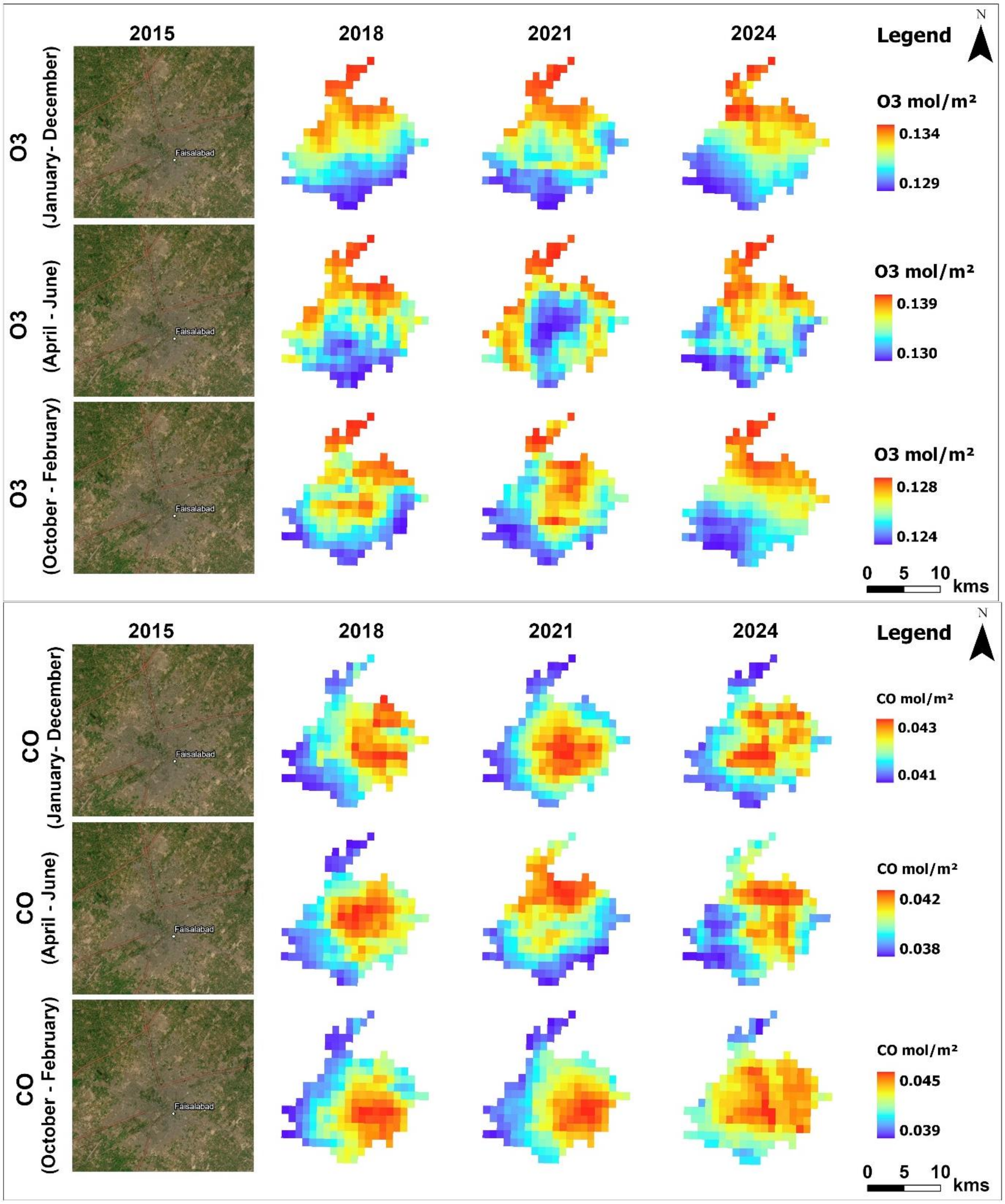


	Annual High	Annual Low	Heatwave High	Heatwave Low	Smog High	Smog Low
2018	0.1298	0.1295	0.1307	0.1303	0.1249	0.1243
2021	0.1298	0.1295	0.1356	0.1351	0.1287	0.1283
2024	0.1345	0.134	0.1398	0.1393	0.128	0.127

	Annual High	Annual Low	Heatwave High	Heatwave Low	Smog High	Smog Low
2018	0.043	0.042	0.041	0.039	0.043	0.04
2021	0.043	0.04	0.04	0.038	0.045	0.042
2024	0.043	0.04	0.042	0.04	0.048	0.044

Source: Author's computations.

Figure 28: Spatial Distributions of O_3 and CO in Faisalabad



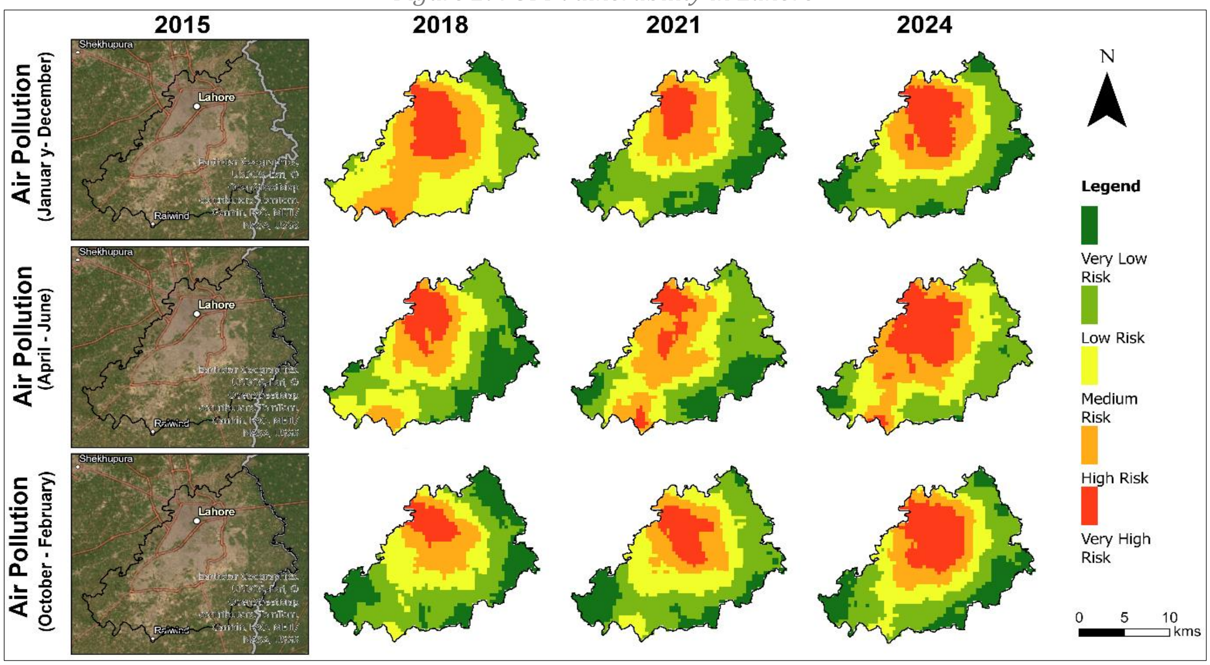
Source: Author's work

4.6. Urban Pollution Islands in Lahore and Faisalabad

The UPI reveals a concentrated air pollution risk in the urban core that gradually declines towards the periphery (Figure 29). In 2018, high to very high-risk areas were concentrated around central

Lahore, especially around Lahore city, which spreads across both the annual and smog seasons. The periphery consistently exhibited low to moderate risk. In 2021, pollution intensity decreased slightly, especially in the outskirts of the city, likely due to lower mobility and industrial activity during the COVID-19 period (Table 12). However, despite this, the core area remained a high-risk zone. Throughout the years, winter showed the highest pollution risk due to increased emissions and temperature inversion that limits dispersion, whereas summer conditions favored greater atmospheric mixing, especially in the peripheral areas.

Figure 29: UPI Vulnerability in Lahore



Source: Author's work

By 2024, high-risk UPI zones extended beyond central Lahore into southern and western sectors, particularly during winter and in annual pollution level measurements. Several peripheral zones shifted from low to medium risk, indicating a gradual outward diffusion of air pollution. Overall, UPI indicates a stable yet expanding air pollution footprint strongly shaped by urban structure and seasonal meteorological conditions.

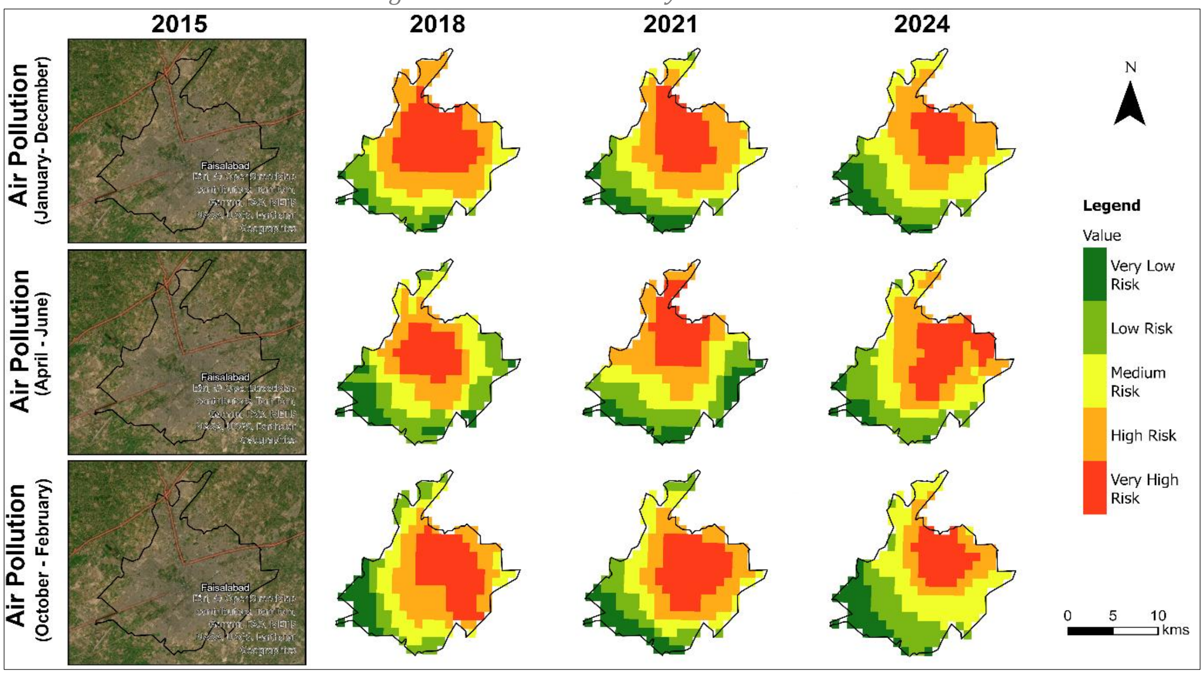
Table 12: UPI Vulnerable Area in Lahore

Year	Period	Very Low Risk	Low Risk	Medium Risk	High Risk	Very high Risk
2019	Annual	77.8	271.8	598.3	527.3	286.3
	Heatwave	333.3	500.8	467.5	279.5	180.3
	Smog	541.9	700.8	470.9	318.8	149.6
2021	Annual	401.7	580.3	333.3	313.7	132.5
	Heatwave	276.1	544.4	359.8	443.6	137.6
	Smog	270.1	596.6	451.3	268.4	175.2
2024	Annual	253.0	628.2	329.9	279.5	270.9
	Heatwave	53.0	518.8	409.4	406.8	373.5
	Smog	328.2	517.9	344.4	261.5	309.4

Source: Author's computations.

The air pollution risk maps of Faisalabad expose spatial-temporal variations during heatwave and smog periods (Figure 30). From 2018 to 2024, areas classified as "Medium Risk" increased, indicating gradual air quality deterioration. Pollution risk peaked around 2018, with severe conditions during heatwaves and smog months, followed by a slight improvement by 2021 and 2024, reflected in a reduction in "Very High Risk" zones (Table 13). Nevertheless, heatwave months in 2024 remain a concern due to climatic extremes and anthropogenic pressures. Spatially, central and northern urban–industrial zones persist as dominant pollution hotspots.

Figure 30: UPI Vulnerability in Faisalabad



Source: Author's work.

Table 13: UPI Vulnerable Areas in Faisalabad

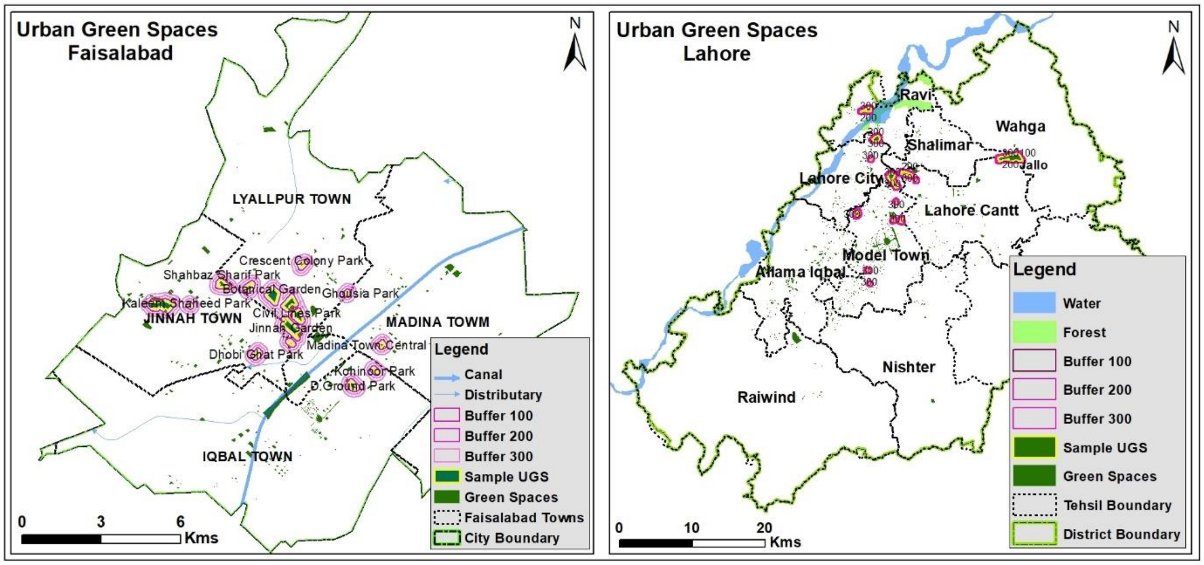
Year	Period	Very Low Risk	Low Risk	Medium Risk	High Risk	Very high Risk
2019	Annual	10.1	26.8	31.8	68.7	63.7
	Heatwave	23.5	48.6	47.7	45.2	36.0
	Smog	20.1	26.0	41.9	58.6	54.4
2021	Annual	20.1	27.6	42.7	63.7	46.9
	Heatwave	26	43.6	39.4	51.9	40.2
	Smog	23.5	28.5	41.0	53.6	54.4
2024	Annual	20.9	31.8	55.3	63.7	29.3
	Heatwave	10.1	42.7	41.9	57	48.6
	Smog	27.6	41.0	64.5	34.3	33.5

Source: Author's computations.

4.7. Urban Green Spaces effects on LST and Air Pollution

The historic parks and gardens of Lahore offer crucial cooling and air quality benefits, but the green cover of this city remains critically low (Figure 31). The city contains only 32 km^2 of green area (1.8 % of 1,772 km^2), including parks (24.3 km^2) and forests (7.7 km^2), equating to only 0.2 ha per 1,000 inhabitants, which is well below WHO standards. Although 65% of residents live within 400 m of green areas, effective accessibility is limited, with only 2.8% within a five-minute walking distance. This demonstrates an urgent need for expanding UGS in both cities.

Figure 31: Spatial Distribution & Selected UGS for UCI

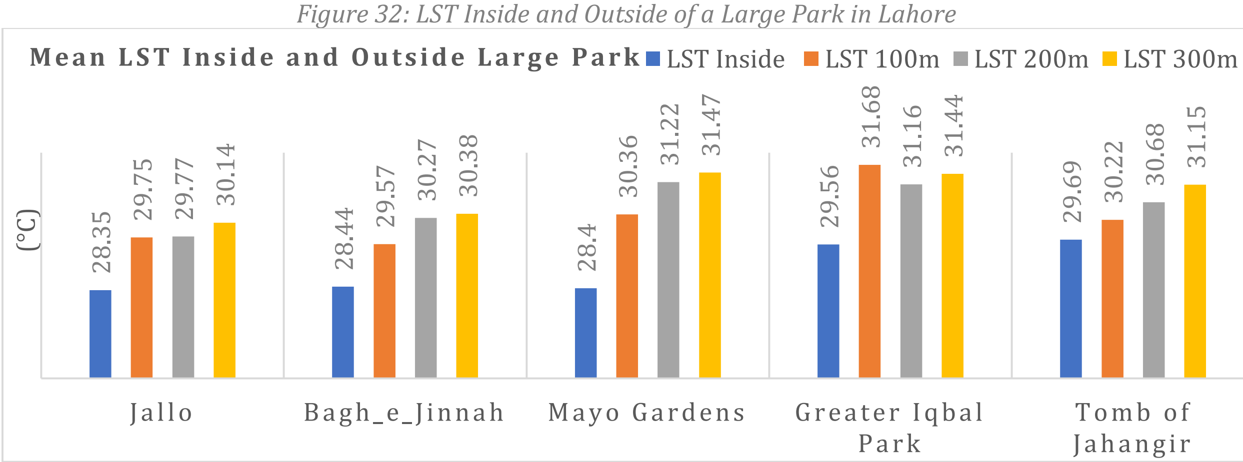


Source: Author's work

4.7.1. Cooling Effect of Large Parks in Lahore

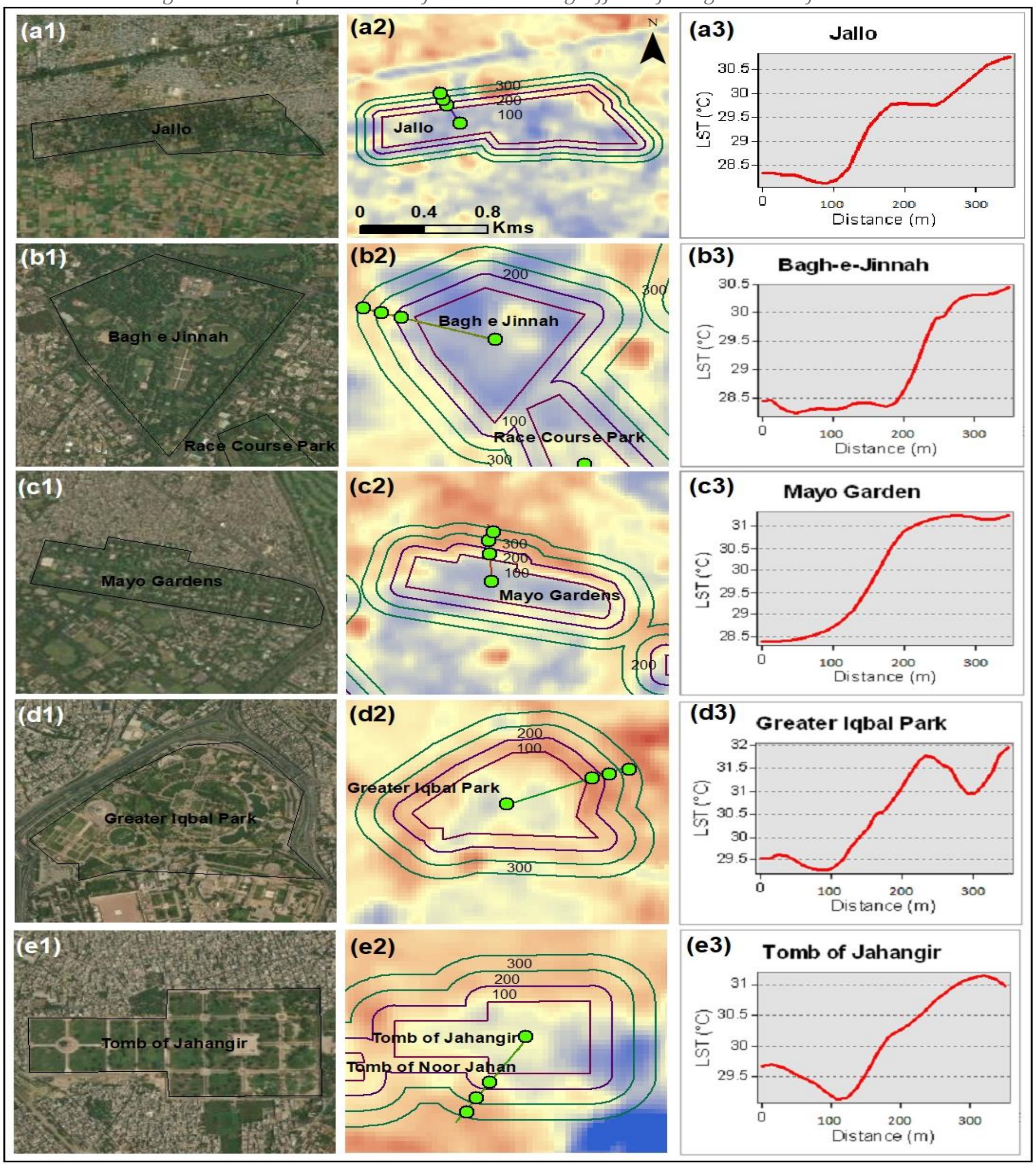
The large parks in Lahore function as efficient cooling islands, substantially reducing LST. The rate of cooling is maximum at the center of the park and decreases with distance up to 100-300 m buffer zones (Figure 32). The Jallo Botanical Garden has the largest effect owing to its size and vegetation, while Bagh-e-Jinnah and other centrally located parks have sharp decreases in cooling, which can be attributed to their high surrounding built-up areas. The Mayo Gardens, Greater Iqbal Park, and Tomb of Jahangir have been observed to have localized cooling effects. Park connectivity helps in increasing this effect, emphasizing the importance of linked large green areas to counteract UHI (Figure 33).

Figure 32: LST Inside and Outside of a Large Park in Lahore



Source: Author's computations.

Figure 33: Temperature Profile and Cooling Effect of Large Parks of Lahore

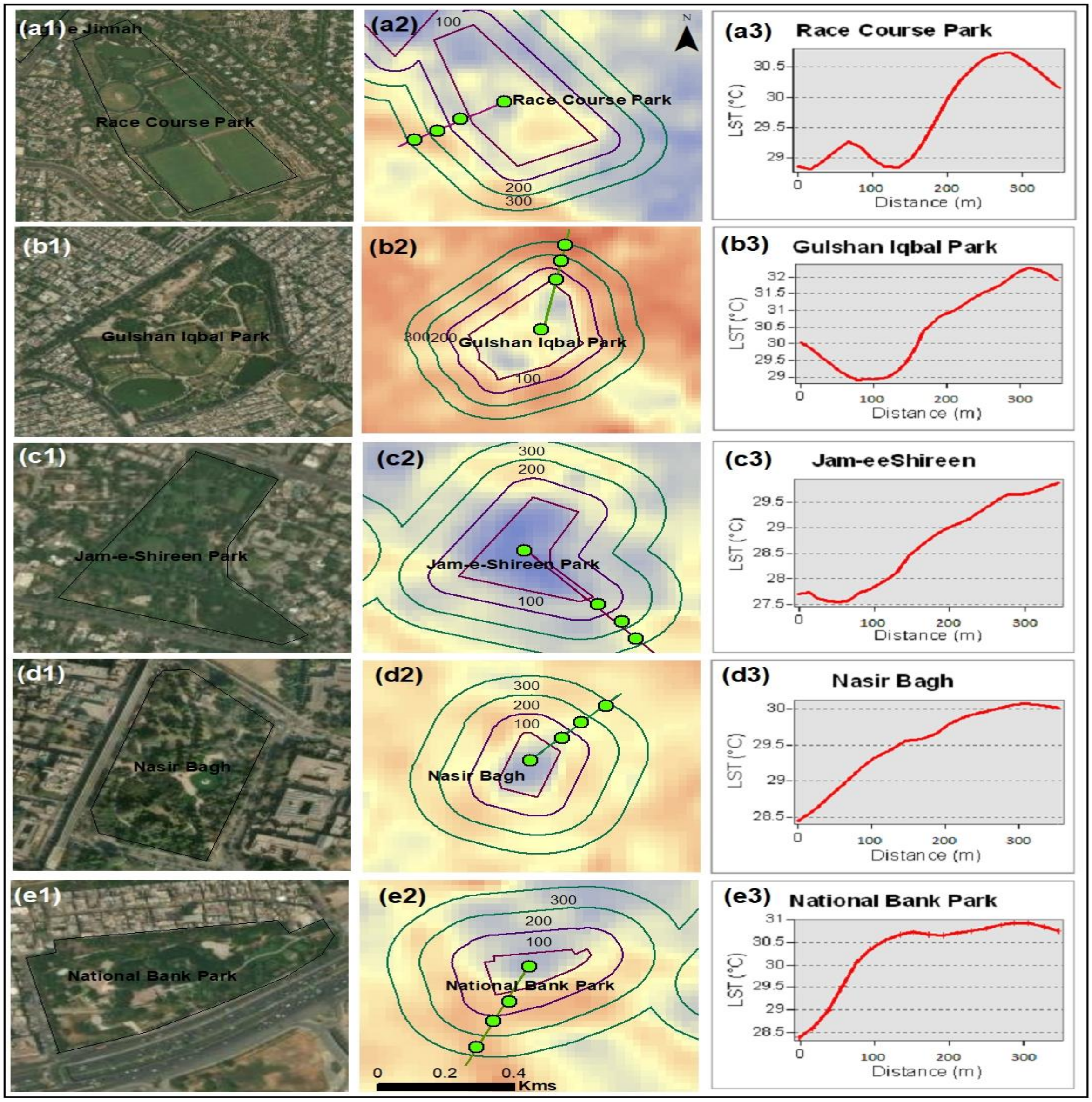


Source: Author's work

4.7.2. Cooling Effect of Medium Parks in Lahore

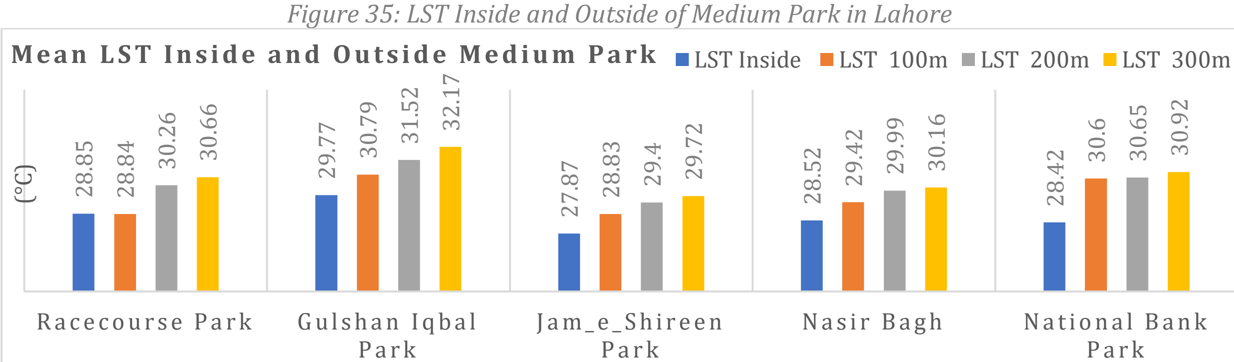
Medium-sized parks also influence urban cooling considerably, ranging up to 300 m (Figure 34). Racecourse and Gulshan Iqbal Parks demonstrate the minimum LST at their center. This increases steadily up to the surrounding built-up areas. Jam-e-Shireen Park provides cooling at a greater intensity because of dense tree canopy, while Nasir Bagh has a lower extending cooling effect due to surrounding congested traffic corridors. Overlapping buffers demonstrate their effectiveness in cooling at the neighborhood scale (Figure 35).

Figure 34: Temperature Profile and Cooling Effect of Medium Parks of Lahore



Source: Author's work.

Figure 35: LST Inside and Outside of Medium Park in Lahore

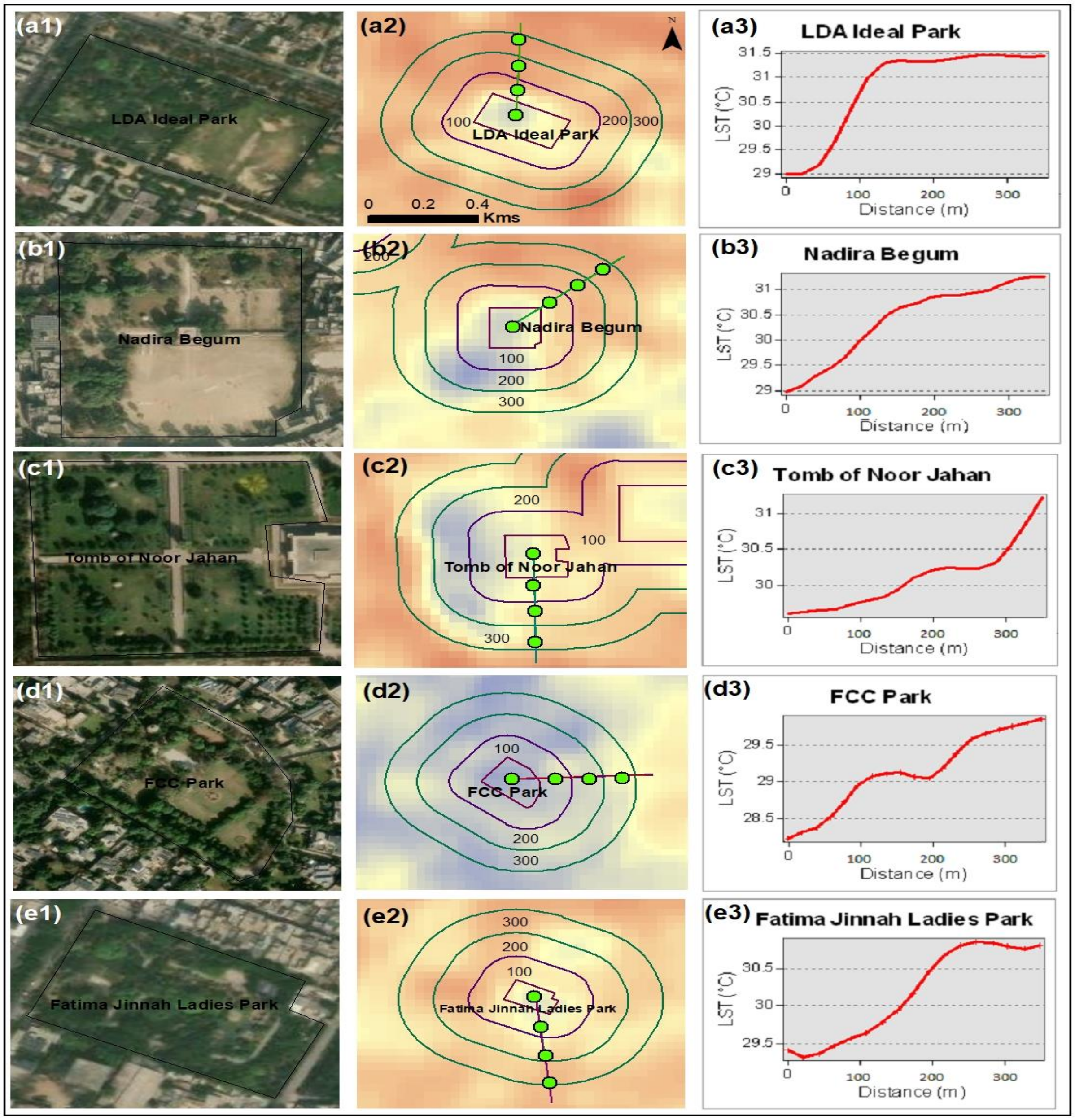


Source: Authors' compilations

4.7.3. Cooling Effect of Small Parks in Lahore

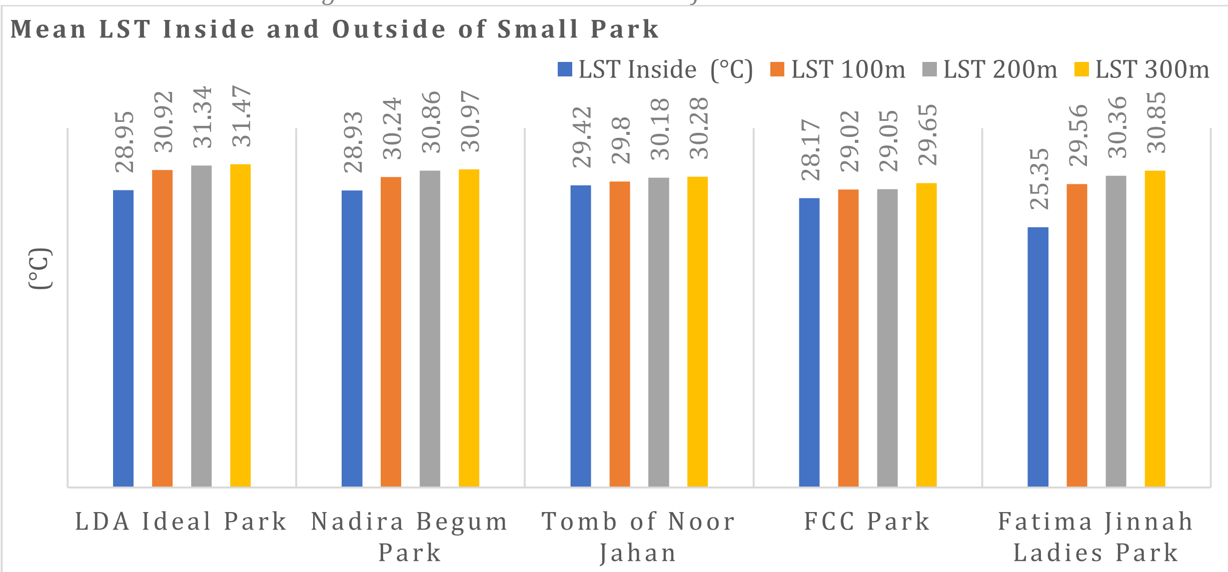
Small parks provide localized but meaningful cooling, particularly within 100 m (Figure 36). Sites such as LDA Ideal Park, Nadira Begum Park, FCC Park, Fatima Jinnah Ladies Park, and the Tomb of Noor Jahan maintain lower internal temperatures, with LST increasing toward 300 m. Dense tree cover enhances cooling despite limited size, while fragmented vegetation limits effectiveness. The observed cooling gradients highlight the need for evenly distributed green spaces to improve urban thermal comfort and resilience (Figure 37).

Figure 36: Temperature Profile and Cooling Effect of Small Parks of Lahore



Source: Author's work.

Figure 37: LST Inside and Outside of Small Park in Lahore

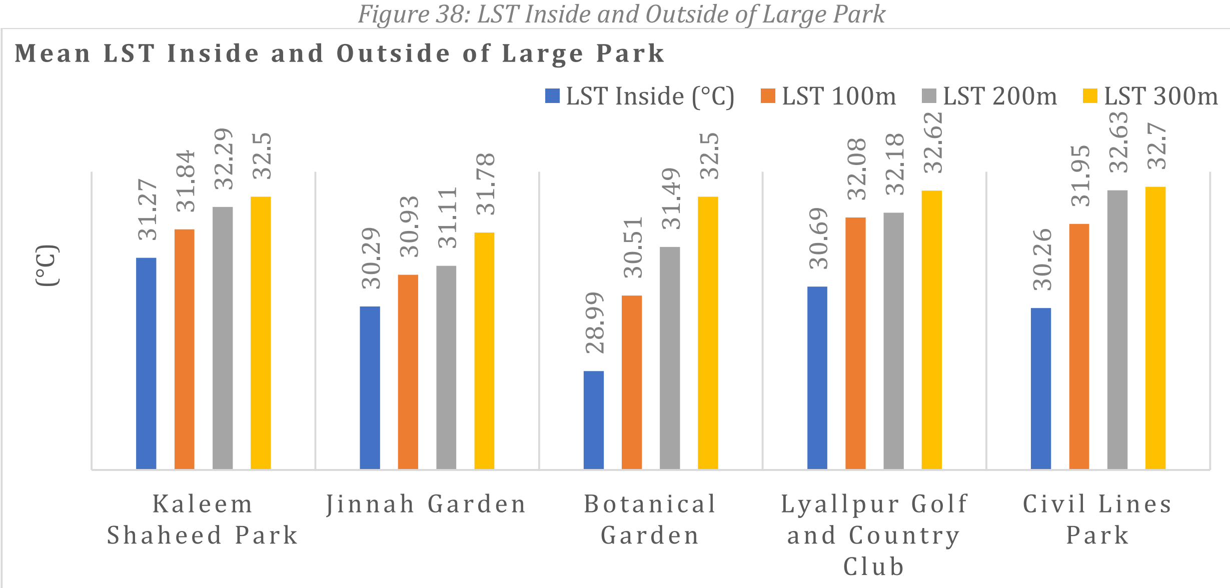


Source: Authors' compilations

4.7.4. Cooling Effect of Large Parks in Faisalabad

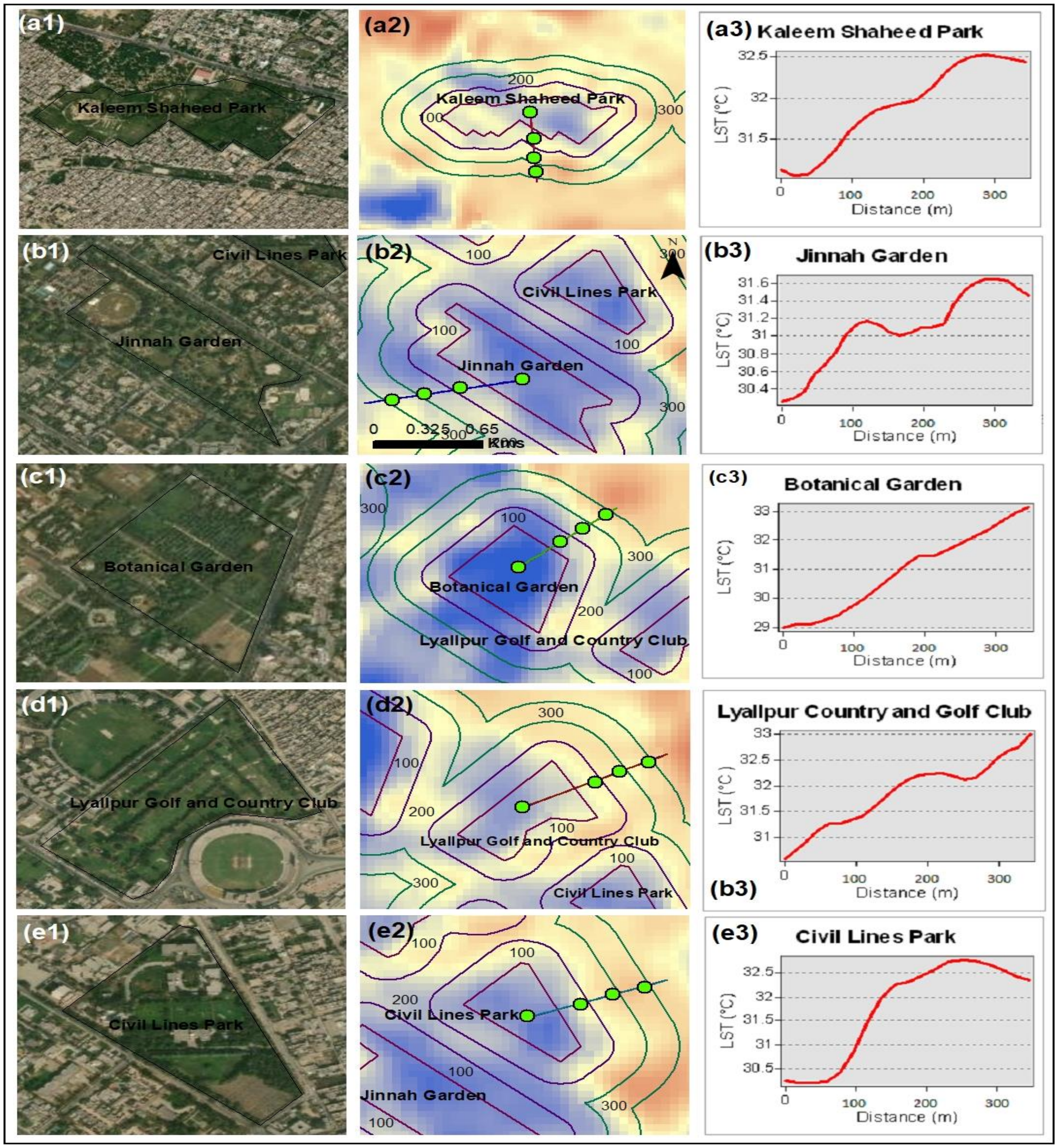
Large parks in Faisalabad function as efficient micro-climate regulators, maintaining low LST (Figure 38). Cooling is strongest in parks with higher densities of continuous vegetation, such as the Botanical Garden and Jinnah Garden. The largest effect is observed in Civil Lines Park, where the temperature rises from 30.26 °C measured within the park to 32.70 °C at 300 m (Figure 39). The results support findings from earlier research that showed that large tree-dense urban parks can reduce the UHI effect to varying degrees.

Figure 38: LST Inside and Outside of Large Park



Source: Author's compilations.

Figure 39: Temperature Profile and Cooling Effect of Large Parks of Faisalabad

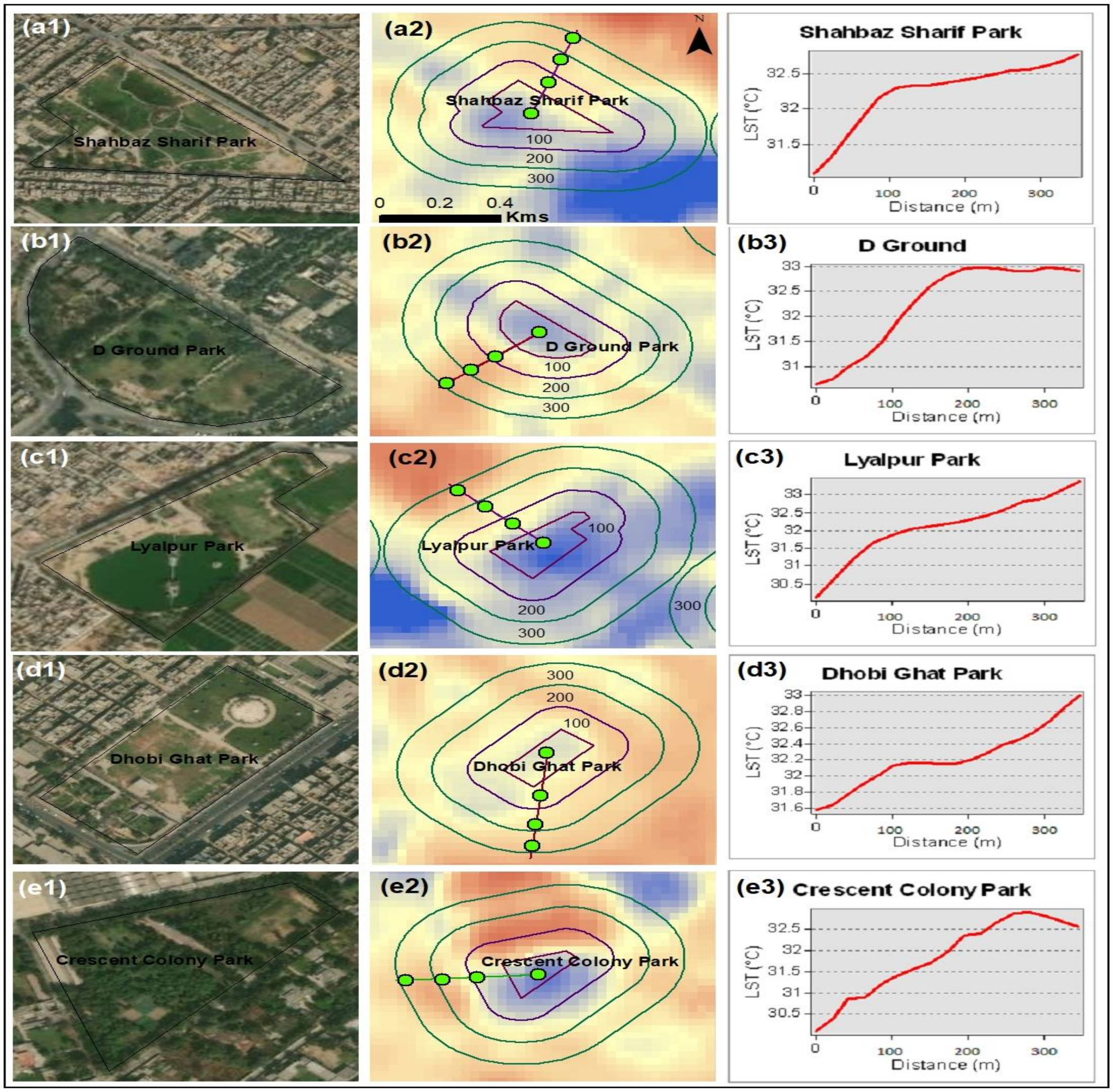


Source: Author's work

4.7.5. Medium Park Cooling Effect in Faisalabad

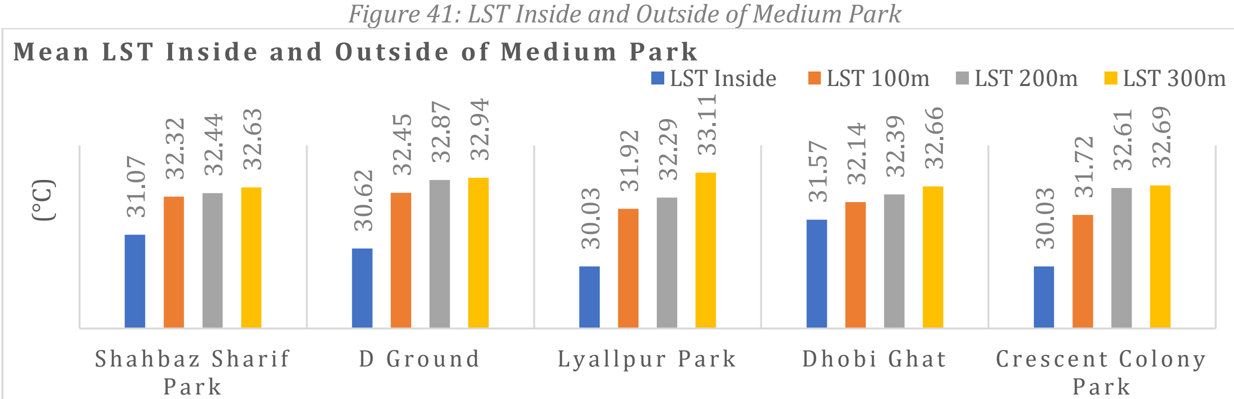
Medium parks function as localized cool islands, significantly reducing LST (Figure 40). Temperatures are lowest within park interiors and increase gradually across 100–300 m buffers, with the strongest cooling within 100 m. The effect of cooling is better at dense vegetation parks and continuous areas compared to patches. Lyallpur Park demonstrates better cooling effects due to water bodies, and LST increases from 30.3 °C to 33.11 °C. Overall, medium parks have a significant effect on reducing heat stress conditions, particularly when integrated with small adjacent green areas (Figure 41).

Figure 40: Temperature Profile and Cooling Effect of Medium Parks of Faisalabad



Source: Author's work.

Figure 41: LST Inside and Outside of Medium Park

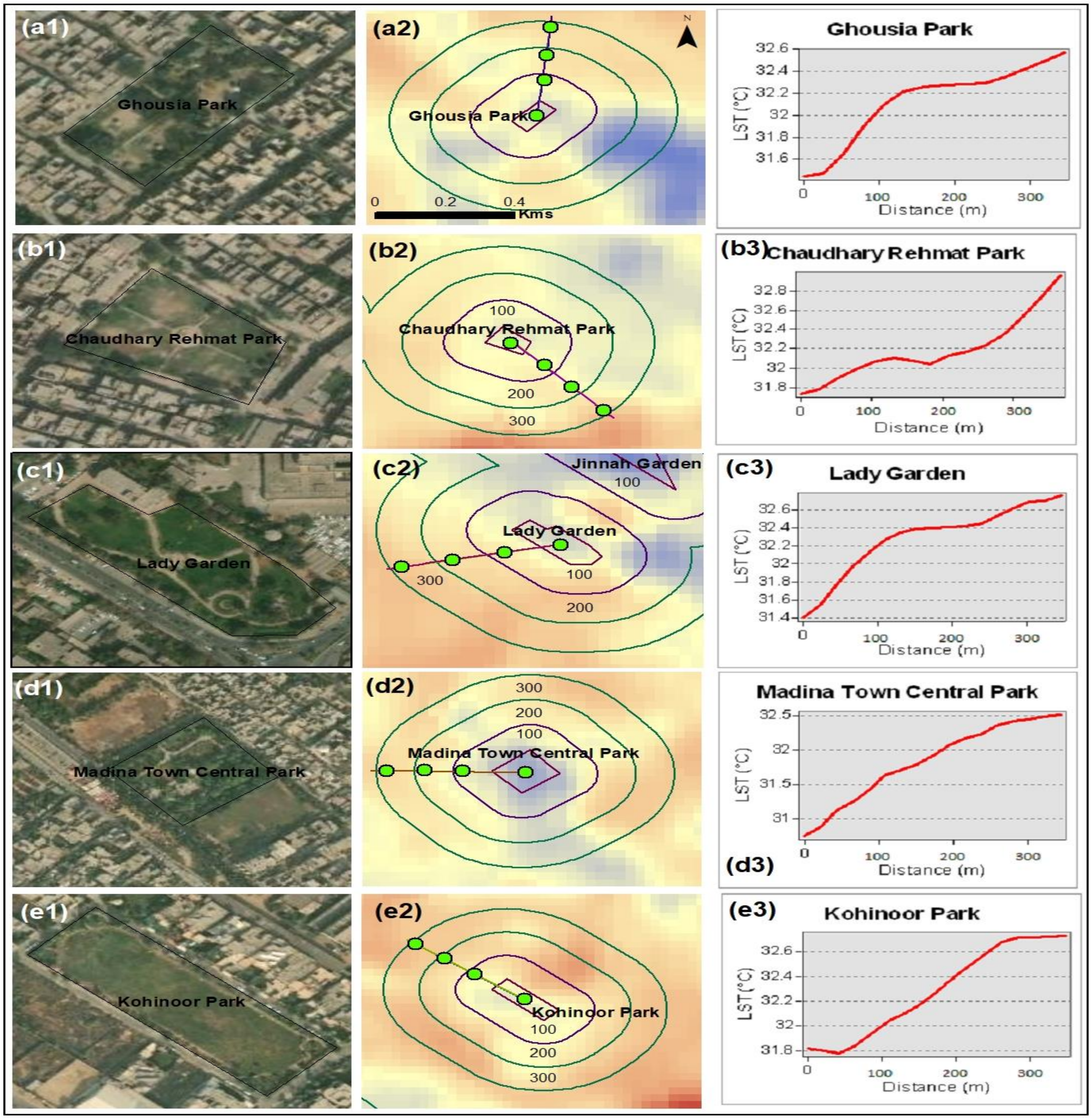


Source: Author's compilations

4.7.6. Small Park Cooling Effect in Faisalabad

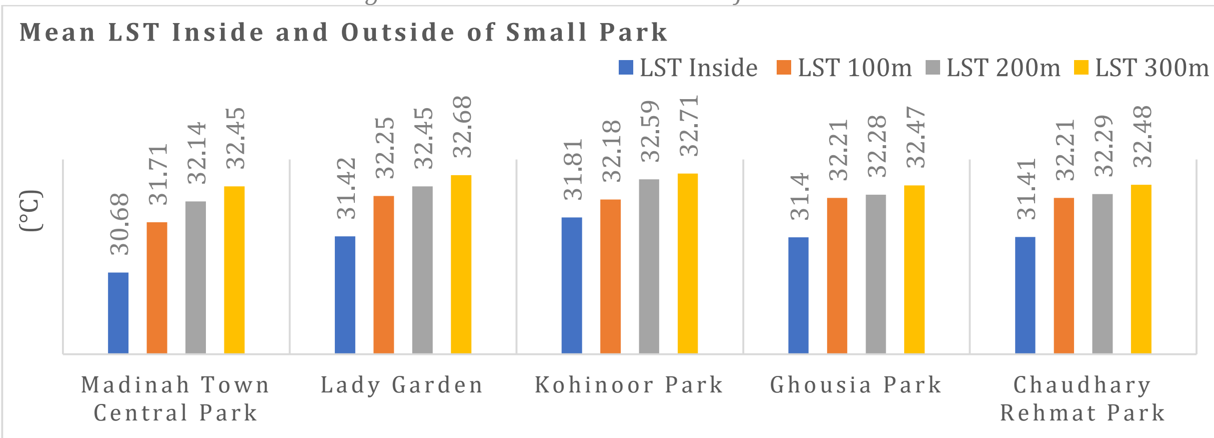
Small parks provide localized cooling within dense urban areas. Cooling intensity decreases with distance, with stronger effects observed in parks with dense vegetation, such as Madinah Town Central Park. In contrast, grass-dominated or fragmented parks, including Ghousia, Chaudhary Rehmat, and Kohinoor Parks, show weaker cooling (Figure 42-43). Although their spatial influence is limited, small parks reduce microclimatic heat stress through shading and evapotranspiration.

Figure 42: Temperature Profile and Cooling Effects of Small Parks of Faisalabad



Source: Author's work.

Figure 43: LST Inside and Outside of Small Parks



Source: Author's compilations.

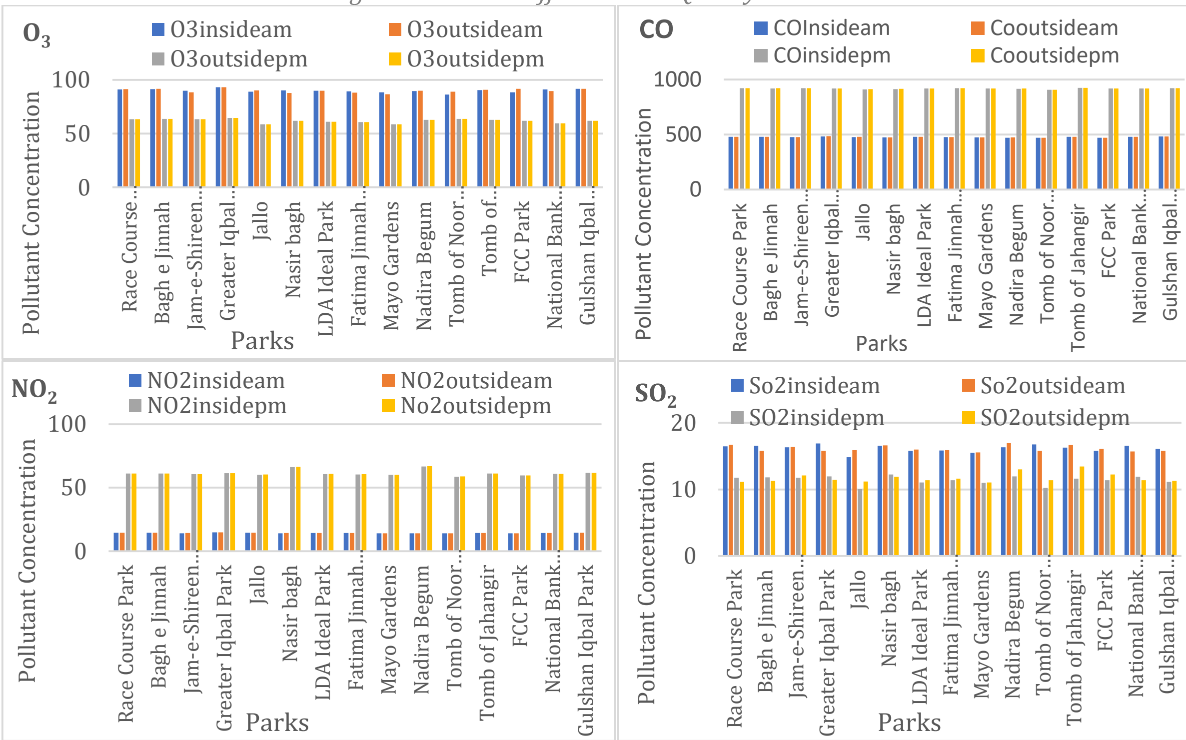
4.8. The Influence of UGS on Urban Air Pollution

The analysis of air pollutants inside and outside urban parks highlights the important role of UGS in improving localized air quality (Figures 44-45). In Lahore, O_3 concentrations are consistently higher in dense, traffic-heavy urban areas than within parks, were less vegetation. Morning concentrations exceed evening levels, particularly outside parks, during peak traffic hours. Evening conditions indicate a stronger vegetation effect under more stable atmospheric conditions. CO exhibits an opposite trend, with higher evening levels, especially outside the parks. Morning values are lower, indicating reduced emissions and good dispersion. Vegetation is an important factor in the removal of pollutants, but CO removal is very minimal (0.2% per year).

NO_2 levels remain lower within the parks at both 8 am and 8 pm, which signifies efficient mitigation policy interventions. Variations at both morning and evening times are minor, but evening levels show a substantial increase owing to traffic density, although they remain lower within the parks owing to the absorption of pollutants. Occasionally, higher levels within the parks could be attributed to roadside congestion. For SO_2, morning levels are more similar for both inner and outer regions, which might signify minimal absorption related to the structure and flora of the canopy.

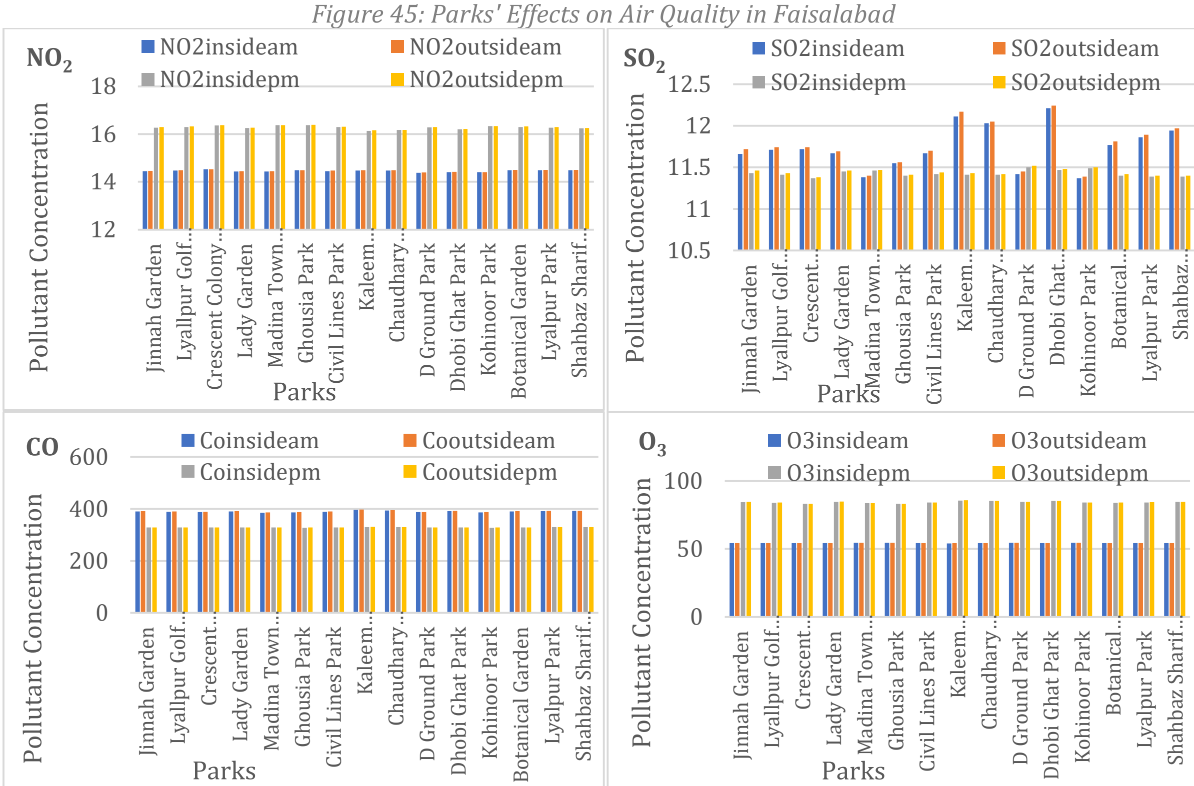
In Faisalabad, NO_2 concentrations are lower within parks, suggesting effective vegetation shielding. The difference in SO_2 concentration remains small for both interior and exterior locations, suggesting minimal absorption because of density and type. The concentration of CO is higher in the outer areas of parks in the morning, signifying emissions occurring in working hours, and drops in the evening with negligible variation. The concentration of O_3 is higher in the evening; however, it remains lower in parks.

Figure 44: Parks' Effects on Air Quality in Lahore



Source: Authors' compilations.

Figure 45: Parks' Effects on Air Quality in Faisalabad



Source: Authors' compilations.

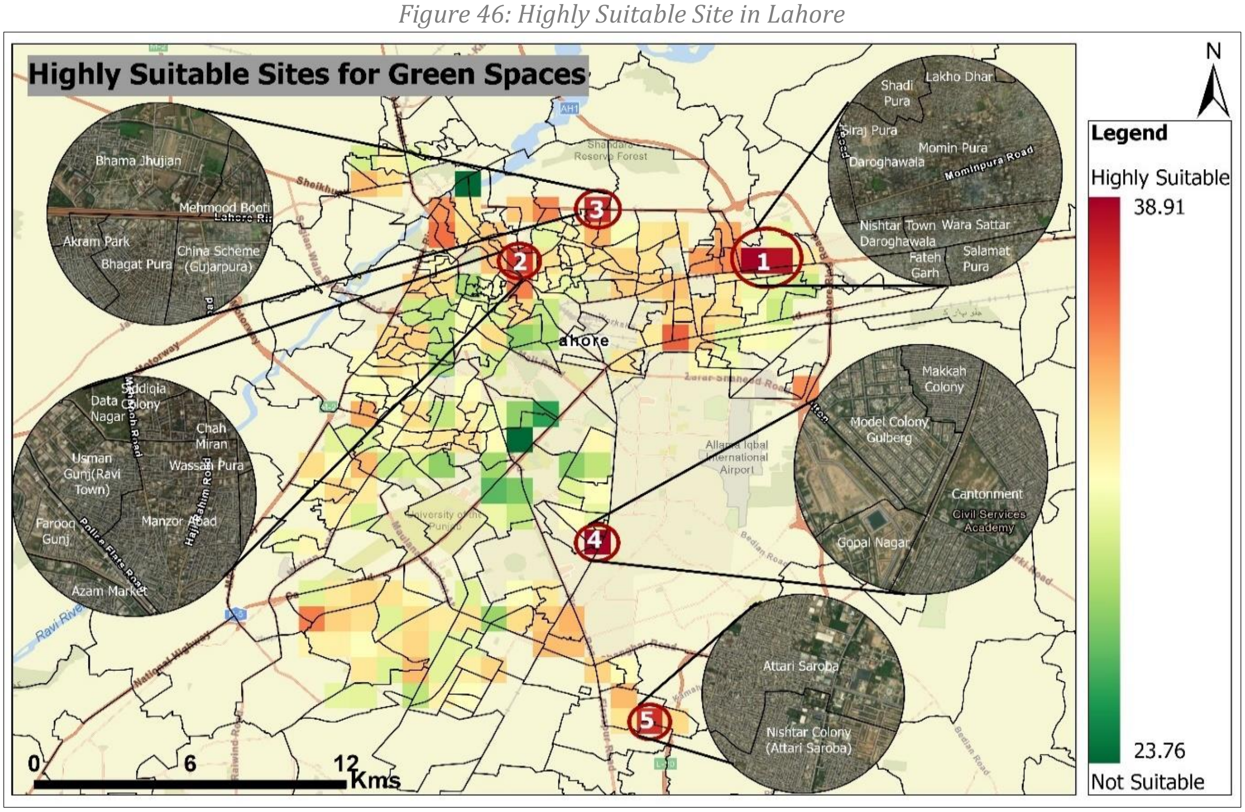
4.9. Suitability Analysis for Green Initiative

Using MCDA and the CPI, 15 sites were initially classified as highly, moderately, or least suitable for UGS. Subsequently, nine priority sites, Sites 1–5 (high), 6–8 (moderate), and 9 (Least) were identified for interventions to combat the combined effect of air pollution and rising temperature to enhance ecosystem and human well-being (Malczewski, 2004; Kabisch et al., 2015).

4.9.1. Highly Suitable Site in Lahore

In Figure 46, the red pixels represent highly suitable areas for green infrastructure, including densely populated, environmentally degraded regions with higher LST, low vegetation, and high levels of air pollution. These regions have also shown high vehicular movement, mixed residential-industrial land use and anthropogenic heat. Enhancing greenery in these high heat-stressed regions can improve microclimate, reduce temperature and pollution hotspots and strengthen ecosystems.

Figure 46: Highly Suitable Site in Lahore

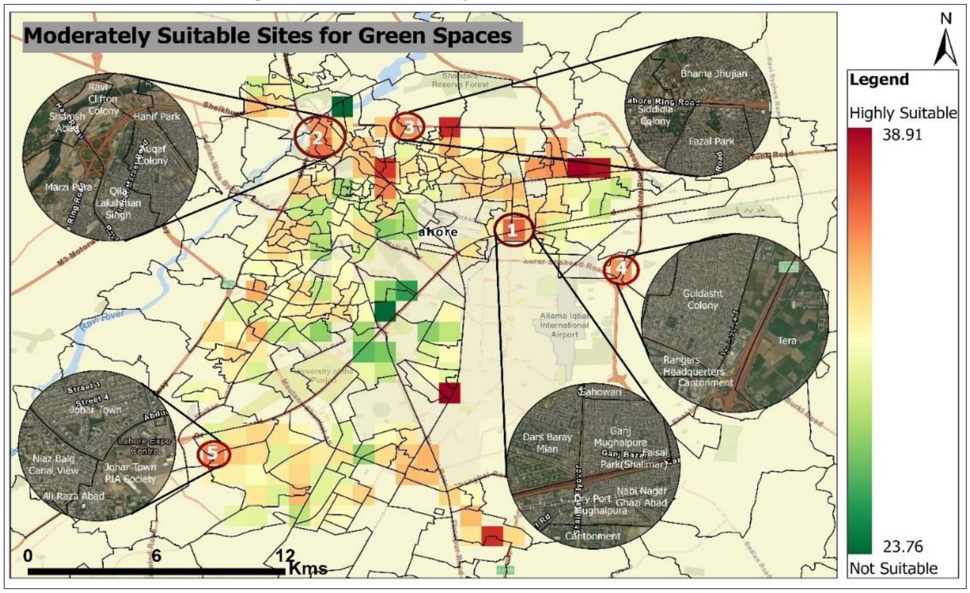


Source: Author's work

4.9.2. Moderately Suitable Site in Lahore

The dark orange pixels in Figure 47 identify moderately suitable sites for green space development, including mixed low-density residential and commercial areas, semi-converted fragmented green patches and green transportation corridors alongside roads. Small-scale urban greening practices, such as pocket parks, green belts, living walls or vertical and rooftop gardens, can enhance cooling, air flow, and decrease pollutants. Distributed urban greening can reduce LST values by 1–3°C and decrease air pollution (Akbari et al., 2005; Gunawardena et al., 2017).

Figure 47: Moderately Suitable Site in Lahore

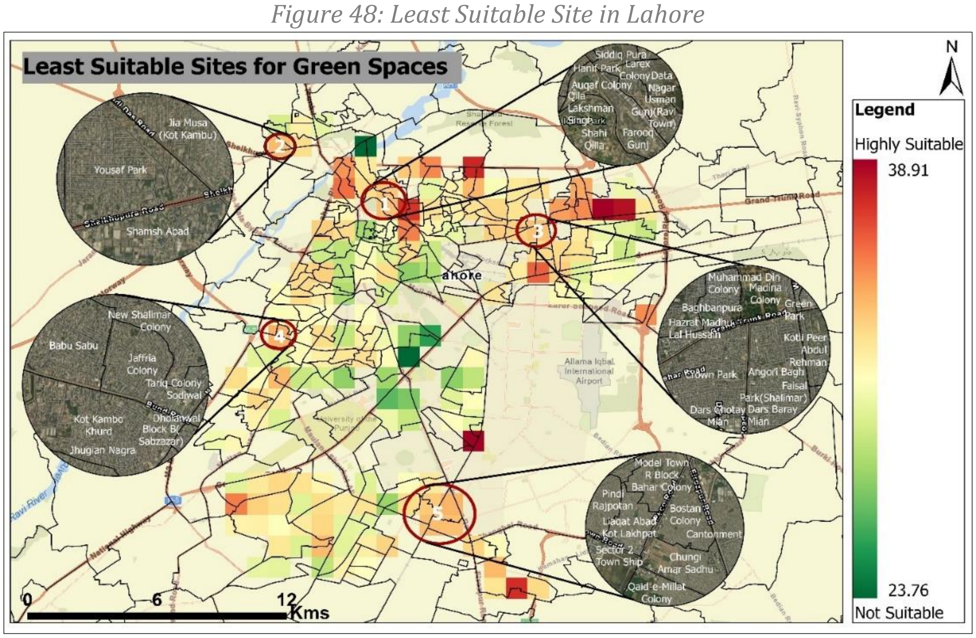


Source: Author's work

4.9.3. Least Suitable Site in Lahore

The light orange pixels in Figure 48 highlight the least suitable areas, including Shamshabad, Jia Musa, Qila Lakshman Singh, Sabzazar, Model Town, Township, Chungi Amar Sadhu, and Kot Lakhpat. However, rapid growth in transportation due to rising demand poses a critical future risk.

Figure 48: Least Suitable Site in Lahore



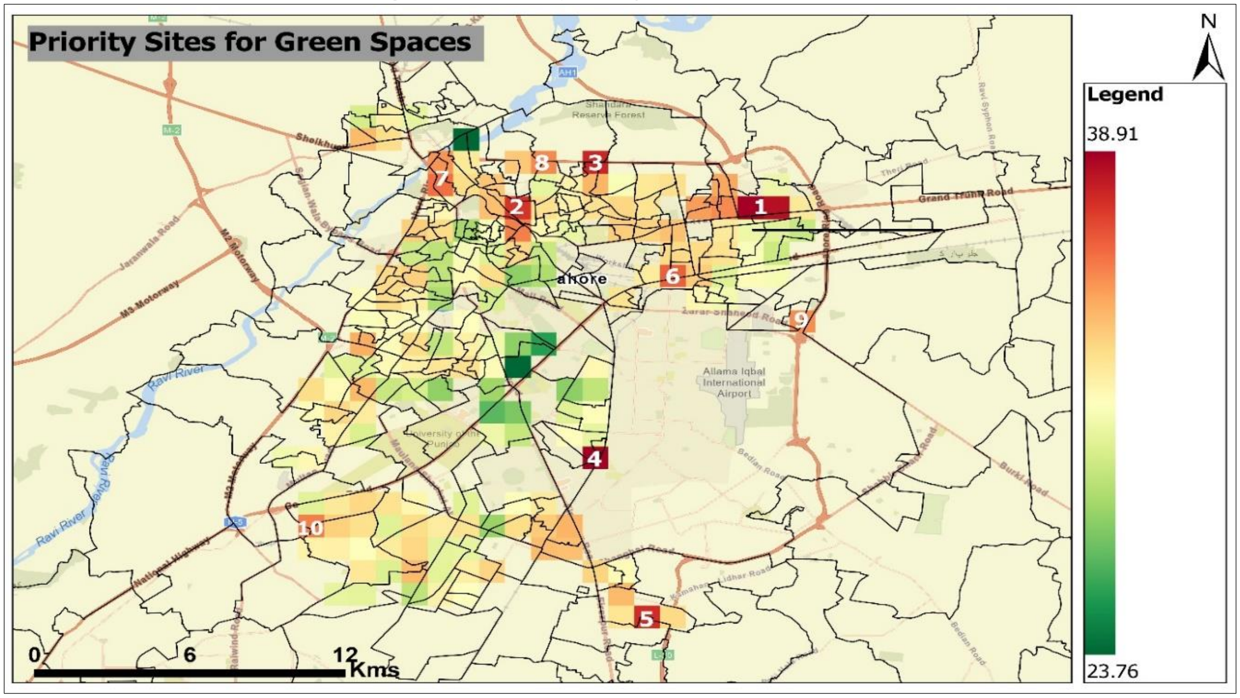
Source: Author's work

Although large greening is not possible due to space constraints, smaller interventions like rooftops, walls, courtyards, or road surface reflection would improve micro-climatic conditions. Small parks, school grounds, or roadside vegetation must continue to remain significant.

4.9.4. Identified Priority Site for UGS Interventions in Lahore

Figure 49 shows the nine priority sites in Lahore for immediate green initiatives.

Figure 49: Priority Sites for UGS development



Source: Author's work

Site 1 consists of an industrial area of Daroghawala and Gujjar Site, indicating high emissions and densely built-up with no noticeable green spaces. Establishing green space in the vacant private land near Heart and Diabetic Clinic with native trees could improve thermal comfort, while maintaining the 5.18 acres green area near Nizami Steel Mills can also significantly reduce heat and pollution exposure. Similarly, 1.82 acres of land should be used to plant with native species. Restoring green space near Gujjar Street (365 m) and vertical greening, including Salamat Pura Orange Line Metro Flyover, will improve the microclimate.

Site 2 includes the Misri Shah and Badami Bagh with dense urbanization. This has industries around Misri Shah, Khokhar, and Peco Road. The urban space on the ground is quite inadequate, consequently preventing tree cover & green areas. The mitigation plan should emphasize increasing pocket parks, green roofs in industries, tree planting on boundaries, and dense tree cover on the roadside. The vacant land (1.43-acre) around Habiba Town places emphasis on tree plantation and the provision of shade.

Site 3 is along the sides of Ring Road and Baghat Pura, with industrial units and the new housing scheme Jarrar Gardens. Green projects add to the development of roadside tree plantations, green roofs, vertical green walls, and pocket parks in densely populated areas such as Baghat Pura, which could be achieved through awareness campaigns. Industries should focus on green walls and roadside plantations, and green belts on Shehbaz Road and China Road can also help to lower emissions.

Site 4 should prioritize green roofs and location-specific native tree plantations surrounding the roads and railways. The most appropriate location includes Falcon Complex, Akram Abad, Railway Colony, Walton, and areas along Bedian Road/RB-47, Academy Road, Balouch Road, and Railway Line. Tree plantation on vacant land in Falcon Complex, preserving existing vegetation within the Civil Service Academy and sports grounds, and establishing continuous green belts would efficiently reduce heat and pollution in these densely populated zones.

Site 5 has dense, compact urban areas with busy roads, heavy traffic, industries, and minimal green patches. The vacant plots are limited, and found in Attari Saroba and Farid Kot, resulting in high thermal discomfort. The feasible measures include green roofs, vertical greening on the boundary walls, and street tree plantations. Green façades and climbing plants should be promoted in industrial areas. The vacant land can be converted into small parks, while the existing parks should be conserved. Roadside plantations along the canal and green development would significantly improve sustainability.

Site 6 is densely populated areas such as Shah Kamal, Shalimar flyover, and Mughal Pura, as well as commercial areas, including Raja Market and Soekarno Bazar, and Canal Road, Shalimar Link Road, Gunj Baksh, Shah Kamal Road and Mughal Pura Railway and port. Limited vacant land requires green coverage to involve rooftop gardens, balcony gardens, and the renovation of smaller green areas. Greening the façades of Shalimar Flyover and wall greenery for Hiba Khatoon Underpass may provide relief, lower heat and pollution and increase air quality.

Site 7 extends from River Ravi to densely populated areas, including Timber Market, Badami Bagh, Qila Lachman Singh, and Qasur Pura. Interventions should prioritize the green belts along roads, enhancing the number of trees in the already existing green sites, and vertical greenery within the Metro Bus Flyover. The River Ravi site functions as a blue-green ecosystem. Space constraints call for the mandatory use of greening along the roads, perimeter sites of buildings, and green building fade. Sites like the already existing Bhatti Chowk Park, the Forest Colony, and Ali Parks are important for a healthy microclimate.

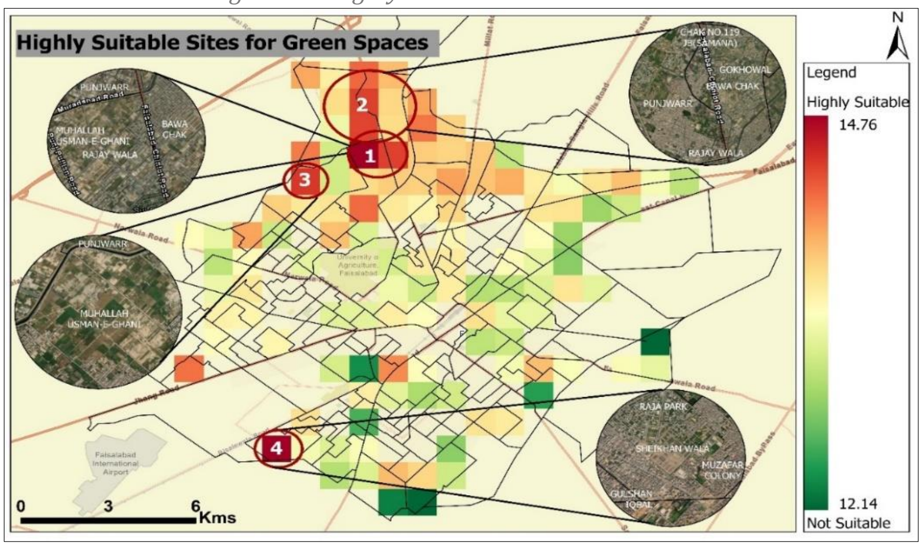
Site 8 consists of mixed residential, commercial, and industrial areas. Priority measures include green areas on vacant land, green roofs, roadside greenery, and vertical gardening on industrial buildings. Green areas along Abu Bakar and Tariq Shaheed Road can help to reduce emissions from vehicles. The vacant land of 8.48 acres along Fiberglass Doors Company on Bhamma Road and Ganda Nala can be developed for greenery. The existing greenery in the form of tree coverage should be maintained and developed for micro-climate resilience.

Site 9 covers Ring Road, the internal, densely residential roadways of Gujjar Pura. Due to compact housing, narrow streets, and a lack of vacant land, the impact of heat and pollution is considerable. The strategies include planting trees at houses, schools, and hostels; vertical gardening and green walls; and planting along streets and roadside planting. Existing green pockets such as Chungi Gogaij Park and Saeed Bin Zaid Park should be restored. Open and green covers of 1.89 and 10.12 acres along Chungi Graveyard can enhance cooling effects, lessen emissions, and improve climate resilience.

4.9.5. Highly Suitable Site in Faisalabad

The red areas in Figure 50 are highly suitable for executing the development of green spaces. These include residential, industrial, and institutional and are characterized by high density, extreme heat, vehicle emissions, and a lack of urban green spaces. Proximity to Sargodha Road establishes hotspots. Strategies such as pocket parks, micro forests, green belts, green roofs and vertical gardens can mitigate heat and air pollution through shade and evapotranspiration.

Figure 50: Highly Suitable Sites in Faisalabad

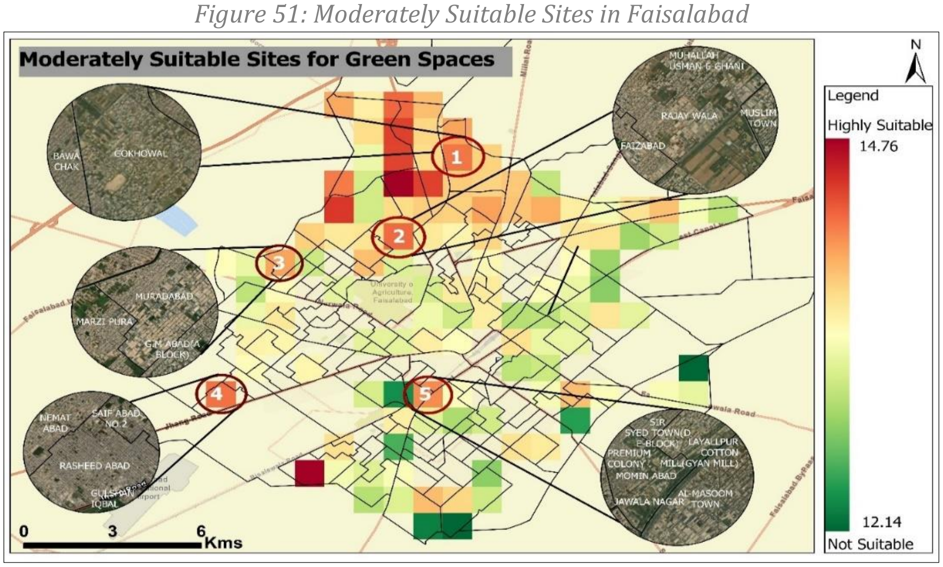


Source: Author's work.

4.9.6. Moderately Suitable Site in Faisalabad

In Figure 51, the dark orange pixels show areas of moderate suitability, where green spaces are fragmented, and pollutants exist at a moderate level, and LST is relatively high, which are identified for UGS initiatives. However, green roofs, pocket parks, and green belts can also help effectively.

Figure 51: Moderately Suitable Sites in Faisalabad

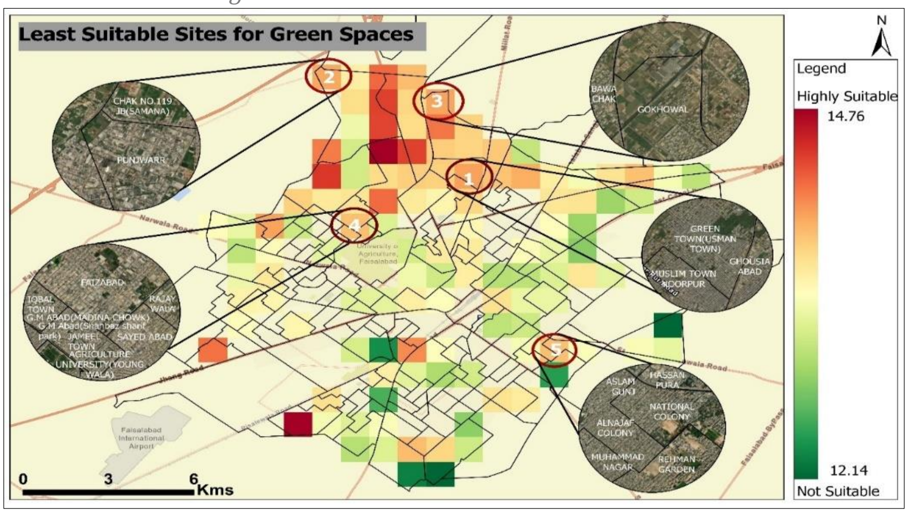


Source: Author's work

4.9.7. Least Suitable Site in Faisalabad

In Figure 52, the light orange areas are the least suitable locations for new UGS, characterized by existing vegetation, low LST, and pollution. These relatively stable residential or semi-urban areas exhibit limited potential for large-scale greening but need proper management. Here, high-priority areas relate to improvements in UGS, micro-scale greening and the use of reflective and/or permeable surfaces.

Figure 52: Least Suitable Sites in Faisalabad

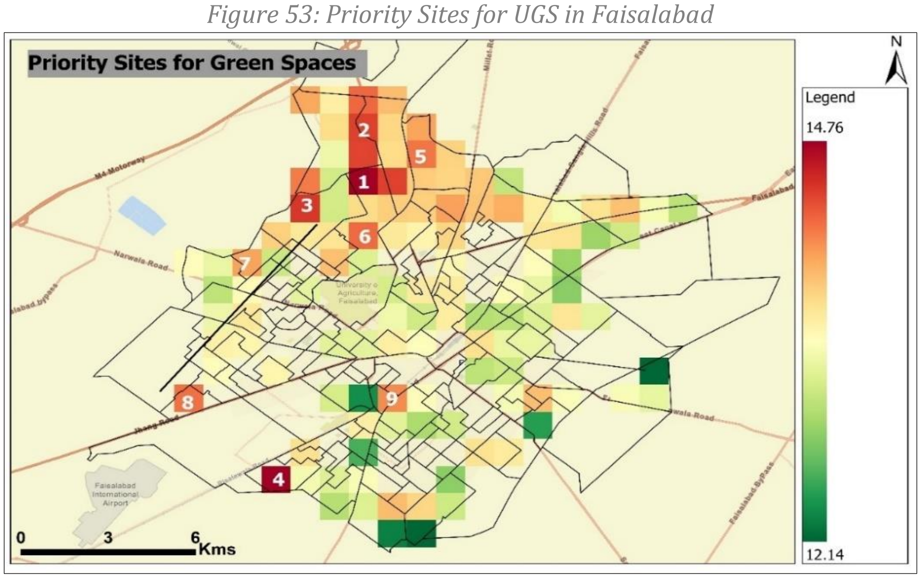


Source: Author's work

4.9.8. Identified Priority Sites for UGS Interventions in Faisalabad

Applying the concept of landscape suitability (McHarg, 1969), nine sites were further identified as priority sites: 1-4 highly suitable; 5-8 moderately suitable; and site 9 (Figure 53).

Figure 53: Priority Sites for UGS in Faisalabad



Source: Author's work.

Site 1 includes residential zones like Wagha Town, Ismail City, Ideal Town, commercial areas, and massive industries like Hanoof Textiles, Polo Packages (Pvt.) Ltd., Rehmant Textiles, & Al Shahzad

Marble Factory, located on Sargodha Road. The site has immense potential for microclimate management with green belts along roadsides, green roofs, and green facades. The vacant, vast industrial land can be used for a green initiative to decrease industrial emissions. A 60-acre vacant lot can be used for a multi-purpose community park. Land vacant on Masjid Ismail Road can be utilized for native tree shade (Figure 54).

Site 2 is the mixture of residential and industrial areas with densely populated areas around Zeenat Town and Ghafoor Town, Pakistan Textile Processing Industries, Bashir Printing Industries, and Al-Rehman Textiles, as well as transportation routes along Sargodha Road and Malik Anwar Road. Linear parks along roads and canals, green roofs, facade gardening, and gardens at street corners are proposals of focus. The vacant and underutilized lands could be utilized as community parks.

Site 3, identified on the outskirts of the city, has agricultural and vacant lands alongside compact housing, residential blocks, and road corridors along Muradabad, Mandi, and Rana roads. This site is a high-priority site for the implementation of environmental projects due to the large extent of vacant lands and limited activities. Agricultural lands must remain unchanged, although indigenous trees must be planted because of the absence of trees and high temperatures. The 38-acre vacant space surrounded by Manj Town, Sidhupura, and Sitara Sapna City, along Rana Road, is identified for the development of a theme park.

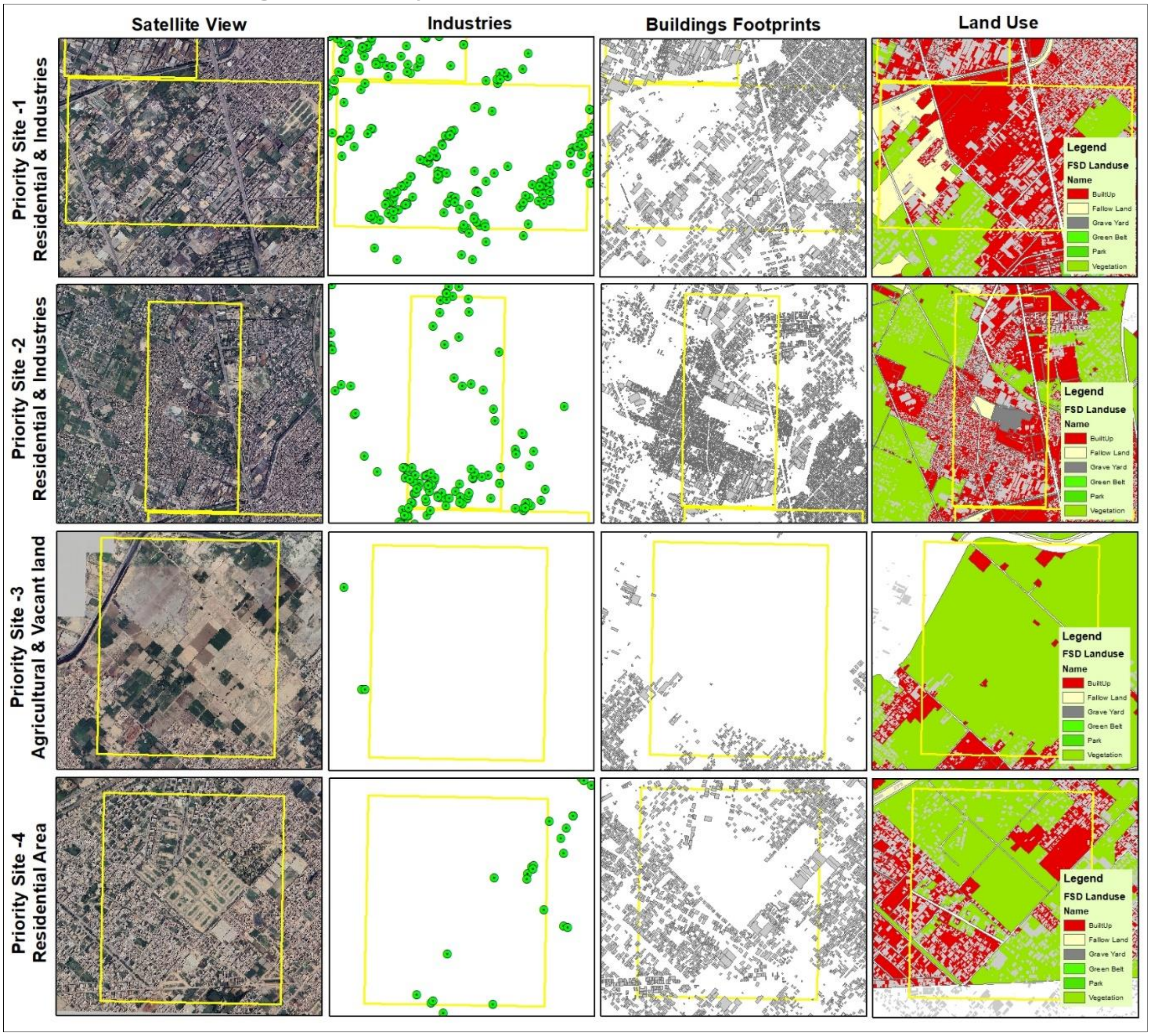
Site 4 is characterized by mixed-use development with urban-block configuration, roads, patches of green spaces, and vacant lots. Eden Villas Park, as well as Defense Paradise Park, may be upgraded to be multifunctional community parks. Macro-level projects such as the establishment of green belts along roads, as well as restored tree canopies along Main Gulshan-e-Iqbal and Sitara Model Road, can help create a cooling buffer.

Site 5, bound by Millat Town, Baba Chak 120 JB, and Gokhowal, comprises empty land, fragmented green areas, no tree cover, extensive roads, and the housing society, Eden Orchard. As industrial units are not present, there is great potential for pollution relief. Greens in Main Zulfiqar Ali Shaheed Road, natural trees, rooftop gardens and plantations in roundabouts, office space greenery, Eden Orchard Park, and cricket grounds can be utilized for UGS development.

Site 6 is a mixture of residential and industrial areas**.** Green potential in this category includes Lasani Garden, Ghousia Abad, International Housing Society, and sites on roads Masjid Ismail, Major Abdul Aziz, Rana, Chauhan, Quba, and Rajput. The major green potentials identified at 18 acres around Masjid Ismail–Qaim Sain–Baby Sufi Wali–AA Bros Traders, 7 acres around Zahid Plastic Industries, and 6.26 acres around Rajput–Rana–Sufi Waali–AKS Industrial. The project proposes roadside green belts, roof gardens, street plantations, and green industrial facade (Figure 55).

Site 7, at the edges of the city's eastern side, covers Rasool Nagar, Ghulam Muhammad Abad, Kashmir, and Sundar Roads, along with the industrial buildings Alisha Embroidery, Naseer Weaving, and commercial buildings Munir Sweet and Noraiz Electric. Owing to the scarcity of vegetation and empty land, green projects include roadside planting, rooftop gardening, and wall climbers. The shades of existing industries can be increased by planting tree belts around industries, planting shop fronts, and turning Mahalla Sadiqa bad (1.02 acres) and Muradabad Road (5 acres) into community parks.

Figure 54: Priority Sites & Land Use Characteristics in Faisalabad

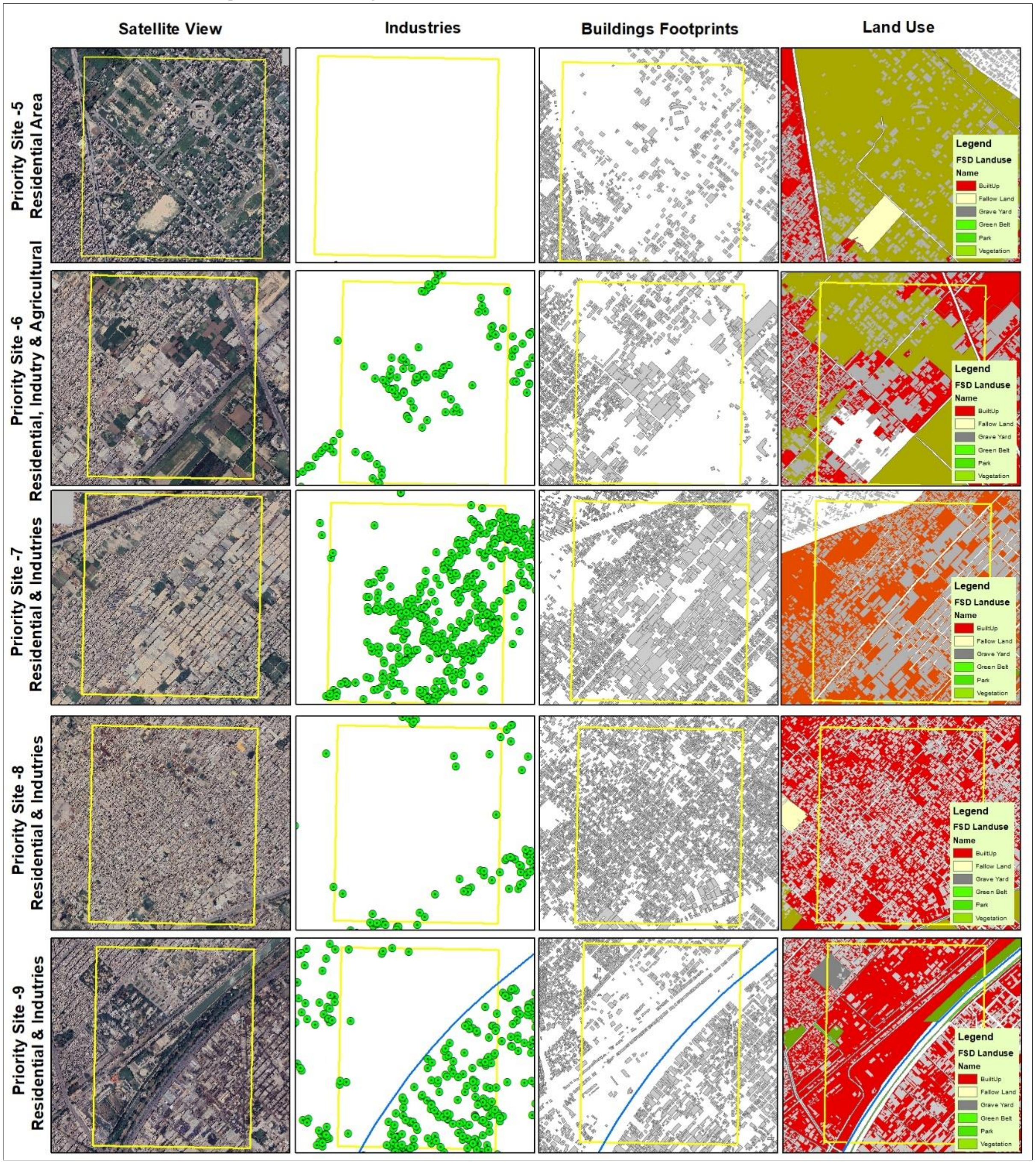


Source: Author's work.

Site 8 includes densely packed housing, a residential and commercial area of Saifabad and Babu Wala, with no vacant land for new UGS and no existing green areas or tree cover. The roadside plantation is rather challenging due to densely packed urban areas. The most appropriate green solution includes vertical gardening and green roofs on houses. The small patches of green can be ideal spots for increasing shade with suitable tree species to fit into the space for a cooling zone.

Site 9, there is a diverse urban environment characterized by residential, commercial, and industrial areas, main roads, a park, open land, and a canal. Linear parks around Rakh Branch Canal, Samundari Road, Allah Hoo Street, Fatima Jinnah Road, and around Pizwan Road may be created. The land between Samundari and Pizwan Roads can be used as ecological buffers. The land around Plastic Can House (0.50 acres), Canal Park, and underdeveloped blocks may be converted for recreational use & flat surfaces may be used for creating green roofs.

Figure 55: Priority Sites & Land Use Characteristics in Faisalabad



Source: Author's work

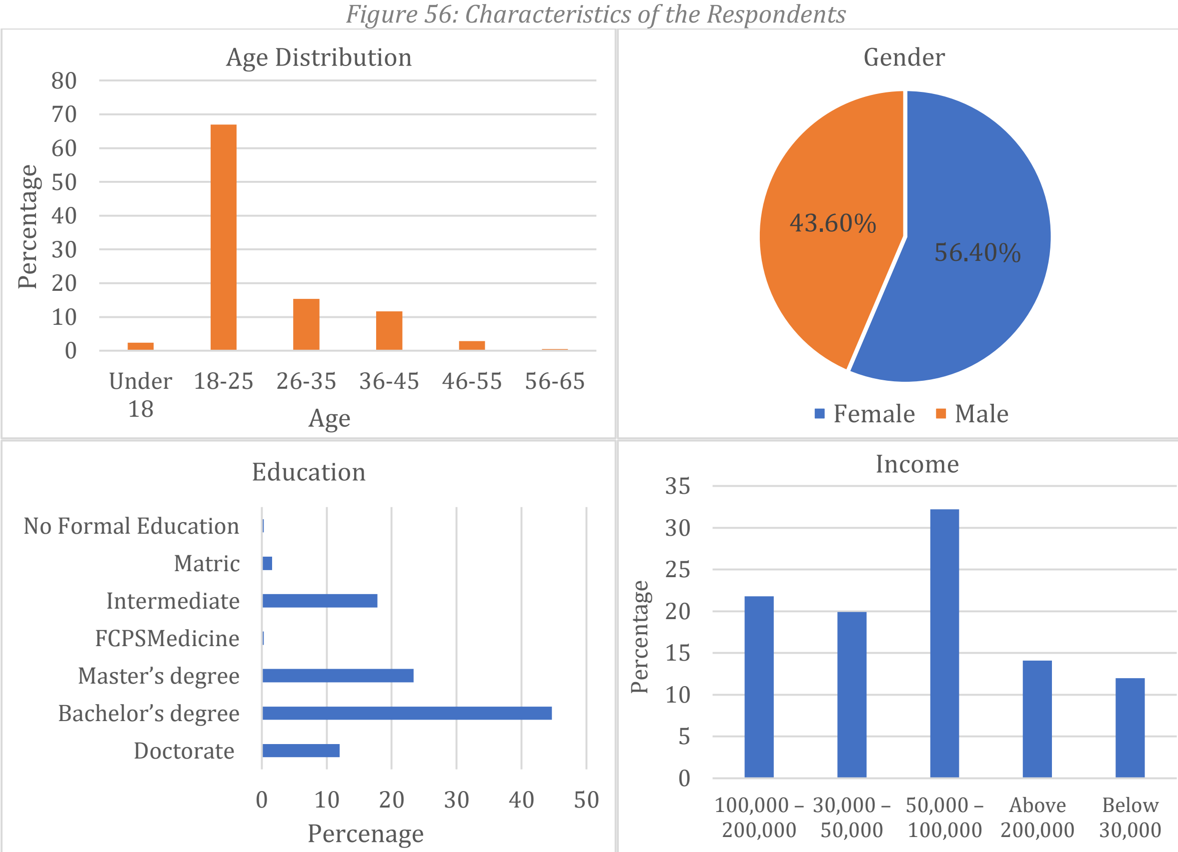
4.10. Public Awareness, Perception and Behaviour

The results are based on two major sections: demographic characteristics of respondents and the THAI Scale Development and Validation. These investigations gauge the role of public awareness, perception, behavior, adaptive capacity, and govt. environmental policies in enabling the combined effects of urban heat and air pollution on health, directed by the HBM.

4.10.1. Demographic Profile of Respondents

The sample comprised a diverse group of respondents representing a wide range of ages, genders, education levels, occupations, and household income categories. For age distribution, 67% (252) of the respondents were 18–25 years old, 15.4% (58) were 26–35 years, 11.7% (44) were 36–45 years, 2.9% (11) were 46–55 years, 0.5% (2) were 56–65 years, and 2.4% (9) were under 18 years. According to gender composition, 56.4% (212) of the respondents were female, and 43.6% (164) were male (Figure 56).

Figure 56: Characteristics of the Respondents

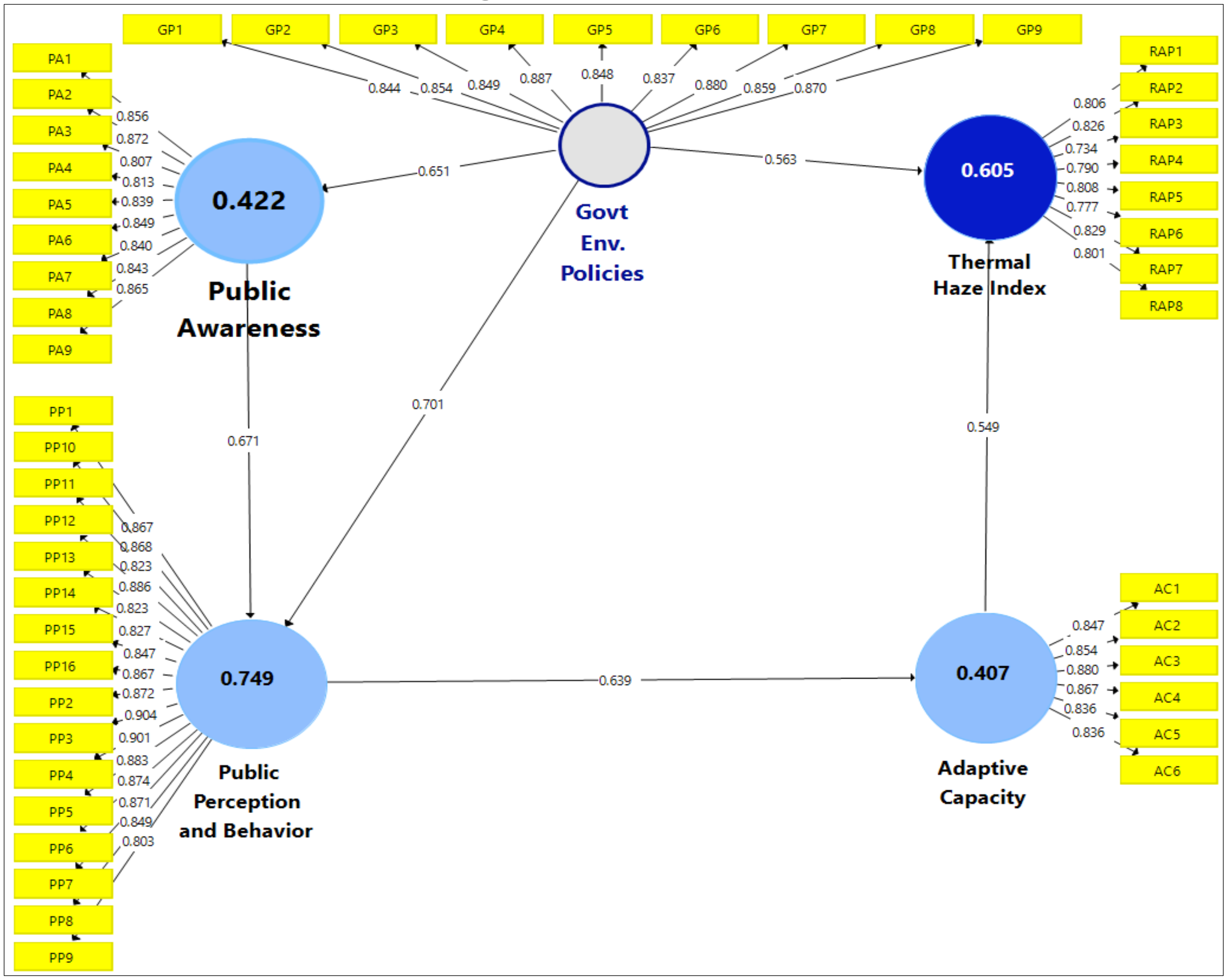


Source: Primary data collection.

4.10.2. The Relation of Air Pollution and Urban Heat with Respondents' Health

Assessing and modelling the respondents' health effects of both phenomena was examined by asking about their (a) awareness, perception and behavior; (b) adaptive capacity and (c) government policies are shown below in Figure 57 with the help of a structural equation model. The measurement model shows the relationships between the constructs. All outer loadings were found above the adequate level 0.7 (Annexure 9). In addition, Adaptive Capacity (AC) moderately predicts the Thermal Haze Index (0.549 $p < 0.001$), Public Awareness (PA) positively influences Public Behavior and Perception (0.671, $p = 0.001$), and Public Perception and Behavior (PP) also positively affects Adaptive Capacity (AC) (0.639, $p < 0.001$). Government Policies (GP) have a strong positive effect on PA (0.651, $p < 0.001$), as well as on PP and PB (0.701, $p < 0.001$). These results support hypotheses H1–H3 (Figure 57 & 58).

Figure 57: Structural Model



Source: Author's construction.

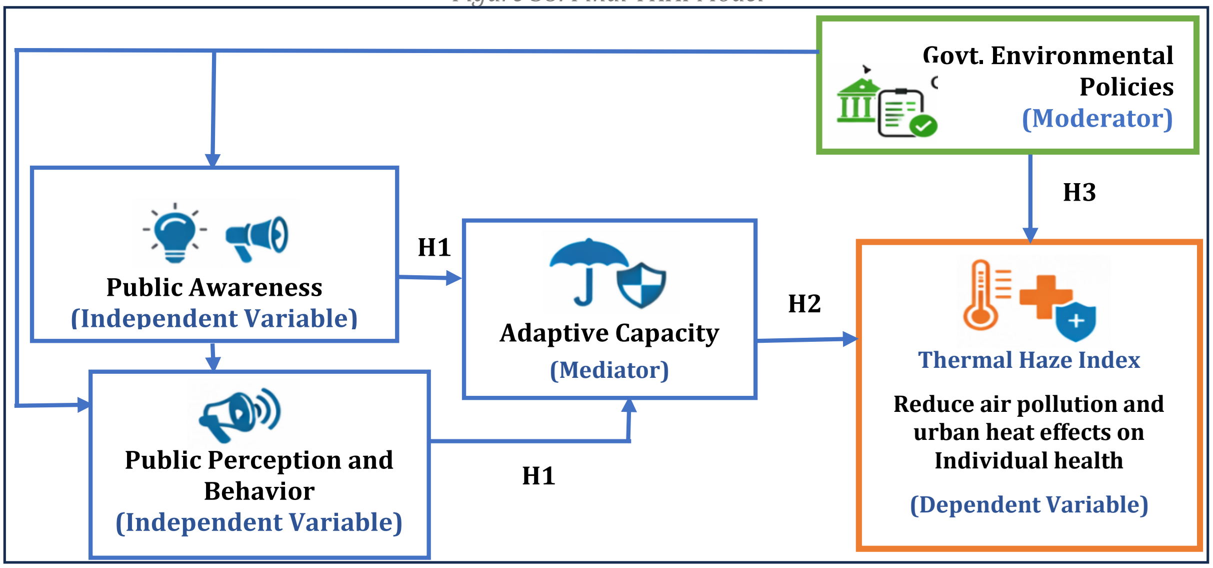
4.10.3. Finalized THAI Scale

Based on the finalized THAI framework, all three hypotheses were supported, indicating that individuals' adaptive capacity to air pollution risk, through perception and behavior, depends on the level of public awareness.

It is also anticipated that increased awareness and more informed perceptions and behaviors will have a positive influence on the creation of adaptive capacity (H1). In addition to this, the model also states that adaptive capacity acts as a significant determinant of health risk to lessen the adverse effects of UPI and UHI effects on the health of individuals (H2). Further, the model also exhibits that the knowledge of environmental policies enhances this relationship. Greater public knowledge of environmental policies strengthens the positive effect of adaptive capacity on reducing air pollution and urban heat–related health risks, confirming the moderating role of policy awareness (H3).

This model explains substantial variance (e.g., R^2 = 0.817 for overall effects, like structural modeling outcomes), highlighting the positive and statistically significant role of the THAI constructs in promoting health-protective behaviors (Figure 58).

Figure 58: Final THAI Model



Source: Author's developed THAI model.

4.10.4. Scale Development Using the Equal Interval Method (Thurstone Scaling)

In phase 4, items are selected for scaling from validated constructs, positioned along the 1–5 continuum based on factor loadings and means based on the equal interval assumption (e.g., the interval between 1–2 equals 4–5). Results are scored by calculating the simple arithmetic mean (average) of the items that belong to each construct, where higher scores indicate better adaptation. As the 5-point metric is treated as equal-interval, the total or subscale mean scores are classified into five perceptually equal categories (each band exactly 0.80 units wide) for the THAI as given below (Table 14).

Table 14: THAI Scale Categories and Description

Score Range	Category	Interpretation
1.00 – 1.80	Very Low Awareness / Highly Vulnerable	People are unaware of haze and rising temperature risks and take little adaptive action; strongly affected.
1.81 – 2.60	Low Awareness / Vulnerable	Some understanding, but limited behavior or adaptation; still at risk.
2.61 – 3.40	Moderate Awareness / Moderately Resilient	Aware of air pollution and rising temperature issues, but adaptive actions are inconsistent.
3.41 – 4.20	High Awareness / Resilience	Good awareness and adaptive behaviors reduce the impacts of haze and temperature.
4.21 – 5.00	Very High Awareness / Highly Resilient	Excellent awareness and strong adaptive capacity; minimal haze and rising impact perceived.

Source: Author's developed THAI Scale.

4.10.5. Interpretation of the THAI Scale

The sample dataset consists of individual scores ranging from 1.0 to 5.0, each representing respondents' awareness of haze and rising temperature issues and their resilience (adaptive capacity). These scores are interpreted using a five-level scale, where higher scores indicate stronger awareness and resilience. Overall, the scale reveals that the sample data results show strong awareness and high resilience to haze and rising temperature risks. The high concentration of scores in the High and Very High categories suggests that respondents are generally:

1- Well-informed about environmental hazards,

2- Capable of adopting protective strategies and experiencing fewer negative impacts due to their adaptive behaviors.

4.11. Climate-Sensitive Health Interventions

The implications show that the effects of urban climate change in cities during rapid urbanization are regarded as secondary in comparison to the rising heat and air pollution, yet they mostly depend on city design (Table 15).

Table 15: Intervention Sustain Environment & Improve Health

Priority	Intervention	Environmental Change	Health, Climate & Pollution Pathways	Target Scale	SDGs Aligned	Global practices
1	Climate-resilient improvement of existing parks	Increased tree density, shaded seating, water features, improved access and biodiversity	Enhances cooling benefits, park use during heat waves, mental restoration, community engagement and air quality	Neighbourhoods and city populations	3, 11, & 13	Fuller et al., 2007
2	Increased provision of public urban parks and green spaces	Development of new parks, urban micro-forests, and recreational green areas	Mitigates UHI, improves air quality, encourages physical activity, and strengthens social cohesion	Neighborhoods and entire cities	3, 11, 13, & 15	Maller et al., 2006; De Sousa, 2006;
3	Street-level greening and urban shading	Tree-lined streets, green medians, vertical greenery, shaded sidewalks	Lowers surface and ambient temperatures, reduces roadside pollution exposure, and improves walkability	Dense urban Neighborhoods	11, & 13	Lindal & Hartig, 2015
4	Indoor greening in workplaces and public buildings	Indoor plants, green walls, and shaded semi-open spaces	Improves indoor air quality, reduces heat discomfort, and improves mental well-being	Office workers, service users	3, 8, & 11	Bringslimark et al., 2007
5	Provision of walking and cycling corridors	Shaded pedestrian paths, green bike lanes, permeable and reflective surfaces	Reduces heat exposure and pollution intake; promotes active mobility, and lowers emissions	General urban population	3, 11, & 13	Fraser & Lock, 2011; Giles-Corti et al., 2013
6	Greening of schools and childcare facilities	Tree planting, shaded playgrounds, green roofs, nature-based play areas	Reduces heat stress in children, physical activity, learning, and well-being	Children, teachers, school communities	3, 4, & 13	Dowdell et al., 2011; Dadvand et al., 2015
7	Community gardens and urban agriculture	Greening of vacant plots, rooftops, and under-utilized land	Improves nutrition, psychological well-being, social cohesion, and local micro-climate regulation	Neighborhoods and community groups	2, 3, 11, & 13	Kingsley et al., 2009

Source: Author's compilations.

CONCLUSION

The project shows substantial environmental degradation in Lahore and Faisalabad, driven by rapid urbanization and vegetation and tree cover loss. The land transformation intensifies the UPI and UHI phenomena, considerably changing local climate conditions. Particularly, Lahore's mean air temperature increased by 3°C and 5°C in the smog and heatwave periods, respectively, with intensified UHI and worsening UTFVI zones in urban cores, industrial areas, and traffic corridors. Comparatively, the maximum air temperature of Faisalabad increased by 1°C in heatwave months, and the minimum air temperature increased by 3°C during the smog period. Thus, the progressive intensification and spatial expansion of the UHI effect are observed.

Large, continuous parks depicted a cooling of 1–4°C within a radius of 100 m, gradually reduced at 200–300 m, while small, fragmented street parks showed minimal cooling effect. Vegetation also maintained LST below 30°C constantly in areas with NDVI above 0.6–0.7. Vegetation reduced surface temperature by 1.5 to 2°C and accordingly lowered pollutant concentration. In Lahore, notable low-UHI reference places include Jilani Park, Bagh-e-Jinnah, University of the Punjab and Model Town Park. While in Faisalabad, Jinnah Garden and the University of Agriculture remain key comfort zones with moderating vegetation effects. Heatwaves represent peak vulnerability, smog periods sustain moderate UHI, and UTFVI results indicate worsening ecological conditions marked by expanding bad zones and declining good zones.

The analysis of air pollution reveals persistent urban hotspots, showing higher CO values. Declining and relatively stable NO_2 and SO_2 concentrations in Lahore by 2024 indicate the effectiveness of control measures and policy interventions, while O_3 contributes slightly to winter smog in both cities. Pollution risk maps reveal persistent high-risk zones, concentrated in central Lahore and central-northern Faisalabad. GIS-based multi-criteria analysis effectively identifies priority sites for UGS development to enhance urban resilience against heat and air pollution. Particularly, highly suitable areas, characterized by dense population, high surface and air temperature, and air pollution, offer prime opportunities for micro-forests, green roofs, vertical greening, and interconnected green corridors. Moderate and least suitable sites can contribute with smaller-scale interventions such as pocket parks, roadside plantations, and green façades. The nine priority sites per city specified targeted interventions, climate-adaptive strategies that reduce heat stress, improve air quality, and promote human well-being through sustainable urban planning.

Furthermore, unlike conventional quantitative environmental indices such as AQI, the THAI scale is validated and developed with strong explanatory power (R^2=0.817). This equal-interval tool (1–5 continuum) computes mean scores per construct and categorizes them into five 0.80-unit bands. This tool confirmed all three hypotheses: that public awareness, perceptions and behaviors drive adaptive capacity (H1), adaptive capacity mitigates the effects of UPI and UHI on health (H2), and govt. environmental policies knowledge moderates this relationship for better protection (H3). Its evaluations individuals' and communities' resilience, coping capacity, and reinforcement to adapt and drive alterations in response to heatwaves and smog. Sample datasets findings show high concentration in "High" and "Very High" categories, indicating strong awareness, resilience, and effective protective behaviors against haze & increasing temperatures.

In conclusion, this study emphasizes the urgent need for integrated urban climate adaptation in Lahore and Faisalabad amid strengthening UHI and UPI mitigation. Overall, the study reveals that UHI and UPI intensify heat and air pollution exposure, driving adverse health and well-being consequences in large Pakistani cities. Spatial comparison of Faisalabad and Lahore distinguishes consistent risk patterns, while THAI confirms they are strongly perceived and behaviorally relevant to neighborhoods. Driven by these findings, targeted UGS interventions are proposed as an effective adaptation strategy to reduce thermal stress, improve air quality, and enhance public health, despite ongoing urbanization.

By combining GIS-based priority site detection for strategic green space planning with the innovative THAI scale, the research offers a human-centred framework to build climate resilience. Expanding UGS is a key mechanism for mitigating UHI and UPI health impacts. As such, the study proposed evidence-based green interventions, such as expansion of large parks, interconnected green corridors, vertical greenery, and promotion of native tree species, to begin closing a critical research gap, offer policymakers and public health expert's insights, and lay the groundwork for future work. These findings are instrumental for improving public health, climate resilience, and sustainability in Lahore, Faisalabad, and similar ecological landscapes in Pakistan and beyond.

POLICY RECOMMENDATIONS

Table 16: Short, Medium and Long-term Policy Recommendations

Recommended policy	**Urgency**	**Priority**	**Impact**
Short Term			
1. Plant Test Areas (Demonstration Beds)	**High**	**Medium**	**Medium**
Policy Action: Develop plant test areas (demonstration beds) employing evidence-based air cooling & cleaning native tree species along roadsides, flyover bridges, schoolyards, and other high-exposure municipal localities. These pilot projects will deliver instant localized & cooling air quality benefits, while testing native species functioning under heat-pollution stress environments. Furthermore, a partnership with local plant nurseries for supply & maintenance is also proposed. Later, pilot-based outcomes, the provincial Govt should begin inexpensive urban native plant outlets. ***Lead Institutions***: PHA, Forest Department & EPA	***Planning Instruments:*** Climate Action Plans and Heat Action Plans, Public–private partnership (PPP) frameworks with local nurseries. ***Monitoring Indicators:*** Survival rate and growth performance (%) of planted species, Reduction of schoolyard temperatures & particulate matter near test areas.		
Medium term			
2. Green Roofs and Green Walls through Incentives	**Low**	**High**	**High**
Policy Action: Large industrial units and commercial buildings should promote the installation of solar panels for clean energy, and green roofs, for insulation and air cleaning, i.e. Daroghawala & Misri Shah in Lahore and Industrial site near Ghulam Muhammad Abad & Saifabad in Faisalabad. ***Lead Institutions:*** Solar power provision companies, PHA, Forest Department and EPA	***Planning Instruments:*** Building bylaws, green building codes, grant programs, and incentive-based schemes ***Monitoring Indicators:*** Reduction in roof temperature and indoor cooling demand, energy consumption, and improvement in air quality indicators.		

3. Expand and protect large, contiguous urban Green Spaces	**Medium**	**High**	**High**
Policy Action: Protect and expand major parks and peri-urban green areas to maximize cooling and ecological benefits. ***Lead Institutions:*** LDA, PHA & Forest Department	***Planning Instruments:*** Master plans, land-use zoning, green space protection bylaws. ***Monitoring Indicators:*** reduction LST, NDVI Increase, per-capita green space ($9m^2$/person)		
4. Develop a green corridor in identified high-risk zones.	**Low**	**Medium**	**High**
Policy Action: Create continuous green corridors along major roads, canals, ravines, watercourses, and open spaces to enhance wind-driven cooling and pollution dispersion The Punjab government should prioritize planning that connects scattered parks and green areas into one continuous network of paths for walking and biking with nature. ***Lead Institutions:*** PHA, Municipal Corporation and EPA	***Planning Instruments:*** Street design standards, environmental regulations, and urban greening guidelines. ***Monitoring Indicators:*** Tree canopy cover (%), corridor continuity, $PM_{2.5}$ and NO_2 concentrations.		
Longterm			
5. Integration of UHI–UPI layers into statutory master planning.	**Low**	**Medium**	**High**
Policy Action: UHI–UPI composite risk maps should be part of development proposals, zoning decisions, and strategic environmental considerations. ***Lead Institutions:*** LDA, P&D and Urban Unit	***Planning Instruments:*** Master plans, development control regulations. ***Monitoring Indicators:*** Share of projects screened using UHI–UPI layers, spatial reduction of high-risk zones		
6. Use THAI for Targeted Adaptation	**Medium**	**Medium**	**High**
Policy Action: Apply the THAI scale to recognize communities in need of heat awareness, air pollution action plan & adaptive support. ***Lead Institutions:*** Punjab Health Department, PDMA, NDMA and Local Governments.	***Planning Instruments:*** Heat Action Plans, public health communication strategies. ***Monitoring Indicators:*** Heat-risk & air pollution awareness levels, early-warning system		
7. Protected Low-Emission Zones (LEZs)	**Low**	**Medium**	**High**
Policy Action: Government should legislate the establishment of protected zones where high-emission vehicles, industries, or polluting activities are restricted, enforced with fines or technology such as video surveillance. ***Lead Institutions:*** Punjab Safe City Authority & Punjab Traffic Police	***Planning Instruments:*** LEZs notification frameworks, smart city surveillance and digital enforcement policies. ***Monitoring Indicators:*** Reduction in traffic-related air pollutants within LEZs.		

Source: Authors' compilations.

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APPENDICES

Annexure-1: Questionnaire: For the Development of Thermal Haze Adversity Index (THAI)

This questionnaire will take approximately 5 minutes to complete. The information collected will be used solely for research purposes. We sincerely appreciate your cooperation.

Demographic and Economic Profile of the Respondents

Name: ___________________ Email ID: ______________________________________

1. Age:

☐ Under 18
☐ 18–25
☐ 26–35
☐ 36–45
☐ 46–55
☐ 56–65
☐ 65+

2. Gender:

☐ Male
☐ Female
☐ Other

3. What is your highest level of Education:

☐ No Formal Education
☐ Matric / O-Level
☐ Intermediate / A-Level
☐ Bachelor's Degree
☐ Master's Degree or Higher
☐ Doctorate/Professional degree

4. Occupation:

☐ Student
☐ Employed
☐ Business Owner
☐ Homemaker
☐ Retired
☐ Other: _________

5. Monthly Household Income:

☐ No Income
☐ Below PKR 30,000
☐ 30,000–50,000
☐ 50,000–100,000
☐ 100,000– 200,000
☐ Above 200,000 PKR

6. Which Residential Area of Lahore and Faisalabad do you live in: ___________________

7. Location ___________________

i.e. Lat___________________ Long___________________

8. How long have you been living in Lahore?

☐ Less than 5 years
☐ 5–10 years
☐ 11–15 years

☐ 16–20 years
☐ 21–25 years
☐ More than 25 years

Instructions: Please indicate how much you agree or disagree with each statement using the scale below.

Scale: 1 – Strongly Disagree | 2 – Disagree | 3 – Neutral | 4 – Agree | 5 – Strongly Agree

Section A: Public Awareness of Air Pollution/Smog and Urban Heat (Independent Variable)

Questions	1	2	3	4	5
1. I know that vehicle emissions contribute to smog.					
2. I understand that smog can aggravate asthma and other respiratory issues.					
3. I can identify health symptoms related to smog and heat wave exposure.					
4. I know the difference between fog and smog.					
5. I understand the long-term health effects of smog and heatwaves (i.e. breathing problems or feeling weak over many years).					
6. I am aware that children and the elderly are more vulnerable to heat and smog.					
7. I understand how weather conditions affect smog levels and heat waves.					
8. I know that urban areas are hotter than nearby rural zones.					
9. I understand how a lack of trees and green spaces can raise city temperatures.					

Section B: Public Perception of air pollution/Smog, urban heat and its Risks (Independent Variable)

Questions	1	2	3	4	5
1. Smog is a serious environmental issue in my city.					
2. Heatwaves are a serious environmental issue in my city.					
3. Smog and heatwaves intensity have been increasing over the years.					
4. Smog and extreme heat both pose serious public health risks (e.g. lung diseases, heart problems, asthma, etc.).					
5. Summers have become hotter in the past decade.					
6. Heatwaves are becoming more frequent in my area.					
7. My city has poor air quality during winter (due to a lack of government policies) and poor thermal comfort during summer (due to a lack of green structures, green spaces and shades, etc.).					
8. Smog is more dangerous than people think.					
9. Smog affects my daily life and productivity, e.g., I avoid outdoor work, feel tired, or find it hard to travel or concentrate.					
10. I believe smog can lead to long-term health problems like coughing or breathing problems that last for years.					
11. Burning crops contributes significantly to smog.					
12. Lack of green spaces causes heatwaves.					
13. Urban planning affects smog levels and urban heat, e.g., the number of trees, road design, and building density in the city.					
14. I feel anxious when smog or urban heat levels are high. e.g., I worry about my health, my family, or when it will get worse.					
15. I believe both smog and UHI are a result of human negligence.					
16. More public awareness is needed about the combined health effects of smog and heat.					

Section C: Adaptive Capacity and Tendency (Mediator)

Citations: IPCC Adaptive Capacity Framework; Environmental Psychology Research.

Questions	1	2	3	4	5
1. I feel prepared to handle high-smog or high-heat days.					
2. I have adjusted my home to reduce indoor pollution and heat (e.g., plants, insulation, curtains).					

3. I feel capable of adjusting my habits during smog season and summer season.					
4. I educate others on ways to cope with smog and heat waves.					
5. I believe my actions can reduce smog and heatwave exposure.					
6. I have access to medical care for smog-related illness and heatwave-related problems.					
7. I refer to the Doctor in case of discomfort during smog and heat waves.					

Section D: Reduction of air pollution and urban heat Effects on Health (Dependent Variable)

Questions	1	2	3	4	5
1. I experience fewer health issues because of protective habits, e.g., wearing a mask, staying indoors, or using an air purifier during smog days.					
2. My habits have helped reduce smog and heat impacts on my health, e.g., drinking more water, avoiding outdoor work in high heat, or using shade and greenery.					
3. I feel in control of my health during smog season, e.g., I use medicine when needed.					
4. My family takes health precautions during smog season, i.e keeping windows closed, using masks, or limiting outdoor play for children.					
5. I have seen health improvements due to lifestyle changes, i.e. eating healthier, exercising indoors, etc.					
6. I have fewer respiratory problems since adopting new habit i.e. using an air purifier, wearing a mask, or avoiding traffic areas.					
7. I have seen improvements in my health due to precautionary actions, i.e. using prescribed medication, staying hydrated.					
8. I can manage existing health issues better during smog and heatwaves.					

Section E: Environmental Policies and Governance (Moderator)

Questions	1	2	3	4	5
1. I support bans on crop burning.					
2. I would vote for leaders who prioritize clean air and cooler cities.					
3. My city needs more trees, reflective roofs, and eco-friendly buildings.					
4. I support restrictions on industrial emissions.					
5. I believe public transport improvements can lower both heat and pollution.					
6. I support subsidies for electric vehicles.					
7. The government should support citizens during smog and heat emergencies.					
8. Urban planning needs to account for heatwaves and air pollution, i.e. more trees and more shaded areas.					
9. Citizens should be involved in both smog and climate resilience policymaking.					

Annexure-2: AHP Process

i. ***Criteria Development***

A pairwise comparison matrix is constructed based on the Saaty scale, as shown in Table 1.

Table 1: Pairwise Comparison Matrix for Pollutant Health Impacts

Criteria					
Column1	**NO_2**	**O_3**	**SO_2**	**CO**	**Total**
NO_2	1.00	3.00	3.00	5.00	12.00
O_3	0.33	1.00	1.00	3.00	5.33
SO_2	0.33	1.00	1.00	3.00	5.33
CO	0.20	0.33	0.33	1.00	1.87
Total	1.87	5.33	5.33	12.00	24.53

ii. Normalization of Data

The normalized values are then averaged across rows to derive initial weights for each pollutant, as shown in Table 2.

Table 2: Normalized Pairwise Comparison Matrix

Normalization of Data				
NO_2	O_3	SO_2	CO	Total
0.535714286	0.5625	0.5625	0.416666667	2.077380952
0.178571429	0.1875	0.1875	0.25	0.803571429
0.178571429	0.1875	0.1875	0.25	0.803571429
0.107142857	0.0625	0.0625	0.083333333	0.31547619
1	1	1	1	4

iii. Consistency Check

To ensure the reliability of the pairwise comparisons, the consistency of the matrix is evaluated using the Consistency Index (CI) and Consistency Ratio (CR). The principal eigenvalue (λ_max) is calculated as 4.0436. The CI is computed using the formula 11:

CI = (λmax - n) / (n - 1)……………………………………………………………………………………………10

Where n is the number of criteria based on the 4 gas concentrations, and λmax is the largest eigenvalue of the pairwise comparison matrix. Thus

CI = 4.0436 – 4)/ (4 – 1) = 0.0145…………………………………………………………………………11

The CR is then calculated by dividing CI by the Random Index (RI) for (n = 4), which is 0.90 (Saaty, 2013):

CR = CI / RI……12

where,

CI is the Consistency Index, and RI is the Random Index, a value that depends on the size of the matrix (n) and is obtained from a predefined table.

Thus,

CR = (0.0145)/(0.90) = 0.0161……………………………………………………………………………13

The computed value of the CR value of 0.0161 (< 0.10) indicates that the pairwise comparisons are consistent and reliable for decision-making.

Annexure-3: Communalities

Variable	Initial	Extraction	Variable	Initial	Extraction
PA2	1.000	.685	AC5	1.000	.602
PA4	1.000	.698	AC7	1.000	.635
PA5	1.000	.551	AC8	1.000	.661
PA7	1.000	.525	AC10	1.000	.611
PA9	1.000	.577	AC14	1.000	.635
PA13	1.000	.640	AC15	1.000	.623
PA17	1.000	.595	RAP11	1.000	.614
PA15	1.000	.601	RAP12	1.000	.512
PA18	1.000	.698	RAP16	1.000	.603
PP3	1.000	.802	RAP2	1.000	.668
PP4	1.000	.790	RAP7	1.000	.521
PP14	1.000	.758	RAP17	1.000	.599
PP5	1.000	.771	RAP1	1.000	.616

PP11	1.000	.746	RAP10	1.000	.561
PP7	1.000	.746	GP10	1.000	.786
PP6	1.000	.738	GP14	1.000	.769
PP19	1.000	.743	GP9	1.000	.713
PP2	1.000	.728	GP15	1.000	.725
PP1	1.000	.730	GP5	1.000	.728
PP8	1.000	.711	GP16	1.000	.742
PP18	1.000	.680	GP4	1.000	.704
PP16	1.000	.649	GP11	1.000	.711
PP13	1.000	.658	GP12	1.000	.697
PP17	1.000	.648	AC5	1.000	.602
PP10	1.000	.612	AC7	1.000	.635
Extraction Method: Principal Component Analysis.					

Source: Author's compilations.

Annexure-4: Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings [a]
	Total	Variance %	Cumulative %	Total	Variance %	Cumulative %	Total
1	25.701	53.543	53.543	25.701	53.543	53.543	23.542
2	3.895	8.114	61.658	3.895	8.114	61.658	17.155
3	2.520	5.250	66.907	2.520	5.250	66.907	17.337
4	1.451	3.023	69.931				
5	1.190	2.479	72.409				
6	0.746	1.553	73.963		*Extraction Method: Principal Component Analysis.*		
a. When components are correlated, the sums of squared loadings cannot be added to obtain a total variance.							

Source: Author's compilations.

Annexure 5: Eigenvalues

Variable	Component				Variable	Component		
	1	2	3			1	2	3
PP4	.917				RAP7		.803	
PP5	.882				RAP17		.780	
PP3	.871				AC5		.778	
PP8	.855				RAP2		.778	
PA4	.852				AC7		.758	
PP1	.850				AC8		.750	
PP11	.846				RAP1		.723	
PP2	.844				AC10		.718	
PP6	.833				RAP16		.704	
PP7	.825				AC14		.683	
PP19	.814				RAP12		.671	
PP14	.802				RAP10		.666	
PA18	.798				AC15		.636	
PP18	.794				RAP11		.600	
PA2	.789				GP10			.823
PP16	.775				GP14			.822

PP10	.765				GP5			.811
PA17	.762				GP11			.790
PP13	.751				GP12			.783
PP17	.751				GP4			.783
PA13	.742				GP15			.781
PA7	.727				GP9			.770
PA15	.709				GP16			.755
PA5	.684							
PA9	.649							
Extraction Method: Principal Component Analysis. Rotation Method: Promax with Kaiser Normalization.								
a. Rotation converged in 6 iterations.								

Source: Author's compilations.

Annexure-6: Component Correlation Matrix

Component	**1**	**2**	**3**
1	1.000	.603	.644
2	.603	1.000	.579
3	.644	.579	1.000

Extraction Method: Principal Component Analysis. Rotation Method: Promax with Kaiser Normalization.

Source: Author's compilations.

Annexure: 7 Heterotrait Monotrait Ratio (HTMT)

	Adaptive Capacity	**Govt Env. Policies**	**Public Awareness**	**Public Perception and Behavior**	**Thermal Haze Adversity Index**
Adaptive Capacity					
Govt Env. Policies	0.622				
Public Awareness	0.658	0.681			
Public Perception and Behavior	0.67	0.725	0.872		
Thermal Haze Adversity Index	0.792	0.68	0.61	0.581	

Source: Author's compilations.

Annexure 8: Fornell-Larcker Criterion

	Adaptive Capacity	**Govt Env. Policies**	**Public Awareness**	**Public Perception and Behavior**	**Thermal Haze Adversity Index**
Adaptive Capacity	0.854				
Govt Env. Policies	0.587	0.859			
Public Awareness	0.619	0.651	0.843		
Public Perception and Behavior	0.639	0.701	0.843	0.861	
Thermal Haze Adversity Index	0.736	0.64	0.574	0.554	0.797

Source: Author's compilations.

Annexure: 9 Validity

Index	Value	Benchmark	Interpretation
Chi-Square (Estimated Model)	2615.280	Lower is better	Suggests some misfit, but depends on the sample size
SRMR	0.043	<0.08 good; <0.10 acceptable	Acceptable fit
NFI	0.863	>0.90 desirable	Slightly below the ideal threshold
d_ULS, d_G	Used for PLS consistency checks	Acceptable if small differences	Values seem reasonable

Source: Author's compilations.

Annexure 10: Outer Loadings (Must be 7 and above)

	Adaptive Capacity	Govt Env. Policies	Public Awareness	Public Behavior and Perception	Thermal Haze Index
AC1	0.847				
AC2	0.854				
AC3	0.88				
AC4	0.867				
AC5	0.836				
AC6	0.836				
GP1		0.844			
GP2		0.854			
GP3		0.849			
GP4		0.887			
GP5		0.848			
GP6		0.837			
GP7		0.88			
GP8		0.859			
GP9		0.87			
PA1			0.856		
PA2			0.872		
PA3			0.807		
PA4			0.813		
PA5			0.839		
PA6			0.849		
PA7			0.84		
PA8			0.843		
PA9			0.865		
PP1				0.867	
PP10				0.868	
PP11				0.823	
PP12				0.886	
PP13				0.823	
PP14				0.827	
PP15				0.847	
PP16				0.867	
PP2				0.872	
PP3				0.904	
PP4				0.901	

PP5				0.883	
PP6				0.874	
PP7				0.871	
PP8				0.849	
PP9				0.803	
RAP1					0.806
RAP2					0.826
RAP3					0.734
RAP4					0.79
RAP5					0.808
RAP6					0.777
RAP7					0.829
RAP8					0.801

Source: Author's compilations.

Annexure 11: Limitations of the Study

To maintain transparency and guide future research, there are several limitations with the availability of data, methodology, and contextual applicability.

Data Constraints

This study relied on moderate-resolution satellite images, which are available as open-source data (e.g. Landsat 8 for LST and Sentinel-5P for air pollutants), limiting microscale intra-urban analysis. Furthermore, cloud cover constrained ground-level pollution estimation, as well as reduced data availability and LST accuracy, particularly during summer. Likewise, coarse resolution of Sentinel-5P, column-averaged concentrations. Temporal inconsistencies between episodic Landsat observations and Sentinel-5P data (available from 2018 onwards) restricted detailed comparisons. Ground validation was limited due to a few PMD stations and the absence of reliable ground-based data for NO_2, SO_2, CO, and O_3. Inconsistent EPA records and the unavailability of 2023 union-council population data required reliance on GHSL, which also has resolution and accuracy limitations.

Methodological Limitations

Several limitations, such as unavailability of urban morphological datasets, restricted the integration of urban form parameters into heat and pollution modelling. This includes data on building height, density, imperviousness, street geometry and updated green spaces. Similarly, the lack of site-specific health data on heat stress and air pollution exposure in small administrative units constrained direct quantification of health outcomes and reluctance among residents, particularly in low-income and less-educated areas, introducing potential response bias.

Contextual Boundaries of Applicability

While the findings are specific to Lahore and Faisalabad due to differences in climate, urban form, and governance capacity, the framework is transferable. Its direct applicability elsewhere may be constrained by variations in data availability, institutional capacity, and socio-economic conditions. Nonetheless, the study presents the implications of air pollution and urban heat, proposing interventions for rapidly urbanizing cities of Pakistan with similar environmental concerns.