

URBAN HEAT ISLANDS AND SOCIAL STRATIFICATION: NEIGHBORHOOD-LEVEL VULNERABILITY IN FAISALABAD

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ABSTRACT

Urban Heat Islands UHIs are amongst the most urgent of urban environmental problems in fast-growing cities, where climatic stress converges with social inequity. In densely populated South Asian megacities such as Faisalabad, Pakistan's third-largest city, the unequal distribution of heat exposure amplifies existing social divisions. Empirical research has shown that low-income communities are disproportionately exposed to the impacts of UHIs resulting from poor quality housing, lack of vegetation, and limited access to cooling infrastructure (Harlan et al., 2006; Jenerette et al. This article examines neighborhood-level vulnerability in Faisalabad, combining satellite-based land surface temperature (LST) data and socioeconomic indicators. We took a mixed-methods approach, using machine learning classification models (Random Forest and Gradient Boosting) to map UHI intensity and qualitative interviews to capture residents lived experience of heat stress. General patterns indicate pronounced spatial disparities: high-dense, low-income residential areas show increased UHI magnitude; the demand for adaptive elements is their rate-limiting factor. More affluent areas on the other hand have better planning, vegetation and access to cooling technologies. These results complement international evidence concerning the concentration of environment risk with social deprivation (Chakraborty et al., 2019). The research highlights the importance of equity-driven climate adaptation interventions, such as heat action plans, urban greening programs and infrastructure upgrades directed at the most vulnerable.

Keywords: Urban Heat Island, social stratification, vulnerability, Faisalabad, machine learning, climate adaptation

INTRODUCTION

Urban Heat Islands (UHIs) in the world's cities are being exacerbated by urbanization, climate change and increased energy use. The UHI—characterized by much warmer temperatures in the heart of a city than its rural setting—has been studied extensively in North America, Europe and East Asia (Oke, 1982; Stewart & Oke, 2012). The research has found that in areas where natural land cover is replaced by impervious surfaces like asphalt and concrete as well as roof-packed buildings, the heat can get trapped leading to decreased airflow and higher night time temperatures. Moreover, human-induced heat sources due to motorized traffic, industry or air conditioning contribute to aggravate the UHI (Grimmond, 2007; Voogt & Oke, 2003).

But research in South Asia is relatively scarce, even though the region is highly exposed to extreme heat. The subcontinent frequently faces protracted heatwaves with adverse societal and health implications (Im et al., 2017). South Asian cities are highly urbanized, with lack of strong governance and low investment in climate resilient infrastructure which make them more vulnerable to UHIs (Rana et al., 2021). Significant UHI signals have been documented in cities such as Delhi and Dhaka (Ahmed et al., 2016; Abbas et al., 2018; Rasul et al., 2019), Lahore, Karachi, though studies empirically linking them to heat vulnerability are limited.

Faisalabad exemplifies the UHI problem. The city, as the third largest in Pakistan, developed rapidly both industrially and demographically since the 1950s and is referred to as 'Manchester of Pakistan' due to its being a center of textile-based trade (Qureshi, 2010). Faisalabad's urban sprawl is largely unplanned and sprang from the need for housing and to develop new industrial sites, primarily due to sudden urbanization caused by an escape of partitioned migrants. The city has grown disproportionately without the necessary infrastructural development creating pressure on the traffic congestion, environmental pollution and the social imbalances (Rana et al., 2021). Low-income settlements areas, known as informal settlements are populated by communities with low income and are defined by poor quality housing

materials, lack of green cover or space, reverse gradient level for slopes and high density overcrowding where people live without electric supply or potable water (Saeed et al., 2020). These circumstances increase urban heat for its city residents, heightening physical and social vulnerability.

Knowledge of neighborhood-specific susceptibility to UHI is crucial as the exposure to heat does not have the same effect on all residents. How social inequality and environmental conditions intersect with each other determines which populations face the highest risks and which have access to resources that enable them to adapt. More affluent residents are likely to have access to planned housing colonies with trees and air conditioning, well-applied landscaping, larger plot sizes, and electricity for air-conditioning that can help protect them from extreme heat (Mitchell & Chakraborty, 2014). Conversely, vulnerable populations are unprotected from this risk and are at least partially exposed during their daily activities to the stresses of high-temperature environments (Harlan et al., 2006).

This disparate allocation of risk is at the core of evolving ideas about climate justice, which notes that those (most frequently) least responsible for contributing to climate change are paying a disproportionate price/serving as its 'victims' (Schlosberg & Collins, 2014). In the case of UHIs, this results in varied health consequences with disadvantaged populations more at risk for disease and illness related to heat, loss of labour productivity and long-term social inequity (Revi et al., 2014). Data from cities, such as Phoenix, USA (Chow et al., 2012), and Los Angeles provide evidence that people of racial minorities and those in low-income communities are disproportionately exposed to UHI impacts (Hsu et al., 2021). Using this lens to examine Faisalabad provides insight on how class, income, and spatial inequality intersect with environmental stressors.

It is unfortunate that area-based studies in Pakistan are few and far between; the extent of the research around dust storm climates and impacts are limited to Lahore, Islamabad and Karachi (Abbas et al., 2018; Saeed et al., 2020). The absence of

research on secondary cities such as Faisalabad has created a crucial knowledge gap, due to quick expansions and exposure to climate extremes. Through probing the neighborhood-level dynamics in Faisalabad, it is important for academic learning and policy intervention (i.e., heat action plans, green infrastructure projects, pro-poor urban planning that designed to address the needs of low-income groups) (Rana et al., 2021).

By embedding UHIs in the larger context of social stratification, this study demonstrates that urban heat is not only an environmental issue but also a matter of justice. In the absence of intervention, climbing temperatures in cities like Faisalabad will only exacerbate those inequalities further, most harshly impacting communities who already endure economic precarity and infrastructural deprivation.

Research Objectives and Hypotheses

1. d) To estimate differences in UHI intensity between areas of Faisalabad.
2. To evaluate associations between UHI hotspots and socioeconomic position.
3. To understand the lived experience of heat stress and adaptation.

Hypothesis: Deprived, congested zones in Faisalabad face more UHI exposure and lower adaptive capacity than wealthier well-planned areas.

LITERATURE REVIEW

Urban Heat Islands (UHIs) have been considered as a key urban climatological phenomenon since the seminal study of Oke [1], who elucidated the energy-related foundation for temperature contrast between urban and rural locations. Follow-up studies have shown that UHIs are not isolated meteorological oddities but reflections of structural urbanization effects. The high densification of building, the high thermal admittance materials used in construction, less vegetation and issue of anthropogenic heat make city warmer as compared to their outskirts (Voogt & Oke, 2003; Grimmond, 2007). This seminal work laid the grounding for the physical causes of UHIs, and has been an influence on decades of research associating UHIs with sustainability, public health, planning.

Since then, more emphasis has been placed in research toward the social aspects of UHIs. Physical processes are relatively consistent around the world, but they engender uneven patterns of exposure and vulnerability that reflect socioeconomic inequality. Harlan et al. (2006) connected the most temperature-impooverished microclimates and emblematic races in Phoenix, Arizona with social stratification at neighborhood scale, where subaltern-status localities had higher UHI values. Similarly, Chow et al. (2012) found that already vulnerable groups suffered disproportionately during heat waves because of poor quality housing and lack of green spaces and less access to adaptive technologies such as air conditioning. These results indicate that UHIs are amplifiers of already existing social inequalities and not just neutral climatic consequences.

The developments in remote sensing techniques have a great impact on the UHI related studies. Satellite systems like Landsat, MODIS and ASTER have thermal infrared sensors which can be used for mapping LST at various resolutions (Voogt & Oke, 2003; Weng, 2009). These data enable the spatial representation of heat hotspots in cities and facilitate comparisons between neighborhoods/land use types. Remote sensing methods have the merit of providing information on extensive areas in a cost-effective way, rendering them especially relevant in developing countries with few ground-based climate measurements (Zhao et al., 2014).

In addition to simple LST mapping, recent developments combined thermal data with datasets on urban shape and land cover. The “Local Climate Zone” (LCZ) classification by Stewart and Oke, 2012 is an integrated framework to compare the UHI intensity in different urban configurations. The model is especially well-suited for comparative urban research in which variations in building density and surface type make measurement difficult.

Though geospatial methods can specify where UHIs are found, understanding who is affected requires a synthesis of socioeconomic data. Social vulnerability analyses frequently employ census data or household surveys, cross-walking indicators related

to income, housing quality and education to spatial heat patterns. Considered from U.S. cities, Mitchell and Chakraborty (2014) coined the term “thermal inequity” which explained as to why disadvantaged communities experience higher relative heat exposure consistently within their urban area. More recently, Hsu et al. (2021) substantiated these disparities at a planetary scale, demonstrating that socially vulnerable groups systematically inhabit warmer neighborhoods in a wide range of urban contexts.

This literature indicates that examining UHI and vulnerability must look beyond the physical features to consider social variables. Disparities in housing, infrastructure and green space access increase exposure for vulnerable sectors, concomitantly reducing adaptive capacity. The disparities are even more pronounced in fast growing cities and urban regions of the Global South where social justice issues tend not to be integrated in urban planning frameworks (Revi et al., 2014).

Recent studies have employed machine learning methods to enhance UHI identification and prediction. Conventional regression models are restrictive due to their assumptions of linearity and collinearity, whereas machine learning algorithms (e.g., Random Forests, Support Vector Machines, Gradient Boosting) can account for complex nonlinear relationships between multiple predictors (Breiman, 2001; Sun & Grimmond, 2019). One such application is to merge thermal imagery, land cover data and indices of urban morphology to produce fine-scale UHI vulnerability maps. These approaches have shown to provide good accuracy performance and were used more and more in urban climate research around the world (Zhou et al., 2019).

Moreover, bringing in big data sources – mobile phone data, social media or crowd-sourced temperature readings – provides new pathways for identifying urban microclimates and human-environment interaction (Goodchild, 2007; Yang et al., 2020). Such strategies are particularly applicable in places such as South Asia, where traditional data assets are weak, but mobile penetration is high.

South Asia has become a focal region of climate vulnerability, and partner countries in it experience annual heat waves resulting in large-scale mortality and morbidity (Im et al., 2017). The cities in the region, for instance Delhi, Dhaka, Karachi and Lahore have witnessed significant UHI signal as depicted by satellite images and ground observation (Abbas et al., 2018; Rasul et al. These cities have high population density, infrastructure death traps and low-income areas urbanized under situations of socio-spatial inequality that amplify the consequences of exposure to heat on health and its economic impact.

UHI studies in Pakistan are limited, but increasing. Abbas et al. (2018) analyzed sprawl-induced UHIs in Lahore with Landsat data, wherein they concluded with higher thermal stress experienced by peripheral informal settlements. Saeed et al. (2020) studied informal settlements in Karachi and Islamabad, emphasizing their extreme susceptibility to climate extremes as a result of precarious housing infrastructure. Rana et al. (2021) offered a general view on climate vulnerability in Pakistani cities and the necessity of adaptive strategies to adopt.

Despite these such contributions, the mid-sized industrial cities in general and Faisalabad in particular is under-research. According to Qureshi (2010) unplanned and high speed expansion of Faisalabad has resulted in environmental strains although studies have predominantly centred on megacities. This is a significant shortfall, given that secondary cities in South Asia are expected to accommodate much of future urban expansion (UN HABITAT, 2019). In Faisalabad, the importance of UHIs is critical for both academic and policy considerations as it offers lessons on how industrial urbanization intersects with social vulnerability in a region left out from much of global climate research.

The literature overwhelmingly shows that UHIs compound social inequities and targets sub-populations. However, in Pakistan studies on UHI have concentrated mainly on large metropolitan cities, ignoring neighborhood level variations in mid-size cities. Additionally, while remote sensing advancements abound, there is sparse

connection between these methods and social vulnerability analysis in combination with local-level qualitative information. This lacuna underscores the complementarity of what can be achieved by geospatial mapping, machine learning and ethnography to get a rounded idea of UHI effects in Faisalabad.

METHODOLOGY

Here, we used a mixed-methods approach that combined geospatial analysis, machine learning, and qualitative interviews. Mixed methods are an emerging methodology in climate and social vulnerability research because they enable spatial quantification of these environmental phenomena as well the investigation into community-level experiences (Creswell & Plano Clark, 2018; Johnson & Onwuegbuzie, 2004). By fusing quantitative satellite-based land surface temperature (LST) observations and qualitative stories, the research comprehensively interpreted multiple dimensions of UHIs and their social impacts in Faisalabad.

The LST was estimated using thermal infrared images acquired by Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) for the period from 2018 to 2022. Because of their 30 m spatial resolution and continuous temporal coverage, Landsat data are extensively applied in urban climate studies (Weng, 2009; Zhao et al., 2014). Socioeconomic index factors such as income, education, type of structure inhabited and population density were obtained from Pakistan Bureau of Statistics (PBS, 2017) in accordance with the practice of merging census-based vulnerability measures with environmental indicators (Mitchell & Chakraborty, 2014). In addition to spatial analysis, the researchers conducted 40 semi-structured interviews with residents in two contrasting neighborhoods (20 from low-income informal settlements; and 20 from wealthier planned colonies). Semi-structured interviews have been widely recommended for vulnerability research as they allow the interviewer to follow up on new lines of enquiry and to probe individual participants lived experiences while still remaining focused on a specific set of themes

(Bryman, 2016). Specific questions addressed perceptions of heat, coping responses and resources for adaptation.

The study population included around 2000 census blocks representing formal and informal settlements in Faisalabad, Pakistan. To ensure variation in socioeconomic status across neighborhoods, stratified sampling was used which is similar to previous studies of UHI in South Asia and elsewhere (Abbas et al., 2018; Harlan et al., 2006).

Remote Sensing: LST used in this study was produced by the methods of radiative transfer equation In Google Earth Engine (GEE), which is a cloud computing system for working with geospatial data, released under Apache License 2.0(Gorelick et al., 2017).

Machine Learning: Two types of ensemble learning—Random Forest (Breiman, 2001) and Gradient Boosting (Friedman, 2002)—were used to classify the UHI hotspots and predict vulnerability patterns. These models have been shown to perform well in the context of urban climate research (Sun & Grimmond, 2019).

Qualitative Coding: We used NVivo 12 to interpret interview transcripts, with inductive thematic coding to identify patterns of vulnerability, adaptation, and experience-based understandings of urban heat.

A university Institutional Review Board provided ethical approval. Informed consent was obtained from all the subjects, and their identity was protected using pseudonyms and by deleting identifying information [Orb et al., 2001]. Rigour was increased through triangulation, where quantitative geospatial data, statistical models and qualitative narratives were combined in this analysis, a technique advocated to boost the validity of environmental social science research (Flick 2018). The trustworthiness of ML output was examined in terms of reliability (e.g. cross-validation), which were validated qualitatively by means of inter-coder checking and member validation.

Through the use of this multi-method approach, we were able to capture both the empirically observable distribution of UHI and lived experiences of heat vulnerability

throughout Faisalabad, thereby gaining a holistic view into how climate stress intersects with social stratification in the city.

DISCUSSION

Such these findings are in line with international research that demonstrates the unequal experience of UHIs overseas, and some studies indicate that populations most vulnerable to the impacts of urban heat tend to be those who are already socially and economically disadvantaged (Mitchell & Chakraborty, 2014; Jenerette et al., 2016). In Faisalabad, unplanned industrial growth has translated into a divided urban landscape in which low-income areas receive the full heat exposure blow. The highest LST and health vulnerabilities were identified in informal settlements, with crowding houses, lack of vegetation and poor infrastructure. The density of concrete houses, the small size of their streets, and lack of air circulation all contribute to heat retentions making daily living too precarious for inhabitants who are met with numerous vulnerabilities like poverty, food insecurity or poor health care access.

These findings are strongly echoed by research in other settings. For instance, Harlan et al. (2006) found that disadvantage neighborhoods were persistently warmer than affluent ones, largely due to varying access to green infrastructure and household quality. There is very also specific research in Chinese cities suggesting that: impervious surfaces and low canopy coverage increase heat exposure in poorer districts, reinforcing existing inequalities (Zhou et al., 2019). The Faisalabad case reinforces these trends, illustrating how socioeconomic residential segregation layers onto climatic stressors to exacerbate urban disparities. The comparison further highlights that UHIs are not only environmental catastrophes in themselves, but also dangers socially produced through failures of governance, infrastructural voids and inequitable distributions of adaptive capacity.

The qualitative data collected additionally demonstrates that adaptive capacity is defined according to a socio-economic gradient. Air conditioning, private gardens and consistent electricity are used by wealthier households to produce cooler micro-

climates and achieve greater thermal comfort. Though less affluent families have no option but to adopt the low-cost coping mechanisms of rooftop sleeping, water sharing (among neighbors); and cooling down with the help of hand fans or wet cloth. While these are creative solutions, they only provide temporary relief and can expose people to other risks like mosquito bites, dehydration, or decrease security at night. This dichotomy is consistent with that reported by Hsu et al. (2021) refer to as “thermal inequity,” in which marginalized groups are not only more susceptible to heat exposure but also less equipped to cope with its effects. Crucially, such disparities in Faisalabad are compounded by systemic pressures such as persistent energy deficiencies, bad urban governance and fast unwilled *déploiement* (Qureshi, 2010; Saeed et al., 2020). Therefore, the scope of adaptation should not be confined to physical measures but also inclusive of institutional changes and social equity.

Its findings have important implications for urban policy and climate adaptation planning. First, urban greening interventions such as tree planting, rooftop gardens and the establishment of micro-parks can substantially lower surface temperatures in impacted neighbourhoods. Global meta-analytical evidence suggests that increasing vegetation reduces local temperatures by up to 2°C (Bowler et al. These are particularly necessary in thickly populated informal settlements of Faisalabad where green space is almost non-existent and public lands come under many competing pressures especially real estate development. Collaboration with local organizations and civil society would strengthen the sustainability of these greening projects, which would have both environmental and social co-benefits.

Second, heat plans of action need to be put into place to help protect people who are vulnerable during severe events. These could potentially include early warning systems, cooling shelters at schools, mosques or community centers and public health campaigns to educate people about hydration and heat-related illness. Crucially, they have to be designed inclusively and consider the elderly, children, women and people with disabilities that are at risk. There are successful models in South Asia with

Ahmedabad's Heat Action Plan in India, which has been effective in reducing heat related mortality through integrated health, planning and communication actions (Azhar et al., 2014). Replicate some of such strategies for Faisalabad and you can have low-cost resilience.

Third, urban planning with a focus on equity is required to tackle systemic inequities leading to vulnerability. Any policy (Schlosberg & Collins 2014) should include elements of climate justice, meaning that adaptation resources are allocated first to the most disadvantaged places. This entails integrating environmental planning into urban governance, including climate change concerns in zoning codes and enacting green building codes. There must also be meaningful community engagement. Informal settlers are often residents who have extensive community knowledge and practices of coping with heat, and involving their voices in decision-making could enhance the relevance and legitimacy of interventions.

The study has some limitations that should be recognized, notwithstanding these contributions. One, that the dependence on secondary socio-economic data might gloss over the micro level variations in neighborhoods. Household-based studies could offer finer-grained assessments of vulnerability, particularly in reference to gendered effects and household energy practices. The qualitative part (a valuable but necessarily context-specific approach) was based on only 40 interviews rigid at generalizing findings. Widening out the sample size, including focus groups and utilizing participatory mapping methods may further strengthen the evidence base. Third, the study's limitation to one city (Faisalabad) limits its generalizability. Comparative studies between Pakistani cities, such as Karachi, Lahore, and Islamabad, would enhance the external validity of the findings since each city experiences specific combinations of climate, governance or demography stressors.

However, despite the high predictive accuracy of machine learning models, they are ultimately constrained by the input data quality and resolution. Adding higher resolution satellite images (e.g., Sentinel-2 or commercial from high-resolution

datasets) and local microclimate observations taken by ground-based sensors would further increase spatial precision of the map and enhance identification of intra-urban heat patterns. Integrating these sets with health outcomes, such as hospitalisations from hot weather events, also has the capacity of strengthening evidence on public health implications of UHIs.

Finally, longitudinal studies are necessary to monitor how UHIs and social vulnerability change under future climate scenarios. Average temperatures in Pakistan are projected to rise, and extreme heat events will become increasingly frequent in the coming decades, and the crossing of these climate thresholds with aggressive urbanization makes places like Faisalabad particularly vulnerable. A long-term viewpoint would enable researchers and policy makers to monitor if interventions—such as greening projects, heat action plans, governance changes—are truly reducing vulnerability or if new inequities are developing. Furthermore, to understand changes in exposure patterns caused by migration, the movement of industry and changing population distribution can be useful for anticipating future needs.

Taken together, this research contributes to the literature around climate and UHIs by drawing attention to the social differentiation of exposure to heat and of adaptation in Faisalabad. It demonstrates that though urbanization leads to economic development, the absence of comprehensive environmental planning poses high risks to poor communities. Grounding Faisalabad in a broader global comparative context, the study illustrates universal but uneven contours of thermal injustice. Meeting these challenges demands an integrated approach linking technical solutions (ecological restoration, early warning systems) with necessary governance reforms and principles of climate justice. This type of integrated approach is the only way for Pakistan's and other developing countries' cities in the Global South to become resilient to the escalating threat that is urban heat.

CONCLUSION

This research illustrates that Urban Heat Islands (UHIs) in Faisalabad are not just environmental issue rather they are one of the social justice issues. The results indicate unequivocally that vulnerability to heat stress is differentiated along social lines: deprived communities are over-represented when it comes to exposure to high land surface temperatures and lack adaptive capacities if challenged by heat. These outcomes are in line with worldwide studies that confirm how UHIs increase social-injustice by localizing social vulnerable communities' residents mainly into these high health-risk areas (Harlan et al., 2006; Mitchell & Chakraborty, 2014).

Through the combination of remote sensing, ML models, and qualitative interviews we aimed to provide insights about the multi-dimensional nature of heat vulnerability in the city. Quantitative findings showed that low-income, high-density areas with sparse tree canopy consistently reported the highest UHI intensities yet qualitative accounts of rooftop sleeping or communal water sharing suggested residents are instead leveraging low-cost but labor-intensive coping strategies. In wealthier neighbourhoods, however, there was greater buffering capacity where access to cooling technology, greenery (which provide shade) and reliable electricity meant it wasn't so sweltering—an example of the model Hsu et al. (2021) describe as “thermal privilege.”

These results underpin the urgency for equity-focused adaptation responses. There is evidence that urban greening, another form of urban intervention in the form of tree planting in deprived areas, can lead to substantial reduction in city surface temperatures (Bowler et al., 2010). Further, localised heat action plans based on successful example such as those in Ahmedabad, India could work as early warnings and community cooling houses with well-targeted public health response (Azhar et al., 2014). Crucially, those interventions need to be situated within more comprehensive urban governance arrangements that are oriented toward climate justice (Schlosberg & Collins, 2014), so that marginalized populations get the best share of adaptation gains.

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