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Computational Review and Assessment of The Urban Heat Island Effect and Its Impact on Building Space Conditioning

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Abstract

This paper reviews and reports the recent progress and knowledge on the specific impact of the urban heat island (UHI) effect on building space conditioning for vulnerable housing where lack of air conditioning and fuel poverty causes indoor overheating, thus increasing vulnerability. Previous studies demonstrated that the increase of the ambient temperature due to UHI and heat waves impacts adversely cooling energy consumption of buildings and raises the peak electricity demand during summer and heat waves. Given the aging and dilapidated housing conditions in low-income communities, mostly of color and minorities, the economic burden of the cooling energy penalty induced by urban overheating is higher. However, literature on overheating is primarily driven by the physical characteristics of the building such as insulation, albedo, and envelope properties, and the Heat Vulnerability Index (HVI) by demographic data such as age, income, education largely remains isolated thus failing to capture the overall understanding of heat vulnerability and the role architects/urban designers can play in mitigation. Through a computational query review of the last fifteen years of publication, we are inquiring, about how UHI impacts building energy consumption in low-income and poor-quality housing and what role city and housing characteristics play in indoor overheating. Our study suggests, that in the US, due to segregated historic planning policies, low-income houses are often located in low tree canopy areas with varying urban typologies, and higher impervious material which substantially increases the air temperature thus determining energy consumption and anthropogenic heat release which contribute to present-day inequitable exposure to intra-urban heat. Both housing characteristics and the location of housing play a crucial role as similar housing will experience different exposure to intra-urban heat if not located in a heat canyon. Through this literature review, it became evident that there is a gap in the research that fails to connect building characteristics and overheating with heat vulnerability. Research involving UHI and heat vulnerability has continued to advance through energy analysis and mitigation studies, but future studies need to redefine the HVI index, especially by incorporating city and housing characteristics, which can help architects/urban designers make informed design decisions.

Keywords: urban heat island, heat vulnerability, building energy consumption, overheating.

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1. INTRODUCTION

The urban heat island (UHI) effect is one of the most significant demonstrations of urban climate change where a considerable difference in air temperature can be observed between cities and their rural surroundings (Oke et al. 2017; Wilson and Chakraborty 2019; Krayenhoff et al. 2014; Santamouris 2015; Bao, Li, and Yu 2015; Stewart, Oke, and Krayenhoff 2014). In the US, extreme heat is recognized as the leading cause of death and continues to challenge many cities to adopt mitigation techniques to reduce the impact on citizens' health due to prolonged heat exposure. However, heat waves receive little public and policymaker attention for adopting mitigation or advanced energy retrofits. In recent decades increased and rapid urbanization modified the outdoor air temperature, thus increasing energy consumption to acquire indoor thermal comfort. With the increasing urban temperature due to surface modification and global environmental inequality, vulnerable populations living in the city center or nearby suburban neighborhoods are affected the most (Chakraborty, Collins, and Grineski 2019). Extreme weather conditions such as heat waves in urban areas have a significant impact on the quality of life and health of urban citizens. Exposure to extreme heat can impact a person's ability to thermoregulate body temperature, resulting in heat stress, which may lead to death (Luber et al. 2006). UHI also enhances air pollutants and heat-stress-related diseases in urban areas which continue to be challenging for the vulnerable population with frequent heat waves where lack of access to health care, and proper housing conditions causes indoor overheating, thus increasing vulnerability (Rathi et al. 2022; Niu et al. 2021; Haddad et al. 2020; Khan et al. 2020). Other than health, UHI and heat waves increase the average cooling energy penalty by increasing peak electricity demand during summer and heat waves (Santamouris et al. 2015; Gonzalez-Trevizo et al. 2021; Declet et al. 2017; Gabbe and Pierce 2020; Sailor 2014). Given the aging and poor housing conditions in underprepared communities, mostly of color and minorities, the economic burden of the energy penalty induced by urban overheating is higher. However, literature on overheating during extreme heat events, primarily driven by meteorological data and physical characteristics of the building (Akbari et al. 2016; Aflaki et al. 2017; Yu et al. 2021) and the Heat Vulnerability Index (HVI), driven by demographic data (Niu et al. 2021; Bao, Li, and Yu 2015), largely remains isolated. By exploring the interrelationship of the above factors associated with heat vulnerability through a systematic review of existing literature, we are inquiring about the role architectural research can play in preparing and improving resilience:

1. How does UHI impact building energy consumption in low-income and poor-quality housing?
2. What role does housing play in indoor overheating?

2. METHOD

2.1. Selection of Scholarly Work

Various causes of urban heat island and their impact on energy consumption is well documented and cited in thousands of literatures over the last few decades. For this study, we limited our search results to the last fifteen years and used computational query language analysis to synthesize large volumes of scientific data from Web of Science, and Scopus Databases for literature on UHI and building space conditioning, using at least two out of five of the following keywords: urban heat island, building energy consumption, overheating, heat vulnerability index, building characteristics.

$$C(n,r) = \frac{n!}{(r!(n-r)!)}$$

Where n=5 and r= 2 or 3 or 4 or 5

n	r	Total Combinations
5	2	10
	3	10
	4	5
	5	1

2.2. Data Processing and Cleaning

After reviewing each abstract, we limited our search to the 1132 literatures out of 3176 that either directly deal with the urban heat island effect and its impact on energy consumption or draw some conclusions, validation, or provide an overview on this topic. We observed that various fundamental energy balance studies have been done outside our search parameter (fifteen years). Thus, we have added a few literatures that were published more than fifteen years ago to explain the fundamentals of heat islands and energy balance. From the 1132 literature dataset, we rejected papers if they were not written in English, repeated, not peer-reviewed, and did not have building and city scale studies, with the final dataset consisting of 617 literatures.

2.3. Database Creation and Management

In lieu of exporting bibliographic information from above-mentioned global citation databases, we used SQL (Structured Query Language) to create an

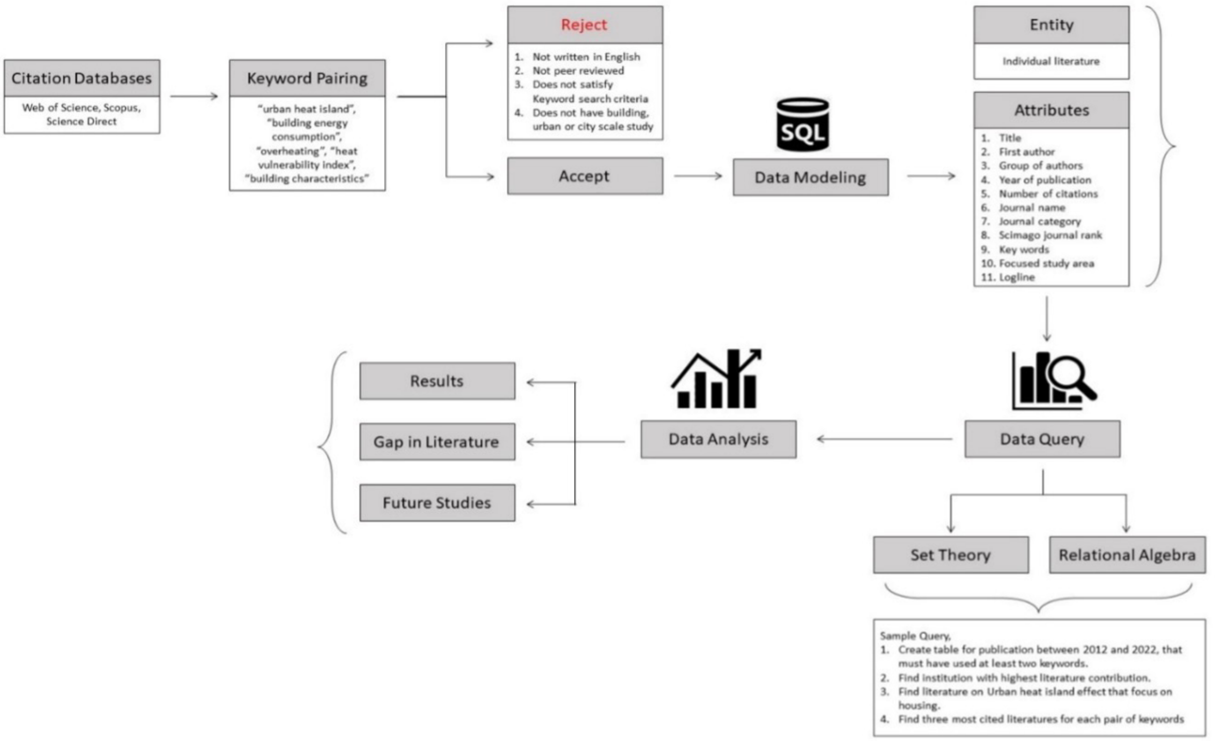

Figure 1: Literature Review Method

independent bibliography database where each entity (row) provides information about individual literature as a combination of multiple attributes (columns). Figure 1 demonstrates the bibliometric literature review process that systematically sorts the literature. We divided the data into two categories, first bibliographic attributes such as title, author(s), year of publication, number of citations, journal name, journal category, SCImago journal rank, and keywords; second, study attributes such as focused study area, logline, energy consumption reduction, climate, study scale, temperature reduction, etc. Through Data Query further tables were created as a set of logical summarized groupings of entities. We used keyword pairings as search queries to organize the existing literature.

3. LITERATURE SEARCH SUMMARY

3.1. Descriptive Analysis

The first part of the results manifests descriptive statistics of the number of articles published per year from Web of Science, and Scopus, from 2007 until 2022 March without using any criteria except year and singular keywords. Across all the databases, the recent interest in the field of UHI and building energy consumption follows a continuously increasing trend (Fig. 2,3), with a substantial increase in publications in the last fifteen years, whereas very little published work can be found in other categories, specifically for heat vulnerability index and building characteristics.

The five highest contributing institutions are presented for each keyword we have used in Table 1 from the Web of Science Database and in Table 2 from the Scopus Database. Across all the sections, Chinese Institutions are the most contributing followed by European Institutions. Arizona State University, the United States Department of Energy, and Lawrence Berkeley National Laboratory are the only US-affiliated institutions who made it onto the list with contributions limited to urban heat islands and building energy consumption.

3.2. Research Interest

To identify the research interest for publications a keyword pairing network was generated. We used author-keyword to identify existing research interests as the keywords chosen by the author that best reflect the contents of their document. We explicitly avoided indexed keywords, as those are chosen by content suppliers, not by the author. Tables 3 and 4 show the three most cited literature for each author-keyword pairing from both Web of Science and Scopus Databases. Even though there is ample literature available on urban heat island, in the last decade only one literature has considered both UHI and building characteristics. We see similar results for building energy consumption and

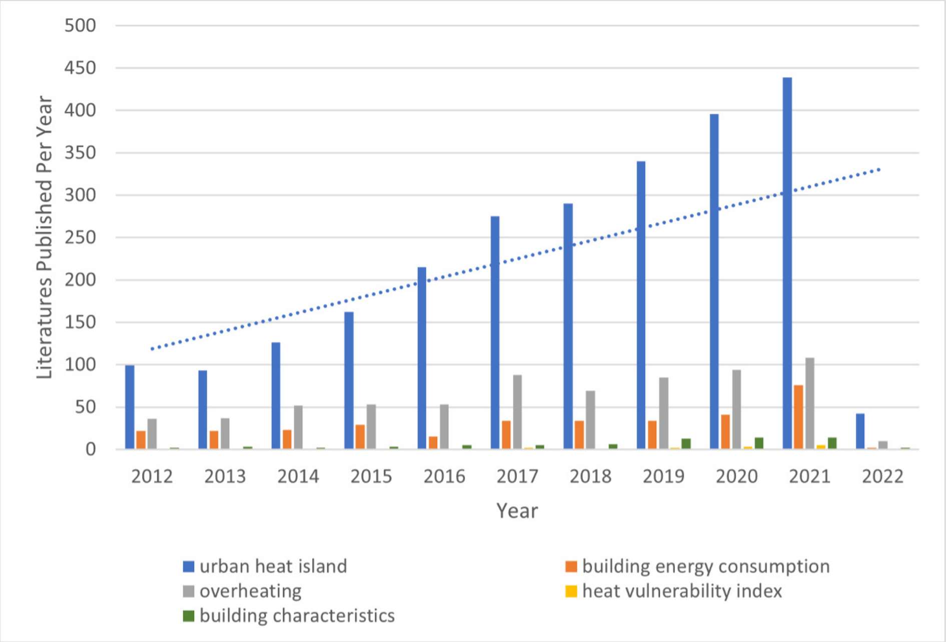

Figure 2: Number of Articles Published Per Keyword—Web of Science

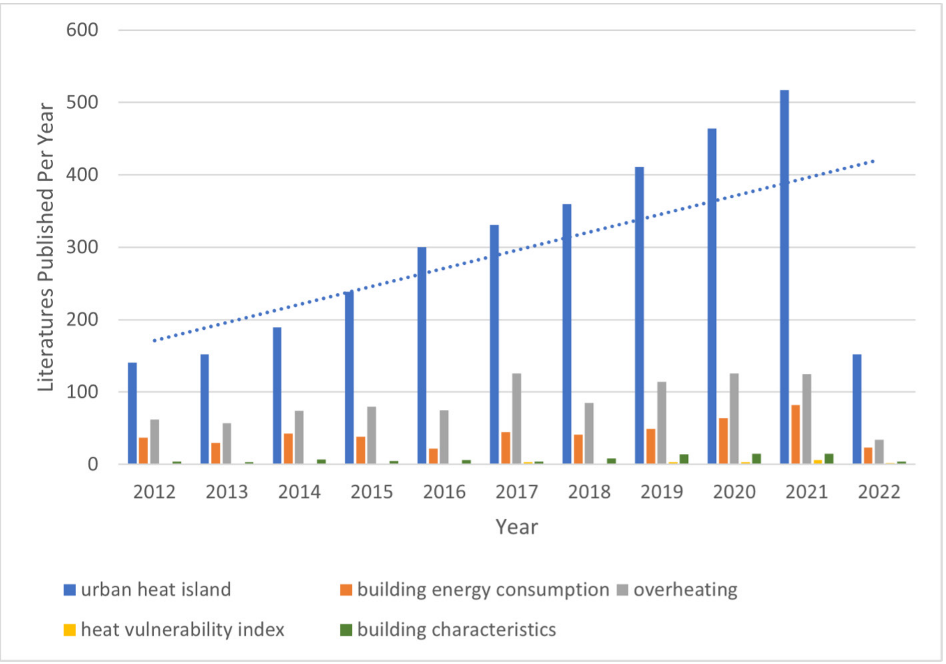

Figure 3: Number of Articles Published Per Keyword—Scopus

Table 1: The five highest contributing institutions for each keyword (Web of Science Database)

Literature Topic	Affiliated Institutions	# Of Literature
“Urban Heat Island”	Chinese Academy of Sciences, China	157
	University Of Chinese Academy of Sciences, China	63
	Arizona State University, USA	62
	University Of Perugia, Italy	61
	University Of New South Wale s Sydney, Australia	59
“Building Energy Consumption”	Chongqing University, China	15
	United States Department of Energy DOE, USA	12
	Tianjin University, China	10
	Chinese Academy of Sciences, China	9
	Shandong Jianzhu University, China	9
“Overheating”	University College London, UK	23
	University Of London, UK	23
	Loughborough University, UK	18
	University Of New South Wales Sydney, Australia	14
	Russian Academy of Sciences, Russia	13
“Heat Vulnerability Index”	Chinese Academy of Sciences, China	2
	Chinese Center for Disease Control Prevention, China	2
	Public Health Foundation of India, India	2
	Administrative Staff College, India	1
	Australian National University, Australia	1
“Building Characteristics”	Tsinghua University, China	5
	Delft University of Technology, Netherlands	4
	University Of Shanghai for Science Technology, China	4
	Tianjin University, China	3
	Aalborg University, Denmark	2

Table 2: The five highest contributing institutions for each keyword (Scopus Database)

Literature Topic	Affiliated Institutions	# Of Literature
“Urban Heat Island”	Chinese Academy of Sciences, China	194
	University of Chinese Academy of Sciences, China	81
	Arizona State University, USA	78
	University Of Perugia, Italy	69
	University Of New South Wale s Sydney, Australia	65
“Building Energy Consumption”	Chongqing University, China	25
	Xi'an University of Architecture & Technology, China	21
	Ministry of Education China, China	20
	Tianjin University, China	15
	Lawrence Berkeley National Laboratory, USA	10
“Overheating”	Loughborough University, UK	27
	University College London, UK	25
	The Bartlett Faculty of the Built Environment, UK	24
	Oxford Brookes University, UK	16
	University of Bath, UK	16
“Heat Vulnerability Index”	Chinese Academy of Sciences, China	2
	Chinese Center for Disease Control Prevention, China	2
	Public Health Foundation of India, India	2
	ID Plastic Surgery Hospital	1
	University Putra, Malaysia	1
“Building Characteristics”	Tsinghua University, China	7
	Delft University of Technology, Netherlands	6
	University of Shanghai for Science Technology, China	5
	Université de Lausanne UNIL	3
	The National Research Center for Work Environment, Denmark	3

Table 3: Three Most Cited Literature Per-Key Pairing Word in the Last Ten Years (Web of Science)

	Urban Heat Island	**Building Energy Consumption**	**Overheating**	**Heat Vulnerability Index**	**Building Characteristics**
Urban Heat Island	(Estoque, Murayama, and Myint 2017), 379	(X. Li et al. 2019), 107	(Santamouris et al. 2015), 357	(Méndez-Lázaro et al. 2018), 33	(Toparlar et al. 2018), 32
	(Santamouris et al. 2015), 357	(Hirano and Fujita 2012), 86	(Oikonomou et al. 2012), 90	(de Azevedo et al. 2018), 8	-
	(Gunawardena, Wells, and Kershaw 2017), 281	(Kandya and Mohan2018), 22	(Virk et al. 2014), 24	(Y. J. Kwon, Lee, and Y. H. Kwon 2020), 6	-
	Building Energy Consumption	(Ahmad et al. 2014), 387	(Baniassadi, Sailor, and Bryan 2019), 8	-	(S. Chen et al. 2020), 25
		(Howard et al. 2012), 257	(Hwang, T.P. Lin, and F.Y. Lin 2020), 7	-	(Yu et al. 2021), 5
		(Delzendeh et al. 2017), 198	(Y. Zhang et al. 2020), 7	-	(Al-Shargabi et al. 2021), 1
		Overheating	(Santamouris et al. 2015), 357	-	-
			(Porritt et al. 2012), 150	-	-
			(Mavrogianni et al. 2012), 135	-	-
			Heat Vulnerability Index	(Bao, Li, and Yu 2015), 68	(Samuelson et al. 2020), 5
				(Méndez-Lázaro et al. 2018), 33	-
				(Krstic et al. 2017), 27	-
				Building Characteristics	(Ioannou and Itard 2015), 92
					(White-Newsome et al. 2012), 91
					(Langer and Bekö 2013), 78

“-“ Indicate no literature was found by using the paired keyword.

Table 4: Three Most Cited Literature Per-Key Pairing Word in the Last Ten Years (Scopus)

	Urban Heat Island	**Building Energy Consumption**	**Overheating**	**Heat Vulnerability Index**	**Building Characteristics**
Urban Heat Island	(Estoque, Murayama, and Myint 2017), 443	(X. Li et al. 2019), 130	(Santamouris et al. 2015), 402	(Méndez-Lázaro et al. 2018), 35	(Toparlar et al. 2018), 41
	(Santamouris et al. 2015), 404	(Hirano and Fujita 2012), 86	(Oikonomou et al. 2012), 90	(Mallen, Stone, and Lanza 2019), 25	-
	(Gunawardena, Wells, and Kershaw 2017), 306	(Magli et al. 2015), 70	(Virk et al. 2014), 24	(Y. J. Kwon, Lee, and Y. H. Kwon 2020), 6	-
	Building Energy Consumption	(Ahmad et al. 2014), 473	(Y. Zhang et al. 2020), 11	-	(Yu et al. 2021), 7
		(Howard et al. 2012), 284	(Baniassadi, Sailor, and Bryan 2019), 9	-	(Al-Shargabi et al. 2021), 1
		(Toparlar et al. 2017), 237	(Hwang, T.P. Lin, and F.Y. Lin 2020), 8	-	(Ibrahim et al. 2022), 0
		Overheating	(Santamouris et al. 2015), 402	-	-
			(Moharram et al. 2013), 267	-	-
			(Porritt et al. 2012), 187	-	-
			Heat Vulnerability Index	(Wolf and McGregor 2013), 159	(Samuelson et al. 2020), 5
				(Bao, Li, and Yu 2015), 69	-
				(Méndez-Lázaro et/ al., 2018), 35	-
				Building Characteristics	(Ioannou and Itard 2015), 102
					(Langer and Bekö 2013), 85
					(Langer, et al. 2016), 80

“-“ Indicate no literature was found by using the paired keyword.

building characteristics. Our search could not locate any literature that has considered both building energy consumption and Heat Vulnerability Index (HVI). Other similar outcomes from the author-keyword pairing search can be found in Tables 3 and 4.

Table 5 shows the focus study area with the number of literatures published by using a keyword search. Buildings are responsible for 40 percent of global energy consumption and 33 percent of greenhouse gas emissions. Thus, architects and urban planners can play a crucial role contributing to studies that lies in the intersection of overheating, mitigation, energy consumption, and heat vulnerability as limited number of literatures are published on these topics. (Tables 6 and 7).

Table 5: Thematic Focus study area with the greatest number of literatures in Ten Years

Rank	Focus Study Area	Number of Literature
1	Environmental Sciences	1,037
2	Construction Building Technology	815
3	Energy Fuels	771
4	Meteorology Atmospheric Sciences	512
5	Engineering Civil	502
6	Green Sustainable Science Technology	460
7	Remote Sensing	333
8	Environmental Studies	307
9	Engineering Environmental	300
10	Geosciences Multidisciplinary	254

Table 6: International Journals with Highest Number of Literatures from Web of Science in the Last Ten Years

Rank	Journal	Number of Literature	Impact Factor
1	ENERGY AND BUILDINGS	205	5.879
2	SUSTAINABLE CITIES AND SOCIETY	176	7.587
3	BUILDING AND ENVIRONMENT	166	6.456
4	URBAN CLIMATE	132	5.731
5	SUSTAINABILITY	126	3.251
6	SCIENCE OF THE TOTAL ENVIRONMENT	99	7.963
7	REMOTE SENSING	96	4.848
8	ENERGY PROCEDIA	66	1.89
9	ENERGIES	50	3.004
10	ATMOSPHERE	47	2.686

*General keyword search Urban Heat Island or Building Energy Consumption or Overheating or Heat Vulnerability Index or Building Characteristics.
**Impact Factor based on 2020

Table 7: International Journals with Highest Number of Literature from Scopus in the Last Ten Years

Rank	Journal	Number of Literature	Impact Factor
1	ENERGY AND BUILDINGS	438	5.879
2	BUILDING AND ENVIRONMENT	292	6.456
3	SUSTAINABLE CITIES AND SOCIETY	244	7.587
4	URBAN CLIMATE	203	5.731
5	SUSTAINABILITY SWITZERLAND	140	3.251
6	SCIENCE OF THE TOTAL ENVIRONMENT	136	7.963
7	REMOTE SENSING	129	4.848
8	ENERGIES	115	3.004
9	APPLIED ENERGY	107	9.746
10	SOLAR ENERGY	79	5.742

*General keyword search Urban Heat Island or Building Energy Consumption or Overheating or Heat Vulnerability Index or Building Characteristics.
**Impact Factor based on 2020

4. RESULTS

This section assesses and synthesizes the impact of urban heat islands on various scales to comprehend the role urban and building fabrics can play in determining air temperature, surface temperature, building energy consumption, and indoor overheating thus impacting a person's mental and physical well-being. First, the following discussion is divided primarily into three categories—the impact of city characteristics on UHI, the impact of UHI on building scale, and the impact of buildings' indoor environment on the individual to determine the interrelation between the three. Second, each section subtracts information from the literature study and discusses primary attributes and determents followed by a summary table. Third, the interrelation between the three is discussed.

4.1. Impact of City Characteristics on UHI

Urban fabrics consist of different climatic properties such as radiative, thermal, moisture, and, aerodynamic. Various surfaces and associated microclimates are found in cities that contribute to complex spatial-temporal variability within a few miles. Local climate zones (LCZ) can modify surface climates and air temperature due to their urban fabric, land use land cover (LULC), structure, and metabolism which determine impermeability, roughness, thermal behavior, and the use of building energy consumption (Stewart et al. 2021; Skarbit et al. 2017; Sangiorgio et al. 2022; Kassomenos et al. 2022). In developed neighborhoods opportunities for change are greatly limited as major parameters that contribute to microclimate modifications have been laid. For example, residential low-income neighborhoods often consist of low-rise high-coverage infrastructure, which increases the plan area fractions of buildings, and impervious land and reduces vegetation cover, and mutual shading, thus generating distinct microscale climate impact (Xu et al. 2012; Agathangelidis, Cartalis, and Santamouris 2019; Yu et al. 2021). As an alternative to low-rise infrastructure and to decrease impervious land coverage along with plan area fractions reduction, high-rise buildings are adapted to accommodate a large number of occupants within a smaller envelope. The following section discusses three primary urban surfaces that have been repetitively considered in recent literature for UHI and mitigation studies.

4.1.1. Urban Greenery

Urban greenery is a significant indicator of intra-urban land surface temperature with a negative correlation with air temperature, surface temperature, heat-related deaths, and summertime energy use (Santamouris et al. 2018b; Krayenhoff et al. 2020). Urban vegetation deflects solar radiation, increases shaded building surfaces, releases moisture, and helps minimize surface temperature significantly by 26 percent and cooling energy savings by 30 percent compared to unshaded surfaces (Akbari et al. 1997). Tree canopy cover has been a widely accepted mitigation strategy when implanted correctly. However, the term urban greenery often uses to indicate a large spectrum of greenery ranging from urban grassland to urban tree canopy cover. The ratio of the radiation received by a planar surface to the radiation emitted by the entire hemispheric environment of an urban tree is much smaller than grassland (Wang and Akbari 2016; Estoque, Murayama, and Myint 2017). Thus, the benefit of the canopy is much more evident in daytime thermal imaging than in nocturnal thermal imaging. Regardless of the undeniable negative correlation between green roofs with roof surface temperature and sensible heat release to the atmosphere, green roofs have demonstrated less potential in reducing ambient air temperature compared to cool pavements and street trees as they modify the energy budget more at a roof level rather ground level. Thus, among other urban greeneries, green roof has less potential as a significantly low contributor to increasing pedestrian thermal comfort at the human level.

4.1.2. Impervious Surface

A large proportion of the city's urban surface is covered by impervious surfaces such as roads, sidewalks, driveways, and parking lots consisting of materials such as concrete and asphalt. Several studies have pointed out that regardless of climate, latitude, and topography; impervious surfaces have strong warming effects in cities, thus, impacting surface temperature, surface UHI, pedestrian thermal comfort, and energy consumption (H. Wang et al. 2017). Increasing impervious surfaces significantly modifies local energy balance in urban areas primarily by increasing surface temperature, which further contributes to surface urban heat island (UHI) formation (Hart and Sailor 2009; Aflaki et al. 2017). Several studies on mitigation and energy balance concluded that impervious surfaces in urban areas have positive linear correlations with land surface temperature (Tran et al. 2017; X. Chen et al. 2006; Pal and Ziaul 2017; Kikon et al. 2016; X. Zhang et al. 2017; Deilami, Kamruzzaman, and Hayes 2016; Karakuş 2019; Y. Li et al. 2020). Additionally, the impact of impervious surfaces on UHI also depends on the ratio of the radiation received by a planar surface to the radiation emitted by the entire hemispheric environment and the ratio of the mean height of the buildings to the width of the street. In densely built urban neighborhoods with a lesser proportion of the visible sky or open canyon space, impervious surface increases nocturnal UHI, whereas low-rise residential neighborhoods with low-street-aspect ratio often experience a significant daytime increase in UHI of up to 10K as the surface absorbs more solar radiation and has greater thermal

Table 8: Research findings on the impact of urban greenery on ambient temperature

City	Climate	Vegetation	Method Used	Temperature Reduction		Citation
				T_{air} (◦c)	T_{suf} (◦c)	
Hong Kong, China	Subtropical	· Svf (<0.2) · Svf (0.2–0.4) · Svf (0.4–0.8)	· Sensitivity test · Modeling and simulation study · Wind-path model · Statistical analysis	1.50	-	Tan, Lau, and Ng (2016)
Montreal, Canada	Humid Continental	· Leaf Area Density:0.473 m2/m3, 10 m height. · Leaf Area Density:0.935 m2/m3, 9 m height.	· ENVI-met · Statistical analysis	2.00 5.10	- -	Y. Wang and Akbari (2016)
Los Angeles, USA	Mediterranean Climate	· Vegetative green roofs · Increased street-level urban vegetation	· ENVI-met · Statistical analysis	0.20 1.50	-	Taleghani et al. (2016)
Rome, Italy	Mediterranean Climate	· Increased Green Cover Ratio by 10%	· ENVI-met-V3.1-numerical simulation and model validation · Statistical analysis	1.35	-	Salata et al. (2017)
Phoenix, Arizona, USA	Desert Climate	· Grass · Tree canopy	· ENVI-met · Statistical analysis	0.50-1.50 1.00-3.10	2.10 8.20	Harlan et al. (2013)
Knoxville, Tennessee, USA	Humid Subtropical Climate	· Tree canopy cover	· ANOVA · Onsite HOBO measurements	1.79		Hass et al. (2015)
Atlanta, Georgia, USA	Humid Subtropical Climate	· Doubling vegetation	· Land Surface Model (LSM) · Onsite measurement	7.00	-	Shepherd and Zhou et al. (2009)
Padua, Italy	Moderately Continental	· Replacing impervious surfaces by increasing Green Cover Ratio by 20%	· Envi-met · Predicted mean vote	2.30		Noro and Lazzarin (2015)
Thessaloniki, Greece	Warm and Temperate Climate	· Significant increase in Urban Green Coverage by up to 40%	· Envi-met	0.35	19.0	Tsoka et al. (2017)

capacities and conductivities. This allows the surface to absorb heat during the day and release it at night (Christen, Meier, and Scherer 2012; Stewart et al. 2021). Impervious surfaces covered with dark materials such as asphalt are a significant contributor to the surface UHI. Parking lots and roads are one of the most significant contributors due to dark material use and traffic emissions (Senanayake, Welivitiya, and Nadeeka 2013).

Landsat data is the most popular data often used by researchers to study the change in SUHI due to LULC. Other data sets such as MODIS, ASTER, HJ-1B, IKONOS, SPOT is also used for high, medium, and low-resolution imagery. In some studies, land surface temperature (LST) is used as a proxy for the surface urban heat island (SUHI) effect to analyze temporal spatial variability between different land use land cover (LULC). Regression analysis, correlation analysis, zonal statistics, and contribution index (CI) are some of the many approaches used to evaluate the impacts of LULC on LST and SUHI.

While studying surface UHI, the urban surface temperature can be calculated either based on plan surface temperature where roofs and canyon floors are considered, or by using complete surface temperature where temperatures of all facets of the complete urban surface are considered. The temperature profile observed from satellite thermal imagery shows the largest UHI in the daytime and during summer, but in all seasons the nocturnal UHI is smaller than in the daytime and it exhibits less spatial variability (Oke et al. 1991; Santamouris and Fiorito 2021). This contradiction is primarily because of the surface consideration. Other major factors that influence surface UHI are soil moisture, cloud, and wind speed. However, it can be assumed that with higher wind speed there will be a rapid temperature mix which should lead to reduced surface UHI. As higher wind mix is associated with the following three factors - proportion of the visible sky in urban street canyons, street aspect ratio, and impervious surfaces; future studies need to be conducted considering the interrelation between these factors to reach further conclusions.

4.1.3. Urban Geometry-Street Aspect Ratio and Sky View Factor

Urban spaces are characterized by various urban geometries such as street width, building height,

height-to-width ratio (H/W), openness to the sky, and orientation of street canyons which significantly contribute toward heat transfer through radiation and convection within urban fabrics and determine wind speed, thus creating a unique thermal environment within an urban area. One of the earliest studies by Shuji et al. (1986) demonstrates the interconnection between SVF (a dimensionless number ranging from zero to one) and local urban temperatures thus establishing its impact on heat island phenomena. In urban areas, the density of building blocks, urban greenery (grassland, park, tree canopy cover), and the height-width ratio between street to buildings act as a predictor variable to determine surrounding obstacles to the sky hemisphere, determine obstruction or exposure to solar radiation (Niachou, Livada, and Santamouris 2008; Lee, Holst, and Mayer 2013). A lower SVF indicates higher obstruction by urban fabrics such as buildings and trees, resulting in less solar and diffuse sky radiation, and higher long-wave radiation between urban surfaces (Mahmoud 2011). Thus, for the same street width low-rise neighborhoods will have a low H/W ratio which will further reduce shading and increase sun exposure to urban surfaces thus elevating urban canyon temperature by 2-4k and contributing to the urban heat island effect which will further increase the cooling load and anthropogenic heat release (Nasir et al. 2017; Park et al. 2016). Additionally, urban surface albedo, emissivity, temperature, and sky view factor play a crucial role in cooling, thus determining the daytime and nocturnal heat island effect (Morini et al. 2018; Touchaei, Akbari, and Tessum 2016). Through solar irradiance, the majority of external heat gain for a building occurs over the building surface during the day. As low-rise building does not get mutual shading; the building's envelope properties, air temperature, and wind speed are the main factors that affect the building's surface temperature (Bakarman and Chang 2015; Kandya and Mohan. 2018). At night, with no short-wave radiation, mean radiant temperature decreases with openness as it is primarily affected by long-wave radiation (Lee, Holst, and Mayer 2013). Hence, an urban canyon with large SVF warmed up faster in the daytime thus increasing the daytime heat island effect and cooled quickly at night, thus reducing the nocturnal heat island. In a hot climate with higher CDD, where the design goal is to reduce solar radiation to achieve indoor and outdoor thermal comfort, compact urban planning with low SVF and high H/W is often desirable to reduce frequent heat stress and time-averaged PET and the reverse is advisable for cold climate with higher HDD (W. Liu, Zhang, and Deng 2016; Charalampopoulos et al. 2013; Kakon, Mishima, and Kojima 2009; Lin, Matzarakis, and Hwang 2010). In addition to street width and SVF, the orientation of the canyon determines day time direct exposure to solar radiation. Thus, streets with similar SVF and H/W will experience different exposure duration based on their E-W and N-S orientation. For E-W streets, sun exposure is maximum, and an improved H/W ratio does not change thermal comfort, whereas N-S street has significantly limited exposure to the sun compared to E-W and an improved H/W ratio does change thermal comfort (Ali-Toudert and Mayer 2006; Andreou 2013). In comparison with E-W and N-S orientations, NE-SW and NW-SE have not been studied very often. Even though the intermediate direction has more sun exposure and thus discomfort, a study by Ali-Toudert and Mayer (2006) suggests with a similar H/W ratio such as an N-S canyon, intermediate streets have less canyon floor temperature, thus better pedestrian comfort.

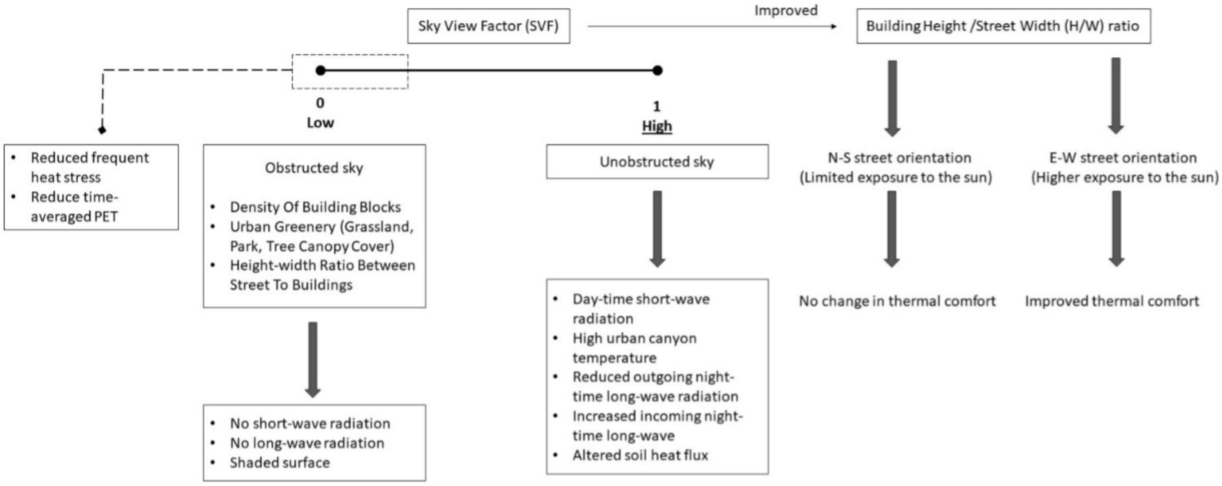

Figure 4: Research findings on the impact of SAR and SVF on temperature increase

4.1.4. Summary Table

Table 9: Summary of UHI studies at city scale: focused study area, outcomes, and parameters

	Focused Study Area	**Commonly Concluded Research Outcome**	**Example Attributes/Parameters**
City Scale	3.1.1. Tree Canopy Cover (Stewart et al. 2021; Krayenhoff et al. 2020; Gunawardena, Wells, and Kershaw 2017; Estoque, Murayama, and Myint 2017)	The impact of tree canopy on street air temperature depends on the building height, and size of the canopy and cannot be generalized. Unequal distribution of tree canopy widely observed in neighborhoods.	· Canopy layer UHI · Land surface temperature · Surface Urban Heat Island · Remote sensing · Resource Vulnerability
	3.1.2. Impervious surface (Hart and Sailor 2009; Aflaki et al. 2017; Stewart et al. 2021; Santamouris and Fiorito 2021)	Impervious surfaces have a strong correlation with increasing land surface temperature which further increases the energy load of buildings.	· Land Use Land Cover · Local Climate Zones (LCZ) · Land surface temperature · Remote sensing · Surface urban heat island (SUHI)
	3.1.3. Street aspect ratio and Sky View Factor (Stewart 2013; Santamouris and Fiorito 2021; Bakarman and Chang 2015; Nasir et al. 2017)	A small H/W value allows access to sunshine, ventilation, and night-time cooling but provides less shading whereas high H/W limits nigh time heat loss hence increasing nocturnal UHI. Geometrical guidelines for street aspect ratio depends on background climate and latitude.	· Surface temperatures · Solar radiation gains · Building average height · Land use land cover · Nocturnal UHI · Albedo

4.2. Impact of UHI on Building Scale

Increasing outdoor temperature interactions between buildings with the urban environment through building components have a significant impact on buildings' energy consumption (Scherba et al. 2011; Y. Wang, Berardi, and Akbari 2015; Santamouris et al. 2018b; S. Chen et al. 2020). Buildings that fail to reduce the impact of outside air temperature in the indoor environment often lead to overheating and indoor discomfort followed by heat vulnerability. During extreme heat events, which are exacerbated by heat islands, the increased demand for air conditioning to cool and dehumidify buildings overload US electrical grid systems causing rolling brownouts or blackouts. The relevance of this matter is reinforced by the fact that climate change also affects extreme weather. The following section discusses the widely studied and reviewed primary impact of UHI on buildings.

4.2.1. Energy Consumption

The energy consumption of a building largely depends on its ambient temperature, relative air velocity, building characteristics, appliances, occupant's activity level, the psychological expectation of thermal comfort, indoor setpoint temperature, and end-use (Howard et al. 2022; Santamouris and Fiorito 2021; Hoody et al. 2021; Baniassadi, Sailor, and Bryan 2019). Several studies indicate a strong correlation between city planning with greenhouse gas emissions and buildings' energy usage (Organisation for Economic Co-operation and Development ,2012). As city planning defines the urban fabric, the location of the building often gets affected by the planning decisions such as proximity to the highway, and large shopping plaza, parking lot, street width, tree canopy, etc. Other than city planning, interactions between buildings with the urban environment through building components (walls, roofs, windows, etc.) have a significant impact on buildings' energy consumption (Scherba et al. 2011; Y. Wang, Berardi, and Akbari 2015; Santamouris et al. 2018b). As canyon temperature rises because of UHI, building parameters that dictate internal heat gain or release for the residential and commercial buildings need to be defined on a case-by-case basis. For example, a building's heat gains through windows and infiltration can be significant for building energy demand (S. Chen et al. 2020). Thus, buildings with similar surroundings will experience a drastic change in energy consumption. Studies suggest that cooling energy demand for residential buildings can increase by 5 percent for each unit kelvin difference (Bueno et al. 2012). Another study shows that the increase of the ambient temperature due to UHI and heat waves impacts adversely cooling energy consumption of buildings by 13.1 percent, an average cooling penalty of approximately 7 kWh/m^2/y/C and raises the peak electricity demand during summer and heat waves (Santamouris 2020). We find,

Table 10: Findings of studies on the impact of ambient temperature on buildings' energy consumption

City	Climate type	Method used	Building type	Data record period	Energy consumption		Citation
					Cooling load	Heating load	
Beijing, China	Continental climate	· Physics-based model- DeST building simulation toolkit	Office	1961-2014	11% increase	16% decrease	Cui et al. 2017
London, UK	Mild winters and temperate summers	· Typical meteorological year (TMY) data · Physics-based model- EnergyPlus	Office	1999-2000	23-30% increase	40% decrease	Kolokotroni et al. 2012
Rome, Italy	Mediterranean climate	· Physics-based model- TRNSYS simulation	Residential	2014-2016	30% increase	11% decrease	H. Li et al. 2018
Singapore	Tropical climate	· Typical meteorological year (TMY) data · Simulation	Residential	NA	4-11% increase	-	Y. Liu et al. 2017
Boston, US	Continental climate	· Physics-based model- EnergyPlus	Residential Office	2011	4-41% increase	4-15% decrease	Street et al. 2013
Manchester, UK	Temperate oceanic climate	· Typical meteorological year (TMY) data · Simulation	Office	2016 July	9.4- 12.2% increase	-	Skelhorn, Levermore, and Lindley 2016
Athens, Greece, 2001	Mediterranean climate	· Physics-based model- TRNSYS simulation	Office	1997	120% increase	27% decrease	Santamouris et al. 2001
15 US cities- Miami Houston Phoenix Memphis El Paso San Francisco Baltimore Albuquerque Salem Chicago Boise Burlington Helena Duluth Fairbanks	 1A 2A 2B 3A 3B 3C 4A 4B 4C 5A 5B 6A 6B 7 8	· Typical meteorological year (TMY) data · Simulation	Office	-	Avg. 17.25% increase	Avg. 17.04% decrease	Sun and Augenbroe 2014

UHI can increase energy demand by 11- 120 percent and can decrease the heating penalty by 4-27 percent. Table 10 shows cities where both cooling and heating energy consumption have been studied. On a very fundamental level, degree-days get used as a proxy variable for energy consumption as it indicates heat exposure to the urban fabric and building surface. Cities with higher CDD experience more cooling load, whereas cities with higher HDD might experience lower heating load. A significant number of previous studies have investigated the impact of the UHI on buildings through simulation, physics-based models, statistical analysis, and geographic information system mapping, and often conclude the energy penalty depends on building type, number of occupants, and behavioral patterns, and thermal quality of the building stock. In our literature search, except for the study by Cui et al. (2017), most of the other studies have a maximum of two years of TMY data, which limits their ability to interpret UHI change for the city over time. The lack of TMY or high-resolution data is another shortcoming of existing studies. In addition, most of the studies in our research study UHI impact in developing countries mostly in the US, Europe, and China. Future studies are needed in developing countries, which can be crucial to understanding fuel poverty and UHI's impact on human health where a lack of health care is evident. Our search also does not locate any study that extrapolates future urban expansion to understand UHI's impact.

4.2.2. Indoor Overheating

Indoor overheating is heat buildup within a building's indoor space that crosses the comfort threshold with or without a natural or mechanical ventilation system and leads to a degree of discomfort to building occupants. In extreme cases it can impact health or can cause mortality. Indoor temperature over 104˚F F can be health-damaging however demographics, age, or preexisting health conditions further increases vulnerability. Hence, buildings that are occupied by vulnerable populations get affected by overheating the most (White-Newsome et al. 2012; Mavrogianni et al. 2012; Langer et al. 2016). However, a major limitation associated with assessing overheating is the lack of guidelines and thresholds to define it (Holmes, Phillips, and Wilson 2016). Previous studies indicate a strong correlation between heat waves and indoor overheating. A study by Khan et al. (2020) shows synergies between urban overheating and heat waves in Western Sydney. Their results show a strong correlation between urban overheating and heat waves both in the coastal and inland sites. One primary negative impact of overheating is the vulnerability of the electric grid due to additional cooling demand caused by increased ambient temperature, dilapidated housing, and electricity consumption by air conditioning to achieve indoor thermal comfort. Our bibliographic literature search does not capture any study that focuses on building age to understand overheating and vulnerability. The date of construction/retrofit and age of housing is another variable that often gets misinterpreted in energy consumption and indoor thermal comfort studies as it cannot always be apparent by physical evidence. Several studies assume older buildings overheat more than newer constructions because of updated energy codes. However, the literature suggests traditional mass construction and building with operable windows are cooler because of thermal inertia as they can regulate indoor temperature better than newly constructed frame walls (Krayenhoff et al. 2018; McLeod, Hopfe, and Kwan 2013; Maivel, Kurnitski, and Kalamees 2015; Samuelson et al. 2020).

4.2.3 Indoor Thermal Comfort

Building characteristics play a significant role in influencing the thermal comfort and dry bulb temperature which further can limit or exceed overheating risk (Ioannou and Itard 2015; X. Li et al. 2019; Baniassadi et al. 2018; Hwang, T.P. Lin, and F.Y. Lin 2020). Overheating risk is mostly associated with indoor thermal comfort as people spend most of their time indoors during heat waves. Despite several literatures on mitigation or resilience in building indoor and outdoor thermal comfort, very limited literature tries to establish the relation between them, in spite of the fact that multiple studied variables are similar for both conditions (building scale vs. city scale) (Stewart 2013; X. Li et al. 2019). Thus, the lack of analysis and study on various latitudes and cities provides limited knowledge on the interrelationship between indoor and outdoor thermal comfort to further create design guidelines specifically for vulnerable buildings. To study the two-way interaction of buildings and microclimate, the limited number of studies that establish a correlation between indoor and outdoor thermal comfort, use whole building simulation and apply meteorological and future projected climate data as input (Al-Shargabi et al. 2021; Ahmad et al. 2014; Ibrahim et al. 2022). In both cases, the lack of traverse and fixed method onsite urban canopy layer air temperature data fails to replicate an accurate scenario, and thus does not capture change in thermal gradient with urban form, urban density, and population (Y. Zhang et al. 2020).

4.2.4. Summary Table

See Table 11 below.

4.3. Impact of Buildings' Indoor Environment on Individual

Buildings and indoor thermal conditions play a significant role in limiting the risk of overheating during heat waves and summer months given the fact that people spend approximately 80–90 percent of their time indoors (Loughnan, Carroll, and Tapper 2015). The increasing urban air temperature due to surface modification and anthropogenic heat increases energy consumption, fuel poverty, greenhouse gas emission, and pollutant concentration in urban areas. With increasing outdoor temperature and static indoor temperature set-point, the difference between the indoor and outdoor air temperature is increasing. Extreme weather conditions such as heat waves in urban areas have a significant negative impact on the quality of life and health of urban citizens. Exposure to extreme heat can impact a person's ability to thermoregulate body temperature, resulting in heat stress, which may lead to death (Luber et al. 2006). Previous studies demonstrate that areas with increased air temperature and more hours of sun exposure can cause heat-related death (Chestnut et al. 1998), cardiovascular disease (Medina-Ramon et al. 2006), and heart attacks (Braga et al. 2002). Higher air pollutant levels can increase respiratory disease (Mastrangelo et al. 2007) and hospital admissions (Mastrangelo et al. 2007). Poor air quality poses a great threat to people, especially those in poverty who lack access to health care and proper housing conditions. Heat waves not only increase health vulnerability and impact individuals' mental health, but in extreme cases, they can cause more deaths in the United States than in all other meteorological events combined.

Table 11: Summary of UHI studies at building scale: focused study area, outcomes, and parameters

	Focused Study Area	**Commonly Concluded Research Outcome**	**Example Attributes/Parameters**
Building Scale	3. 2.1. Energy Consumption (Scherba et al. 2011; Y. Wang, Berardi, and Akbari 2015; Santamouris et al. 2018a; Baniassadi , Sailor, and Bryan 2019; Xu et al. 2012; Hoody et al. 2021; Santamouris and Fiorito 2021; Howard et al. 2012; S. Chen et al. 2020)	Cities with higher CDD experience more cooling load, whereas cities with higher HDD might experience lower heating load.	· Ambient temperature · Relative air velocity · Building characteristics · Appliances · Occupant's activity level · Psychological expectation of thermal comfort · Indoor setpoint temperature · End-use · Building design
	3.2.2. Overheating (Santamouris et al. 2017; Yang et al. 2017; Haddad et al. 2020; Pyrgou et al. 2017a,b; Ulpiani et al. 2020; Holmes, Phillips, and Wilson 2016; Oikonomou et al. 2012; Virk et al. 2014; Delzendeh et al. 2017; Hwang, T.P. Lin, and F.Y. Lin 2020)	Peak electricity load and electricity penalty during heat waves and summer months increased significantly with the per degree of temperature increase per person.	· Ambient temperature · Building orientation · Hours of Sun Exposure · Building characteristics · Shading · Ventilation · Internal-heat gains · Solar radiation through windows · Psychological adaptation
	3.2.3. Indoor thermal comfort (Pyrgou et al. 2017b; Mavrogianni et al. 2012; Langer and Bekö 2013; Baniassadi et al. 2018; Gobakis et al. 2011; Yang et al. 2017; Delzendeh et al. 2017)	Thermal comfort includes radiative and convective heat transfer at the skin surface and within the body. Achieving thermal comfort is difficult as the human response system and psychological regulation of thermal sensitivity vividly vary from person to person.	· Access to air conditioning · Dry bulb temperatures · Air velocity · Relative humidity · Clothing insulation · Metabolism · Outdoor-indoor temperature gradient · Age and gender · Preexisting health conditions · Psychological expectation
	3.2.4. Health Vulnerability (Sailor et al. 2016; Samuelson et al. 2020; Y. J. Kwon, Lee, and Y. H. Kwon 2020; Bao, Li, and Yu 2015; Yang et al. 2017; Kassomenos et al. 2022; Paravantis et al. 2017;	UHI enhances air pollutants and heat-stress-related diseases such as lung diseases, asthma, chronic bronchitis, etc. and in extreme circumstances can cause death.	· Access to healthcare · Access to air conditioning · Indoor-outdoor temperature gradient · Building Characteristics · Pre-existing health condition · Air pollution

4.3.1. Health Vulnerability

The location and typology of housing play a crucial role as similar housing will experience different exposure to intra-urban heat if not located in a heat canyon. Literature review suggests, in the US vulnerable households are often located in areas with low tree canopy cover and a higher ratio of impervious material, which significantly increase air temperature thus impacting indoor/outdoor thermal comfort, anthropogenic heat release, and buildings energy consumption (Park et al. 2016; Jandaghian and Akbari 2020; Grimmond et al. 2010; Hirano and Fujita 2012; Magli et al. 2015). In addition, low-income neighborhoods experience drastically low real estate investment, thus lack of environmental amenities and retrofits create present-day spatial patterns of inequitable exposure to intra-urban heat. UHI enhances air pollutants and heat-stress-related diseases such as lung diseases, asthma, chronic bronchitis, etc. and in extreme circumstances can cause death. Even though health vulnerability studies mention increases in outdoor temperature, we could not find literature that overlaps city fabric, temporal variation with the built environment, and health vulnerability data such as access to healthcare, air conditioning, pre-existing health condition, ambient temperature, poverty, occupant's age, household income, etc. Thus, the attributes remain isolated and fail to capture the overall understanding of health vulnerability. Heat vulnerability can be defined as a function of,

> Heat Vulnerability = f{Adaptivity, Sensitivity, Accessibility, Invariability}

Adaptivity:
Adaptive capacity to thermoregulate depends on the household structure and education. A person's ability to adjust to potential heat damage and to take advantage of facilities available to respond to extreme climate events depends on household income, the number of people in a household, and city facilities such as nearby greenspace and water bodies that are not equally distributed in cities as a derivative of historic segregated housing policies. Studies indicate people of color often live in areas with low tree canopy cover and

poor infrastructure which resist their capability to adapt to extreme heat events. English-language proficiency can affect a person's ability to understand heat wave warnings, therefore immigrants and people with limited ability to understand English are more at-risk. Thus, adaptivity can be defined as,

> Adaptivity = f{Household (Income, Head of household, The average number of people per household, Race, Gender), Education (English proficiency, Population without a high school diploma)}

Sensitivity:
The elderly, children, and people with disabilities and preexisting conditions are most at risk due to their inability to adapt to extreme weather events. Several studies indicate people aged above sixty-five and below seven are often the most affected populations. Disabled populations are also at higher risk because of difficulty in relocating to cooling shelters. People with vision and hearing impairments are often at higher risk of missing heat wave warnings. People with a higher BMI have brown adipose subcutaneous fat tissues that effectively insulate the body's core and influence thermoregulatory abilities. Hypertension and diabetes are the other two prime diseases that often limit the ability to thermoregulate. Thus, sensitivity can be defined as,

> Sensitivity= f{Age (Children aged under five years, Population aged above sixty-five years), Health (Population with preexisting conditions, Disability, Social Isolation)}

Accessibility:
Socioeconomic variables such as access to public transportation and healthcare have been prominent determinants of heat vulnerability. The elderly, and people without a personal vehicle who live in areas with no public transportation often fail to reach cooler shelter during heat waves. US census reports show in 2020, 8.6 percent of people, did not have health insurance at any point during the year. People with access to healthcare and insurance often avoid seek medical care, even when they suspect it may be necessary, even individuals with major health problems or who are experiencing symptoms avoid seeking medical care. Thus, accessibility gets defined as,

> Accessibility= f{ Public Amenities (Access to public transportation, Access to healthcare)}

Invariability:
Unlike other determinants of heat vulnerability, local climate, housing conditions, and cityscapes are beyond individuals changing capability. Children and the older population are most vulnerable as demonstrated by existing vulnerability studies. Such a population residing in poor-quality houses exacerbates heat and air pollution-related health issues (Beck et al. 2014). Historic and traditionally constructed buildings make up a unique segment of the existing building stock (Webb 2017). Aged buildings often have compromised or under-maintained wall and roof insulations, poor AC status, window-to-wall ratio, etc. which are major determinants of indoor thermal comfort inside a building. The distinctions between vulnerable and non-vulnerable households are convoluted and vary as parameters are often set by individual studies. A study by Coley, Kershaw, and Eames, (2012) uses dynamic simulation to demonstrate occupants' behavioral adaptation to temperature is equally important to buildings' structures' thermal adaptation. However, behavioral adaptation to indoor temperature is strongly correlated to age, mobility, health, and housing characteristics such as the availability of operable windows, etc. Vulnerable households are often classified by race/ethnicity, household income, age, social isolation, physical mobility, etc. Heat-related mortality in the US was reduced with the increasing use of centralized air conditioning, however, there is a strong correlation between race and access to air conditioning and the quality of housing. Housing types, envelope properties, ventilation, solar orientation, roof, and wall albedo, air conditioning status, etc. can play a significant role in determining indoor heat exposure, thus playing a crucial role in heat-related mortality and morbidity during heat events. Other than housing characteristics, behavioral adaptation to indoor temperature; rapid urbanization, and the associated urban heat island effect increases ambient air temperatures and prevents the cooling of buildings at night. Upper stories and southern orientation with an elevated wall-to-window ratio increase solar gains as windows conduct heat better than walls and allow solar radiation into the building (McLeod, Hopfe, and Kwan 2013). The absence or poor-quality window shading makes the building more vulnerable to solar heat gains (Porritt et al. 2012). Another significant parameter that impacts indoor temperature is the external wall area-to-volume ratio and the number of occupants inside a household, which are often prominent characteristics of vulnerable housing. As a result, a lack of wholesome housing stock consideration in the vulnerability of built environment studies can negatively impact their credibility as it fails to capture the underlying physics of heat exposure and exchange. Therefore, the vulnerability of the built environment research is limited in its ability as it fails to account for indoor exposure and its health consequences. Thus, invariability is a function of,

> Invariability= f{Housing (Date of construction, Housing ownership, Air conditioning status, Building material), Climate (Temperature, Air pollutant), Cityscape (Land use land cover, Tree canopy)}

Table 12: Summary of heat vulnerability index studies: classification and parameters

	Classification	**Parameters**
Adaptivity (Rathi et al. 2022; Reid et al. 2012; Bao, Li, and Yu 2015; Niu et al. 2021; Krstic et al. 2017; Méndez-Lázaro et al. 2018; Wolf and McGregor 2013)	Household	Income
		Head of household
		The average number of people per household
		Race
		Gender
	Education	English proficiency
		Population without a high school diploma
Sensitivity (Wilson and Chakraborty 2019; Gabbe and Pierce 2020; Karanja and Kiage 2021; Klein Rosenthal, Kinney, and Metzger 2014)	Age	Children aged under 5 years
		Population aged above 65 years
	Health	Population with preexisting conditions
		Disability
		Social Isolation
Accessibility (Méndez-Lázaro et al. 2018; Wolf and McGregor 2013)	Public Amenities	Access to public transportation
		Access to healthcare
Invariability (Mallen, Stone, and Lanza 2019; White-Newsome et al. 2012; Samuelson et al. 2020; Y. J. Kwon, Lee, and Y. H. Kwon 2020, Reid et al. 2009; Rathi et al. 2022; Reid et al. 2012; Bao, Li, and Yu 2015; Niu et al. 2021; Krstic et al. 2017)	Housing	Date of Construction
		Housing ownership
		AC status
		Building material
	Climate	Temperature
		Air pollutant
	Cityscape	Land use land cover
		Tree canopy

4.3.2. Impact on Mental Health

Increased heat is associated with suicide, psychiatric hospital visits, and ER visits, in addition to increased anxiety, depression, and stress. Disrupted sleep, daytime discomfort, or skin irritation due to a lack of ability to thermoregulate in extreme heat causes anxiety, stress, and depression, for example, for people who need the assistance of air conditioning during an extended heat wave. According to the American Psychiatric Association, high temperatures are linked with memory, attention, and reaction time. Sleep difficulties associated with extreme heat can contribute to and further exacerbate mental health symptoms. People with mental health disorders, substance misuse, and those taking prescribed medications such as lithium, and various neuroleptic, and anticholinergic drugs are the most vulnerable during heat waves and are subject to morbidity and mortality. People with mental illness might have pathological dysfunction of thermoregulation associated with schizophrenia that affects their ability to cope and adapt to the change in temperature. Mental health medications such as neuroleptic medications can cause loss of sweating ability to dissipate heat which further causes hypothermia or hyperthermia, depending on the ambient temperature.

5. DISCUSSION

Urban areas with their evaluation of modified surface and built environment act as a catalyst for altering urban energy balance with extreme heat episodes, heat waves, increased air, and surface temperature, increasing cooling load, heat-related health issues, and mortality in addition to increasing pollution and modifying humidity. Past world-wide studies on varies cities have almost always concluded UHI is one of the most prominent demonstrations of urban surface modification and a measure to study the urban-rural surface and air temperature differences due to human activity. UHI studies in the majority describe comprehensive quantification of urban-rural air and surface temperature differences to develop possible strategies for adaptation and mitigation in urban areas, focused on a micro and macro scale with limited recent progress with a focus on theoretical and methodological contributions to the field of urban climatology. The dynamics of climate-responsive planning and design require a thorough review, not only of the design and planning approaches, but also of research problem formulation and design tools. Micro climate adaption varies widely between cities and even between neighborhoods as climate threats and vulnerability depend on socioeconomic and territorial characteristics.

Vulnerability Index (VI) is often used as a measure of the possibility of risk subjection of a population or demographic to natural and economic hazards such as infectious diseases spread, economic collapse, public housing need, heat exposure, poor air, and water quality, etc. (Krstic et al. 2017; Wolf and McGregor 2013; Méndez-Lázaro et al. 2018). The United Nations' environmental program first created vulnerability indexes as a policy planning tool to identify vulnerable populations for disaster planning and to decrease the associated risks. With global temperature rise, frequent heat waves, and increasing heat-related health issues, the heat vulnerability index (HVI) and corresponding maps were created to identify areas and populations that are vulnerable to extreme heat (Karanja and Kiage 2021; Klein Rosenthal, Kinney, and Metzger 2014; Samuelson et al. 2020). HVI is calculated through multiple quantitative indicators often determined by the research group to deliver index-variable for various determinants of hazardous issues that can be combined into a standardized framework for making comparisons possible.

Table 13 below summarizes the number of studies available for each HOLC city and state. As shown below, more than 85 percent of cities/states are not studied. Even though redlining and gentrification played a crucial role in determining the urban morphologies, the role of city and housing variables on under privileged populations are not explored. During heatwaves, 50–85 percent of heat-related deaths are associated with indoor heat exposure (Langer and Bekö 2013; Sailor et al. 2019), yet housing characteristics are not included in heat vulnerability studies. The distinctions between vulnerable and non-vulnerable households are convoluted and vary as parameters are often set by individual studies. Dynamic simulation demonstrates occupants' behavioral adaptation to temperature is equally important to buildings structures' thermal adaptation (Coley, Kershaw, and Eames 2012), despite heat vulnerability studies are often limited to race/ethnicity, household income, age, social isolation, physical mobility, etc. For housing characteristics, our bibliographic analysis shows studies and government reports only consider air conditioning status but fail to capture fuel poverty, which can impede individuals from using their air conditioning system. Some studies indicate racial profile, poverty, and education as the primary indicator of vulnerability, other studies indicate access to resources such as air conditioning systems, existing health conditions, and age as the primary indicator of heat vulnerability.

Table 13: Summary of heat vulnerability index studies: classification and parameters

Redlining Studies by HOLC city (Archived by the University of Richmond's database)	**Number of literature**
Albany, Allentown, Union Co., Bergen Co., Bethlehem, Davenport, Columbia, Shreveport, Little Rock, Covington, Peoria, Lincoln, Kenosha, Huntington, Harrisburg, Lansing, McKeesport, Port Arthur, Phoenix, Portsmouth, Ogden, Waterbury, Scranton, Savannah, Topeka, Lower Westchester Co., Woonsocket, Charleston, Chelsea, Wilkes-Barre, Belmont, Wheeling, New Britain, Essex Co., Pueblo, Brockton, Stamford Darien and New, Canaan, Utica, Augusta, Braintree, Newton, Rockford, Norfolk, Winchester, Akron, Youngstown, Haverhill, Worcester, Lancaster, Pawtucket & Central Falls, Needham, Mobile, Knoxville, Macon, Medford, Bay City, Pontiac, Saginaw, Portsmouth, Battle Creek, Chattanooga, Watertown, Milton, Elmira, Rochester, New Haven, Brookline, Lexington, Revere, Dayton, Toledo, Camden, Holyoke Chicopee, Asheville, Joliet, Tacoma, Troy, Jacksonville, Saugus, Terre Haute, Nashville, Portland, Omaha, Buffalo, Lorain, Wichita, Austin, Springfield, South Bend, Cambridge, Hartford, Binghamton-Johnson City, Dubuque, Springfield, Lake Co. Gary, St. Paul, Trenton, Waterloo, Sioux City, Waltham, Dedham, Johnstown, Waco, Memphis, Bridgeport, Lake Co. Calumet/Hammond, Amarillo, Houston, Galveston, Fort Worth, Tulsa, Lexington, Hamilton, Atlantic City, San, Diego, Quincy, Manhattan, Philadelphia, Tampa, Aurora, Providence, Jackson, Muncie, Birmingham	0
Des Moines, Springfield, Queens, Salt Lake City, San Francisco, Miami, Dallas, Flint, Richmond, Brooklyn, Minneapolis, Council Bluffs, Chester, New Orleans	1
Sacramento, St. Louis, Louisville	2
Detroit	3
Los Angeles, Atlanta, Columbus, Baltimore	4
Pittsburgh, Oakland	5
Redlining Studies by States	**Number of literature**
Arizona, Arkansas, Delaware, Florida, Hawaii, Idaho, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Minnesota, Mississippi, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, North Carolina, North Dakota, Oklahoma, Oregon, Rhode Island, South Dakota, Vermont, West Virginia, Wisconsin, Wyoming	0
Alaska, Colorado, Connecticut, Pennsylvania, South Carolina, Tennessee	1
Michigan, Utah, Virginia	2
Georgia, Illinois, Massachusetts, Missouri, Ohio, Texas	4
Maryland	6
Washington	7
California	8
New York	9

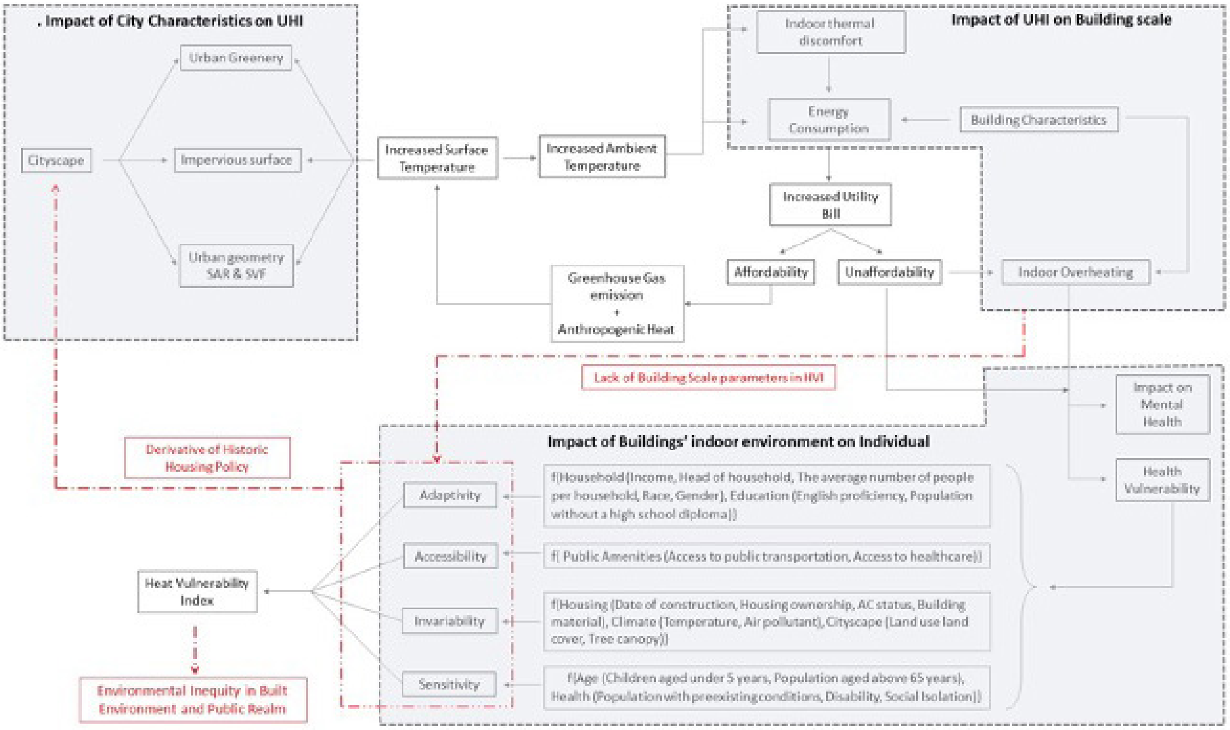

Figure 5: Findings summary of studies and interrelation between the impact on UHI.

Hoffman, Shandas, and Pendleton (2020) studied 108 urban areas to understand the effects of historical housing policies on resident exposure to intra-urban heat. Their study shows present-day spatial patterns of inequitable exposure to intra-urban heat have a strong overlap with the historically redlined neighborhood. DiMento (2009) pointed out that the majority of the US infrastructure network was developed after HOLC originated redlining in 1935. As land values were significantly lower in the hazardous "D" zone, major infrastructure such as roads, highways, and shopping complexes, were built through redlined neighborhoods. As the majority of these infrastructures required less canopy cover and more land alteration, the current population of lower-income and communities of color often experience a significant difference in land surface temperature. The scope of this paper does not include policy studies but rather focuses on the overall understanding of the urban heat island effect and heat vulnerability. The diagram below showcases the role architects/urban designers can play in mitigation and possible design intervention.

As housing characteristics play a crucial role in indoor overheating and health vulnerability, excluding building stock and urban characteristics such as building envelope properties (window, wall, roof), construction type (wood frame, stone, brick, concrete), age of the building, housing type (detached or attached single family, multifamily), mutual shading, air conditioning status, infiltration, the ratio of pervious and impervious material, tree canopy cover, proximity to the highway, nearby large parking lot, sky view factor, street aspect ratio from heat vulnerability index limits its ability to capture heat vulnerability to move toward environmental equity in the built environment and public realm for resilient future.

Future studies need to identify housing characteristics that distinctly impact mass and heat exchange between indoor and outdoor environments to develop and validate appropriate proxy variables that would allow for accurate extrapolation of thermal-related factors from existing less robust housing stock databases. For example, proximity to the highway and parking lot can be a proxy variable for daytime temperature rise, age of housing can be used as a proxy for housing characteristics (Rinner et al. 2010)) and building codes can be used as a proxy for insulation, window, and roof properties. At present HVI assists in identifying and distributing adaptation resources based on the level of vulnerability. However, adding cityscape and housing properties to it can inform long-term renovation, retrofit, and refurbishment of existing buildings as heat-mitigation planning efforts in the community. On a larger scale, revised HVI can be used to change the existing design code to develop community resilience.

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