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Article

Heat adaptation and health in the informal housing—An exploratory research in Ahmedabad, India

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Abstract: As the global temperature rises, Urban Heat Island (UHI) impacts are slated to enhance in the cities due to temperature increase. The informal settlement dwellings, constructed of heat-absorbing materials, having poor ventilation, and located in neighborhoods with a lack of green and open spaces, are more vulnerable to heat than the formal housing settlements. Rising temperatures are expected to adversely impact the health of the population in general and of the dwellers of the informal settlements in particular. While replacing the entire informal housing stock with formal housing requires stupendous costs, modifying this housing through introducing cool roofs is an interim physical adaptation solution to mitigate the heat impacts. The objective of this exploratory study is to assess whether built environment characteristics, with emphasis on cool roofs introduced in dwelling units in the informal settlements in Ahmedabad City in India, have improved thermal comfort within these dwelling units and, if so, whether this intervention has translated into mitigating health impacts of heat. The study reveals that the cool roofs have reduced temperatures within the dwelling unit by 1 ℃ to 1.5 ℃ during peak summer days. But other built environment characteristics such as cross ventilation, ceiling height, trees adjoining the dwelling unit, and open space in the neighborhood too have contributed toward reducing indoor temperatures. Adaptation to high temperatures in the informal settlements requires localized, doable solutions in the immediate term.

Keywords: climate change & heat; informal housing adaptation; health

1. Introduction

The increase in average global temperatures is expected to have adverse consequences for health. The Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) states three facts: (i) the globe has experienced an average increase of 0.99 ℃ in the first two decades of the 21st century; (ii) the temperature increase recorded in the last decade (2011–2020) is higher by 1.09 ℃ over the 1850–1900 levels [1]; and (iii) there is a 50% likelihood of global warming reaching or exceeding 1.5 ℃ in the near term (i.e., 2021–2040) for the low greenhouse emissions scenario.

A long-term warming trend in annual mean surface temperature has been observed across Asia during 1960–2015, and the warming accelerated after the 1970s [2–5]. Furthermore, in South Asia, the projected warming is of 5 ℃ or less in the RCP8.5 [2]/SSP5-8.5 [3] scenarios and limited to 2 ℃ under the SSP1-2.6 [4]. The number of days experiencing excess heat stress 41 ℃ and above is expected to increase by 50–150 days for SSP5-8.5 at the end of the century and up to 30 days for SSP1-2.6 and above 35 ℃ by 10–50 days by the mid-century under SSP5-8.5 [5,6]. India could experience heat waves beyond human survival limits, states a World Bank Report [7]. In a business-as-usual scenario of global emissions, India's average temperature will rise by 4.4 °C (39.9 °F) by 2100, while heatwaves will multiply by a factor of two or three and their duration will double compared to the 1976–2005 period [8,9].

The year 2024 is said to be globally the hottest year so far [10]. The year 2023 has experienced unprecedented high temperatures; up to 2nd October, around 86 days in the year have been over 1.5 °C warmer than the pre-industrial average [10]. In India too, a recent study points to unprecedented heat waves across Indian cities [11]. Heat waves in cities translate into Urban Heat Island (UHI) effects, which have worsened the local effects of rising temperatures [11]. UHI is an outcome of multiple factors at the city level, which is discussed later in this section. The heat stress or thermal discomfort thus created is not just a function of rising temperatures but a combination of air temperature, land surface temperature, and relative humidity [11].

The rising temperatures, along with humidity factors, are expected to have health implications. The IPCC's Reports of the Sixth Assessment Cycle have indicated that the heat-related risks have increased. Certain groups are vulnerable to heat-related health risks, such as infants, the elderly, people with physical disabilities, the underprivileged, outdoor laborers, slum dwellers, and others [12,13]. High temperatures present a hazard, but risk related to heat is a function of social, economic, demographic, infrastructural, and physical environmental variables in particular [14,15]. In the cities of the global south, the poor tend to work in the informal economy and live in crowded housing, experiencing high heat stress [16]. They also have limited capacity to cope and hence are more vulnerable to heat conditions due to, in general, poor nutrition and health that reduces their immunity to heat, and poor access to water are more vulnerable to heat conditions [16,17].

Recognized direct effects of weather and climate on physical health include heat stress; respiratory conditions linked to heat combined with air pollution and aeroallergens; injury from floods, landslides, and windstorms; plus illnesses from vector-borne and infectious disease, as well as water- and food-related pathogens [18,19]. There is also growing evidence of "unseen" impacts of extreme weather events on mental health, such as post-traumatic stress disorder, anxiety, depression, complicated grief, survivor guilt, recovery fatigue, substance abuse, and even suicide [20,21]. The physiological responses to excessive heat exposure are well-known—ranging from heat rash, oedema, dizziness, dehydration, and cramps to heat exhaustion, heatstroke, and death [22]. Existing pulmonary, cardiac, kidney, and psychiatric illnesses also may be aggravated by heat. Heat-related mortality and morbidity are expected to rise in Asia over the coming decades, driven by a combination of climate change, rapid population and urban growth, and demographic change [23].

In the recent heat waves in India, more than 100,000 people have died [24,25]. Azhar et al. [24] have speculated that the increase in mortality in Ahmedabad during periods of high temperatures is heat-related mortality. High temperatures lead to heat-related mortality and morbidity, such as dizziness, unconsciousness, blood pressure increase, abdominal pains, chest pains, and vomiting [26]. In summer 2017, of the 10,135 heat-related emergencies handled in Ahmedabad by the emergency ambulance service during April–May 2017, abdominal pain constituted 25 percent, followed by unconsciousness (22 percent), victim falling (15.2 percent), and chest pain (11.9 percent) [27]. In May of 2022, based on the data from an emergency ambulance service, 5055 cases of heat-related emergencies needed patients to be transported to hospitals in the city, i.e., 163 patients per day [28]. Dehydration and salt loss lead to low blood pressure, further causing dizziness and then body ache. It also leads to fever. The ultimate effect is loss of working days. The heat-related morbidity and mortality were not reported in the summer months of 2020 and 2021 due to the health systems being overrun by COVID-19 cases [29]. The heat-related illnesses are an outcome of a combination of pre-existing medical conditions, exposure, age, and access to health information and resources [30], which does not take away the fact that heat has been the trigger of the health effects mentioned above. This paper focuses on heat stress experienced within Dwelling Units (DUs) in a city in India, namely Ahmedabad.

1.1. Built-form and indoor thermal stress

The indoor heat experience is influenced by the immediate outdoor ambient temperature and housing characteristics. The immediate outdoor ambient temperatures are influenced by different factors at different levels in a city (**Table 1**), besides the changes in average temperatures at the city level [31]. The built-form factors such as land use, density, transport systems, housing type, building materials, and Dwelling Unit (DU) built characteristics influence temperatures experienced within individual Dwelling Unit (DU). This implies that adaptation to rising temperatures requires actions at all these levels. In this paper, we focus on actions at the individual DU and immediate neighborhood level, where households and communities have control. The actions at other levels are in the remit of the city government, which is outside the scope of this research.

Table 1. Factors influencing heat experience at the dwelling unit level.

	Level	Factors	References
1	City-level	• Density of the city	Schatz and Kucharik [32]; Wang et al. [33]; Zander et al. [34]; ADB [16]
		• Spatial structure: land uses and built form	Xu et al. [35]; Soltani and Sharifi [36]
		• % Green and Blue spaces	Schatz and Kucharik [32]; Gunawardena et al. [37]; Emmanuel and Loconsole [38]; AbotElata and AbdElfattah [39]; Yu et al. [40]; Rahul et al. [41]; Borthakur et al. [42]
		• Local weather such as cloud cover, wind speed, relative humidity, etc.	Schatz and Kucharik [32]
		• Availability of Public Transport / Traffic congestion	Lee et al. [43]
2	City's Sub-region level	• Density	Pramanik et al. [44]; Stone et al. [45]; Zander et al. [34]
		• Spatial structure: land use and built form	Xu et al. [35]; Elmarakby et al. [46]
		• % Green and Blue Cover	Schatz and Kucharik [32]; Gunawardena et al. [37]; Emmanuel and Loconsole [38]; AbotElata and AbdElfattah [39]; Yu et al. [40]; Rahul et al. [41]; Borthakur et al. [42]
		• Income of neighborhood	Jacobs et al. [47]
		• Air pollution level	ADB [16]

Table 1. (*Continued*).

	Level	Factors	References
3	Immediate Neighbourhood level	• Density	Pramanik et al. [44]; Stone et al. [45]; Zander et al. [34]
		• Spatial structure and Built form including building materials	Xu et al. [35]; Lee et al. [43]; Elmarakby et al. [46]
		• % Green and Blue Cover	Schatz and Kucharik [32]; Gunawardena et al. [37]; Emmanuel and Loconsole [38]; AbotElata and AbdElfattah [39]; Yu et al. [40]
		• Proximity to open space	Xu et al. [35]
		• Use of air-conditioning	Lee et al. [43]
		• Income of neighbourhood	Jacobs et al. [47]
		• Street canyon direction and materials	Xu et al. [35]
4	Individual DU level	• DU roof and wall materials	Alexandri and Jones [48]; Doick and Hutchings [49]; Zhao et al. [50]
		• Storey on which DU is located	Tomilson et al. [51]
		• Number of walls exposed to direct sun	Alexandri and Jones [52]; Doick and Hutchings [49]; Zhao et al. [50]
		• Cross Ventilation	Satterthwaite et al. [52]; Head et al. [53]
		• DU layout	Lomas and Giridharan [54]
		• Treatment of roof for increasing albedo and reducing heat transfusion or vice versa (i.e. use of heat absorbing materials such as tar)	ADB [16]
		• Use of cooling devices	Jay et al. [55]

Source: By the author.

At the city level, the temperatures are, first of all, impacted by overall weather and the formation of heat waves [31]. Thereafter, density is considered to be the primary driver of temperature patterns; the higher the density, the higher is the temperature [33,34]. Density at the sub-city level and neighborhood level too matter. There is a strong positive relationship between the density index and heat index, which then translates into heat-related health impacts [44]. While climate change mitigation promotes high density, this also has the possibility of creating local heat islands [45,56], which is indeed an issue that requires further attention. Urban morphology, that is, the built-up density, building heights, street pattern, land use, surface cover, etc. also determine Urban Heat Island Impact (UHI) effects [46].

The secondary drivers of the temperatures are wind speed, cloud cover, relative humidity, etc. Wind circulation can have two different types of impacts; if there are water bodies nearby, then when hot air rises, cool air from the surrounding areas with either higher tree cover or a water body moves in and reduces the temperatures.

Both blue and green spaces and their proportion in the city influence the average temperatures at the city level as well as smaller than city spatial levels [37–39]. Green areas have high albedo. The canopy of trees prevents heat from reaching the street canyon. Air temperature in spaces with green cover is lower than in spaces without green cover at the same time of the day [39]. Research shows that the blue-green spaces have cooling effects not only in the area where these are but also in the surrounding areas [40]. More built spaces and fewer green spaces lead to intense UHI [36].

Evidence is growing that rapid urban expansion and loss of green space are contributing to more intense heat waves in tropical cities. Conversely, the protection of green areas and water bodies can create a cool "oasis effect," especially for cities in arid and semiarid climate zones [41,42]. Unfortunately, people residing in high-density, informal neighborhoods are more exposed to higher ambient temperatures than those residing in affluent neighborhoods [46].

At the sub-regional and neighborhood level, open spaces provide a possibility of reducing air temperatures. Open spaces help in heat diffusion [35]. Mahadevia et al. [57] also find that more open space and green cover assist in reducing indoor temperatures; however, open space has a greater impact than tree cover.

At the sub-city and neighborhood level, the UHI effect is enhanced by the materials used in building façade; glazing and concrete used in façade and asphalt roads enhance UHI effects [43]. The use of air conditioners, which are prominent in dense urban areas as well as commercial areas, also leads to an increase in the UHI effect [43]. In dense areas, there is high traffic and hence congestion, which also leads to an increase in local temperatures [43]. Narrow streets, low urban permeabilities, and tall buildings that create road canyons where the wind does not flow can also lead to a high UHI effect [46].

Building design and layout, occupancy level (crowdedness), ventilation [52,53], and building materials in particular the roofing materials [48] (discussion on roofs follows) influence indoor temperatures at individual building levels. Indoor fans are beneficial up to 45 ℃ [55].

In cities of the global south, low-income housing such as squatters, slums, and other informal housing is more vulnerable to heat stress than formally built housing [52,58] due to crowded living conditions, low-quality housing [58] with inadequate ventilation, and limited access to cooling in the former [16]. The DUs in informal housing are generally made of heat-trapping materials such as tin, asbestos, cement sheet, plastic, cardboard, plywood scraps, polyvinyl chloride or PVC tarps, etc., especially for roofing [16], which transfer heat indoors, which cumulatively reduces the ability to cool down [59]. The prevalence of cooking stoves inside ill-ventilated DUs and economic activities within these exacerbate the indoor heat experience [60]. The absence of greenery and tree shade around the houses also adds to indoor heat stress [60]. Many households lack reliable water and electricity supplies [16], two essential items for cooling during heat waves. These housing do not meet mandated building or planning standards and are often poorly located, such as near industrial states, in settlements with no or little open spaces and narrow roads preventing air circulation [52].

In the cities in India and South Asia, where a large proportion of households are living in the informal housing described above, immediate interventions to cope with rising heat stress are required. One option for heat adaptation in the informal settlements is transiting the households living in these settlements to formal housing, with planned neighborhoods, basic services such as water supply and electricity, and well-ventilated DUs. This is an expensive option, as proved by Mahadevia et al. [57], taking the example of Ahmedabad. Thus, modifying housing is an important immediate local-level adaptation intervention to heat and building short-term resilience to climate change [16,57,61].

1.2. Adaptation measures in informal housing

Housing-related adaptation measures include solutions at individual DU levels that deal with roofs, wall materials, building form, ventilation, etc., as well as neighborhood level, such as treating pavements (cool pavements) [16], if any, and greenery around. In low-income housing, the individual DU-level interventions have to be simple and cost-effective. If informal housing has to be made heat-proof, investments are required, which would require policy measures and fiscal support for upgrading, which, however, Satterthwaite et al. [52] argue is hard to come by. Nonetheless, actions are recommended to deal with increasing heat stress in informal housing.

One of the widely used measures to reduce heat transfer within DUs is to modify roofs. These measures include roof insulation, cool roofs, and radiant barriers. Although roof insulation is quite commonly used, cool roofs and radiant barriers are relatively new solutions. Cool or high-albedo roofs refer to the outer layer or exterior roof surface that acts as the key reflective surface. Radiant barriers are a way of increasing the thermal performance of a roof by introducing a new layer with low emissivity below the roof surface [62]. Based on the literature, cool roofs appear to offer the most viable solution for the urban poor: they are more cost-effective than insulation and feasible for new buildings as well as retrofitted ones.

There are three types of cool roofs: naturally cool roofs (use of white vinyl or white surface materials), coated roofs, and insulated roofs (using a thermal barrier) [16]. Studies [59,63] have categorized cool roof techniques in the context of lower-income communities into three categories: Tiled or painted cool roofs, membrane cool roofs such as a sheet covering existing roofs, and special cool roof materials such as Mod Roof. Tiled/painted cool roofs, which includes the application of white paint, or in the case of Ahmedabad (the focus of this paper), the application of white lime paint. Ultra-white vinyl paints can achieve more than 98 percent sunlight reflection [64]. Membrane cool roofs, that is, adding a membrane or sheeting to cover the roof, as used in the Hyderabad Cool Roofs Programmer, which uses a high-density polyethylene (HDPE) cool roof membrane [65]. Special cool roof materials such as Mod Roof, which is made of coconut husk and paper waste, have been installed in households around Gujarat and Delhi and can serve as an alternative to reinforced cement concrete (RCC) roofs. The introduction of a thermal barrier (thermocol, cardboard, etc.) as a membrane also insulates roofs [64]. Made of packaging waste and coconut fiber held together by a natural binder and covered in waterproofing material, the Mod Roof panels are made to be strong, waterproof, fireproof, and long-lasting, which improves safety and decreases maintenance.

We have limited research available on housing, heat experience, and health in Indian cities and whether physical adaptive measures at the DU level positively impact both. There can be many local-level physical adaptive measures, such as increasing blue and green cover and shifting from hard to soft surfaces in the immediate neighborhood level and changing the building materials to ones that have high albedo, such as brick walls instead of concrete or glass walls, and replacing GI or asbestos sheet roofs with concrete or covering GI or asbestos sheet roofs with less heat-absorbing materials, as discussed above. In this study, we focus on these physical adaptive measures, starting with the cool roofs and then including other physical variables such as open and green spaces in the neighborhood and micro conditions such as the height of the ceiling, availability of cross ventilation, and shades over openings.

This study is different from available studies on heat impacts in India as well as in Ahmedabad. There are general studies on changing temperatures and factors influencing experienced heat stress in selected cities in India. A few studies have analyzed temperature trends and linked these with the reported mortality rates at the city level. One such study is by Azhar et al. [24], which links excess in reported mortality rates to periods of high temperatures. We find fewer empirical studies of the health impacts of cool roofs on the residents of informal housing. The ones available measure the impact of roof treatment on heat stress within informal housing. For example, a study in South Africa found that cool roof paints can improve the performance of uninsulated, low thermal mass homes in informal settlements by lowering heat stress conditions by 42%–63% [66]. A study in Ahmedabad [67] showed Mod Roof was found to be 4.5 °C cooler than conventional roof types. Both these studies stopped short of assessing health impacts. Studies related to adaptation efforts are restricted to specific work groups such as police, construction workers, etc. But adaptations at the house level are a few. Furthermore, we do not have studies that analyze the combined effect of cool roofs, other local housing conditions such as open and green spaces in the neighborhood, and micro conditions such as the height of the ceiling, availability of cross ventilation, shades over openings, etc. The Cool Roofs programme is recommended as a solution to heat adaptation in Indian cities. Thus, such micro-level analysis of what works at the individual DU level offers a grounded solution to heat adaptation. Hence, learnings from this research will contribute towards a swifter adaptation of informal housing to increasing temperatures due to climate change. These are the low-hanging solutions that can be easily implemented at the local community and household level.

This is an exploratory study, with 120 sample households living in the informal sector in the city. This paper assesses the impact of cool-roof intervention as a mechanism to adapt to extreme heat in the informal housing in Ahmedabad City (population of about 8 million), India, and its consequent health impacts. The city has been selected because of the implementation of the Cool Roofs programmer in the city by Mahila Housing Trust, first on a pilot basis in 2017, and then 15,000 DUs in the slums in 2020 [68]. The city introduced the first Heat Action Plan (HAP) in 2010 [69], which is reviewed every year. But this HAP is an early warning system. In recent years, after the first pilot Cool Roof implementation, the Cool Roofs programme has also been included in the city’s HAP. About 22 cities in India have HAPs, of which a quarter have proposed Cool Roofs and one in five have proposed increasing green cover as solutions (This data is based on sifting through climate adaptation measures announced by 133 cities in India).

The objectives of this study are (i) to assess the impact of the built environment characteristics with an emphasis on cool roofs on temperatures experienced within the dwellings in the informal settlements, and (ii) if the temperatures experienced indoors have reduced due to built environment characteristics, then to assess whether it has impacted the health status of the residents of these dwellings.

2. Approach, materials & methods

Generally, epidemiological studies of heat-related health effects use outdoor weather conditions as the primary indicator to estimate indoor heat stress [70,71], and policymakers too use heat-health warnings based on outdoor temperatures [72], as in the case of Ahmedabad's Heat Action Plan (HAP) [73]. This reliance on outdoor conditions can mislead the interpretation of health effects and associated solutions since most people who stay indoors are assumed to be protected from outdoor thermal conditions [74].

The study is located in Ahmedabad, which has had the Ahmedabad Cool Roofs Programme [63] since 2017. We adopted the granular approach of looking at the housing conditions in great detail, such as roof materials, type, treatment, and height; wall materials, walls exposed to sun, and overhang on walls; and openings and their locations. We also looked at the characteristics of the immediate neighborhood, such as street conditions, tree cover, and neighborhood-level land use. The granular analysis at the immediate neighborhood level and the house levels gives adaptation solutions at the housing as well as neighborhood level, which local communities and NGOs can assist in implementing.

Ahmedabad, located in Gujarat state (**Figure 1**), has been selected for the research site because of the ease of conducting fieldwork—the research team being located in the city, high and increasing average temperatures in the city (see **Figure 2**), a non-governmental organization (NGO) (Mahila Housing Trust (MHT)) working with the slum dwellers to increase their resilience to increasing temperatures, and a heat action plan (HAP) at the city level. The MHT has been assisting individual households to treat their roofs; for example, replace their roof with a Mod Roof [70], and paint their roofs white (with lime-mixture or paint) to reduce internal temperatures. The municipal area, which covers an area of 466 sq. km, is under the jurisdiction of the Ahmedabad Municipal Corporation (AMC).

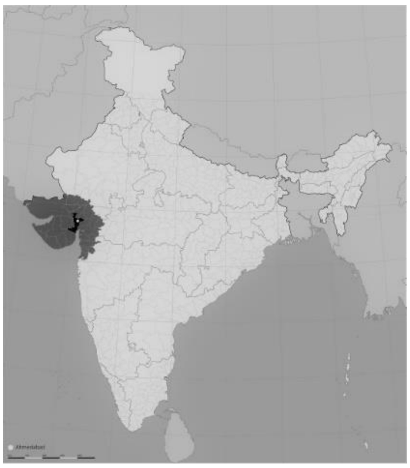


Figure 1. Location of Ahmedabad.

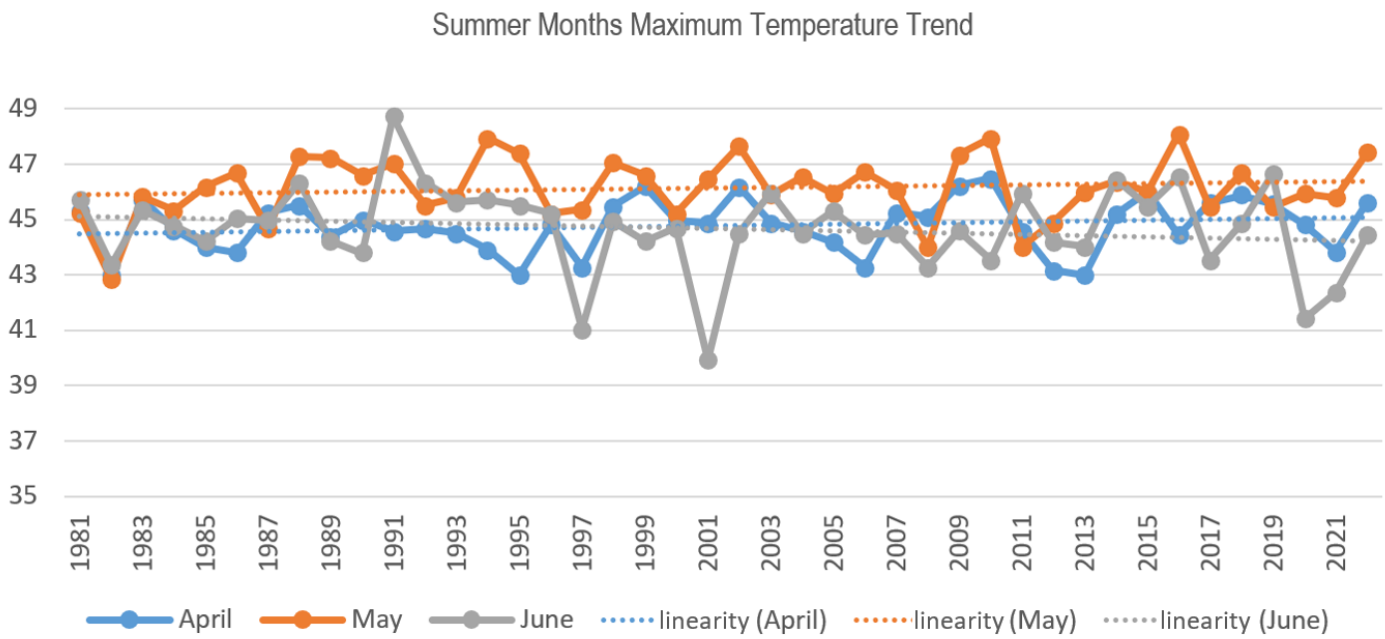


Figure 2. Summer maximum temperature trend, Ahmedabad [75].

Ahmedabad faces a major climate risk, i.e., the increase in observed ambient temperature and frequency of heat waves [76]. The city's warm, dry conditions are conducive to heat waves. The Ahmedabad HAP defines a heat wave as daily maximum temperatures in excess of 40 °C (104 °F) as measured at the Ahmedabad Meteorological (Met) Centre [68]. It issues a yellow alert when the temperature is between 41.1 °C and 43 °C, an orange alert for 43.1 °C–44.9 °C and a red alert when temperature exceeds 45 °C.

Morphologically, Ahmedabad is broadly divided into two segments, the east and the west. Eastern Ahmedabad, to the east of the river Sabarmati, consists of the 600-year-old walled city and the industrial areas around it on the north, east, and south, all the way to the eastern boundary of the city. The low-income households live close to the industrial areas in eastern Ahmedabad. The western parts of the city are occupied by higher income groups and locate new high-end gated community developments. The western parts of the city have more green and open spaces than the eastern parts. On the whole, only 2% of the AMC's land area is under green cover, which is very low by the norms mentioned in the city's Development Plan [77].

We decided to conduct a household-level survey in collaboration with the MHT, whose settlement-level contact person identified sample DUs with cool roofs. We then decided to select other DUs close by without a cool roof to assess the benefit of the intervention. In no way is the purpose of this research to assess MHT's efficacious intervention but to assess what types of interventions have helped in reducing temperatures experienced within a DU. Being knowledgeable about the diversity of DUs in informal housing and weary of the reductionist approach of bunching all of these under one broad brush of 'informal housing', we decided to explore the differences within such DUs. The sample DUs in the nine selected informal settlements varied in their floor layouts, materials used for roofs in particular, treatment of roofs, roof heights, openings in the walls, number of storeys, green coverage nearby, and road conditions. The household survey solicited information related to the physical characteristics of the surveyed DU, including the location of the kitchen, availability of water supply and electricity, neighborhood characteristics such as street features, green cover, and open space nearby, and land use of the city's sub-region, the socio-economic profile of the household, reported illness in the 15 days before the survey, and measures taken to address illness.

We measured temperatures immediately outside the DU and within the DU with the fan on and fan off using a hand-held Wet Bulb Global Temperature (WBGT) device. The city's average temperature was the one measured by the Indian Meteorological Department and displayed on smartphones. We recorded the city's average temperature in the survey form at the time of indoor and outdoor temperature measurement in the selected households. Household surveys were carried out from 2 June to 17 June 2022, in the daytime. We did not measure nighttime temperatures. It is important to mention that we could have installed temperature-measuring devices within the DU and could have asked the residents to record night temperatures as well. However, we were not confident of the response rates from among those surveyed.

We have created a measure called Local Heat Island (LHI) that gives the difference between the city's average temperature at the time of the survey and the outdoor temperature measured using WBGT. We have refrained from using the concept of UHI, which is commonly used in research, as it is hard to obtain temperatures around the city's periphery to assess the UHI.

The survey was conducted in 121 households spread over nine settlements, three in West Ahmedabad, one near the walled city of Ahmedabad, and the rest five in East Ahmedabad (**Figure 3**). The valid answers received were 117. Two peripheral settlements in East Ahmedabad were located in the industrial area (**Table 2**). Although we started to identify our sample around cool roofs, only 17.9 percent of sample households had cool roofs, and in three settlements none had any treatment of roofs to deal with heat. The survey covered 553 individuals.

Table 2. Housing characteristics by settlement.

Settlement	Location	Number of sample HHs	% HHs with cool-roofs	% HHs living in single-storey DUs	% HHs with ceiling height <10ft	% HHs having open ground nearby	% HHs having a tree adjoining DU	% DUs having cross-ventilation
Bhagwatinagar (E-1)	East Ahmedabad-periphery	6	50.0	100	100	0	33	0
Mahavirnagar (E-2)	East Ahmedabad	10	60.0	100	80	10	0	40
Sarapur (E-3)	East Ahmedabad	21	28.6	100	95	38	29	71
Patannagar (E-4)	East Ahmedabad	17	11.8	100	76	6	6	29
Vishwasnagar (E-5)	East Ahmedabad-periphery	11	18.2	100	45	18	0	100
Prem darwaza (C-1)	Walled City	10	10.0	100	90	0	20	20
Jadibanagar (W-1)	West Ahmedabad	16	0.0	94	87	25	6	88

Table 2. (*Continued*).

Settlement	Location	Number of sample HHs	% HHs with cool-roofs	% HHs living in single-storey DUs	% HHs with ceiling height <10ft	% HHs having open ground nearby	% HHs having a tree adjoining DU	% DUs having cross-ventilation
Akhbarnagar (W-2)	West Ahmedabad	11	0.0	100	93	53	33	60
Rajeevnagar (W-3)	West Ahmedabad	15	0.0	73	82	18	18	82
Total		117	17.1	97	84	22	16	59

Source: Primary survey.

3. Results

3.1. Sample profile

In the sample of 553 persons, 36 percent, or 207 were, children and 12 senior citizens. The average household size of the surveyed is 4.8. The average monthly income of the households covered was INR 15,881 (USD 203 (At the exchange rate of1USD = INR 78 in June 2022)). All households, therefore, belong to the low-income category.

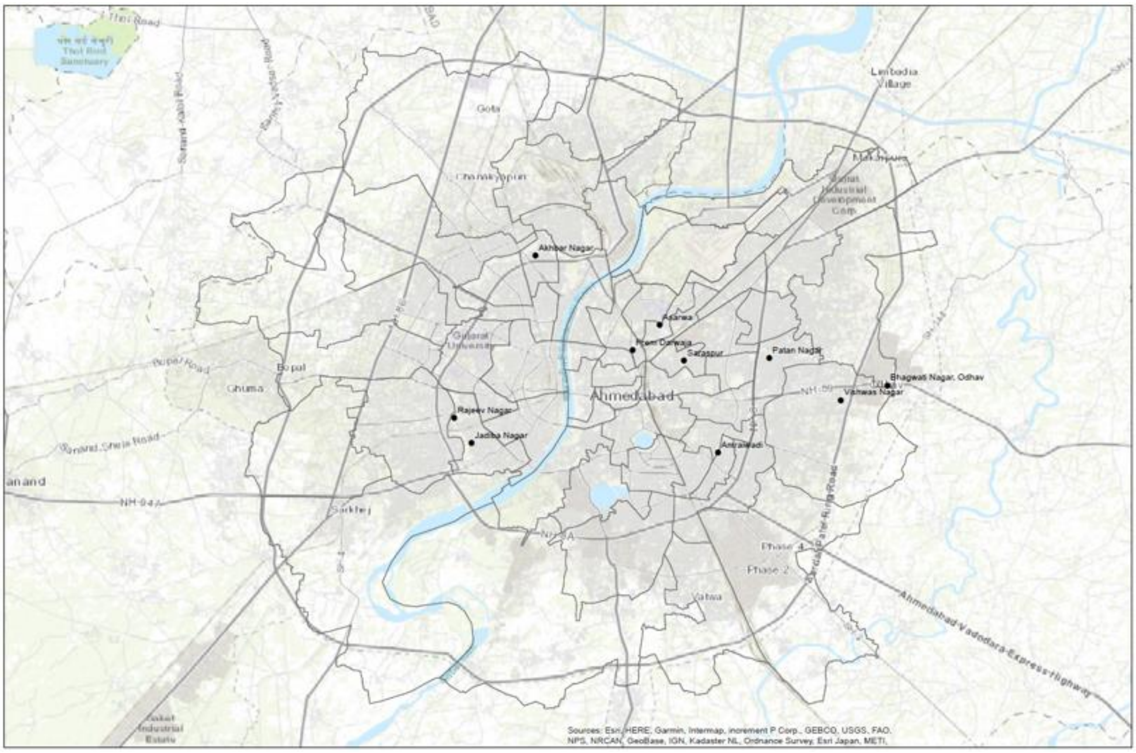


Figure 3. Surveyed settlements on Ahmedabad map.

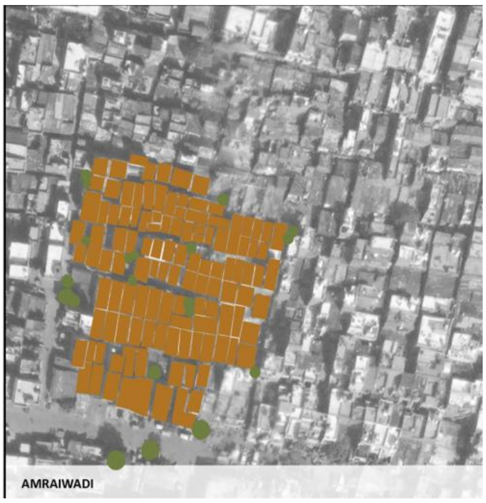
Source: Prepared by the author.

Table 2 gives housing conditions for the surveyed households in each of the settlements. All but four Dwelling Units (DUs) in the sample were single-storey or ground floor. The implication is that all of these DUs would have been exposed to direct heat from the roof. Twenty DUs used mechanisms to cool the roofs (**Table 2**). However, in two settlements, E-1 and E-2, more than half the surveyed DUs had used some method of cooling roofs. Seven DUs had modified roofs, such as adding a bamboo layer at the top, putting thermacol sheets or cardboard below the roof, and putting porcelain tiles or wood planks on the roof. Thirteen households had painted the roof with white paint. All DUs had brick walls. Half the DUs were with GI or asbestos sheet roofs, another 42 (36 percent) used cement sheet roofs, and 11 DUs had concrete roofs. Five DUs had *katcha* roofs using bamboo, thatch, plastic, etc., as roof materials. Most DUs were in good condition. Eighty-four percent of DUs had a ceiling below 10 feet, and the remaining ones had a ceiling higher than 10 feet. All surveyed DUs had electricity access; all surveyed households reported access to toilets; 97 percent of them had an individual toilet. All households except three reported access to tap water. Thus, all the surveyed DUs had basic services.

About 60 percent of the DUs had cross-ventilation, but none in E-1 and less than 30 percent of the DUs in in C-1 and E-4 had cross-ventilation. Most of the DUs had two walls shared with adjoining DUs and thus had only two walls exposed to direct heat. Lastly, 65 percent of the surveyed DUs were located on streets that were shaded. These settlements are crowded and lack open grounds. Only 16 percent of DUs reported having a tree in proximity. The plans and photos of the surveyed settlements and DUs in them are presented in **Figures 4** and **5**.

E-1

E-3



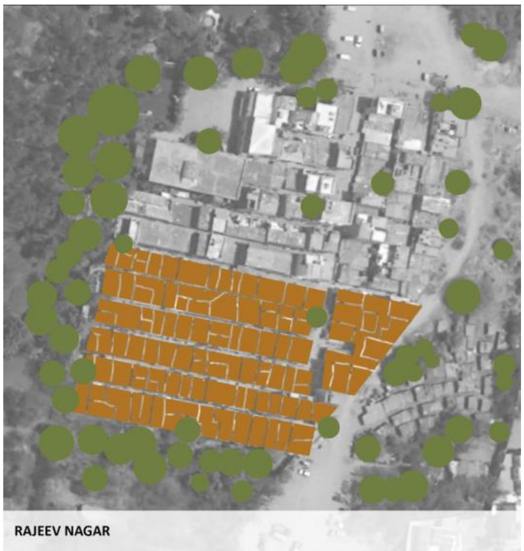
E-2

E-4

C-1

W-1

W-2

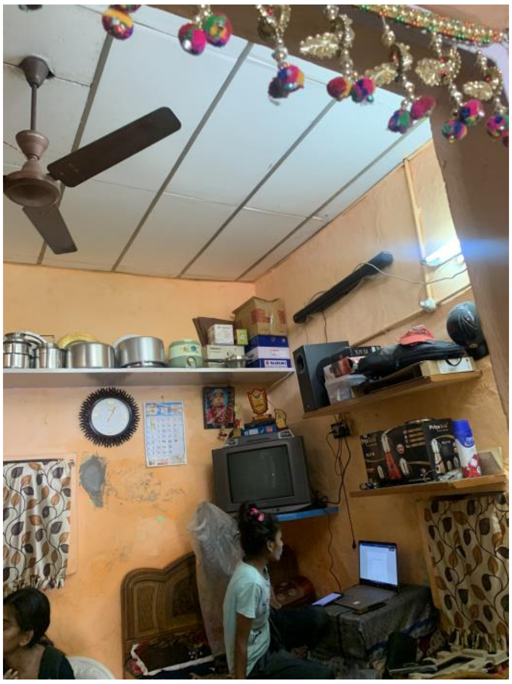


W-3

Figure 4. Settlement layouts and photos.

Dwelling Unit Entrance

Cool Roofs



Cool Roof

Figure 5. Settlements' visuals.

3.2. Temperatures experienced

During the period of our survey, which spanned from 2 June to 17 June 2022 but was carried out only for nine days during the period, the city's average temperature was 37.06 ℃, with a maximum being 40.16 ℃ and a minimum of 32.72 ℃ (see **Figure 6**). On all the days of the survey, the temperatures recorded outside the DU were higher than the city's average at the time of the survey, indicating the formation of a Local Heat Island (LHI) (**Figure 6**). The average indoor temperatures recorded with or without a fan on, as well as outdoor temperatures on all days of the survey, were higher than the average temperature of the city at the time of the survey (**Figure 6**). Thus, we can observe the LHI that has kept indoor temperatures high in the surveyed DUs.

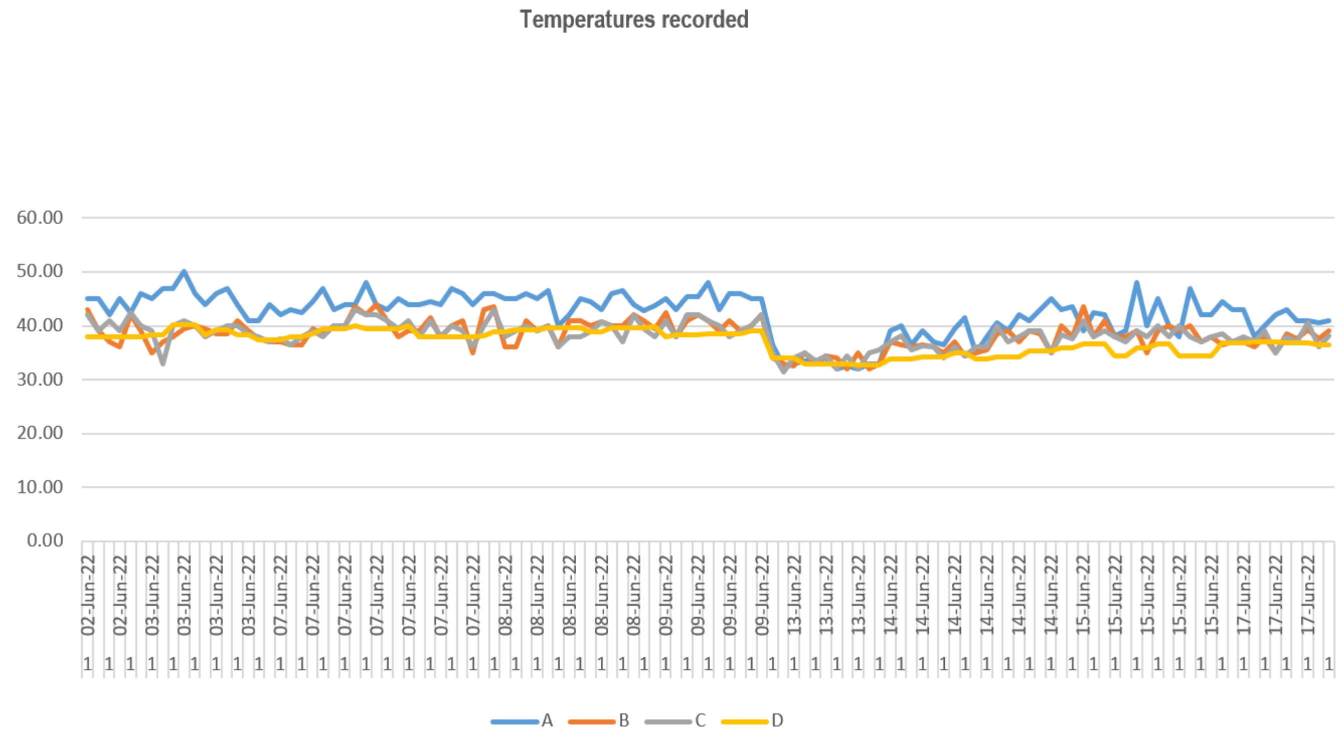


Figure 6. Temperatures observed during survey period.

A = Temperature Recorded Outside DU; B = Temperature Recorded Inside House with Fan On; C = Temperature Recorded Inside House with Fan Off; D = City's Temperature at the Time of Survey (displayed on smart phone).

Geographically, the settlements in East Ahmedabad, except E-5, experienced much higher LHI, which is the difference between the city's average temperature at the time of survey and the on-site temperature as compared to the three settlements in West Ahmedabad. The exception is W-2, where the LHI impact is 6.34 °C on the day of the survey, but the average temperature outside DU in the settlement is lower than in East Ahmedabad settlements. Average temperatures recorded in the settlements in East Ahmedabad, i.e., outside DU, and temperatures experienced within the DUs are higher than in settlements in West Ahmedabad (**Table 3**). On the day the survey was canvassed in E-5, the highest temperature of the day was 35 °C [78] as it was a cloudy day. We have thus excluded E-5 from further analysis. The LHI impact was observed in all the settlements. It has led to an increase in temperature in the settlements studied, represented by the temperature measured outside the DU (**Table 3**). On average, over the whole sample, the temperature increase due to LHI impact is 5.20 °C, indicating that most settlements selected for the study have experienced higher local temperatures as compared to that of the city at the time of the survey (**Table 3**).

Table 3. Temperatures recorded on survey days by settlements (in °C).

Settlement	Temperature outside DU	Temperature inside DU with fan	Temperature inside DU without fan	City's average temperature	LHI Impact measured in °C (A-D)
	A	B	C	D	
E-1	44.25	39.33	40.58	37.98	6.27
E-2	45.70	38.60	38.85	39.05	6.65
E-3	44.21	39.26	39.26	38.57	5.64
E-4	44.54	39.99	39.24	39.35	5.19
E-5*	33.22	33.46	33.86	33.15	0.07
C-1	45.20	40.55	40.30	38.49	6.71
W-1	39.53	36.63	36.72	34.37	5.16
W-2	41.95	38.90	38.47	35.62	6.34
W-3	41.55	37.39	37.65	36.81	4.74

* Vishwasnagar data has been excluded from further analysis due its data captured on low temperature day.
Source: Primary survey.

3.3. Effect of cool-roofs on IN-DU temperatures

Seventeen percent of surveyed households had made efforts to cool their roofs with the purpose that the temperature experienced inside is lower than that of the outside. In this paper we have used the adaptive thermal comfort band as 24 °C–35 °C based on Mahadevia et al. [57]. Faheem et al. [79] give this range as 26.1 °C–32.8 °C. Rawal et al. [80], taking samples from different climatic zones, estimate 80 percent of the Indian residential occupants experienced a neutral thermal sensation in the indoor operative range of 16.3 °C–35 °C. In all settlements (excluding E-5) the temperatures experienced within the DU with the fan on are above 35 °C (**Table 3** and **Figure 7**). The first part of the chart are the DUs with cool-roof interventions. In these DUs as well, the inside temperatures recorded are above 35 °C, but are lower than the inside temperatures recorded within DUs without cool-roofs.

Figure 7. Temperatures outside and within DUs, city average and cool roof impact.

A = Outside Temperature; B = Inside Temperature with Fan; C = City's Average at the Time of Survey; A−B = Difference between Outside and Inside Temperatures.
Source: Primary survey.

We also analyzed the combined impact of other built environment characteristics on temperatures and cool roofs (**Table 4**). The combination of a cool roof with each of the three other built environment characteristics, such as a tree nearby, open ground in the neighborhood, and cross ventilation, reduces indoor temperatures further. Thus, the difference between the outside and inside temperatures too increases.

Table 4. Temperature comparison of houses with cool roofs and other housing characteristics.

Built environment characteristics	Average Temperature Inside DU* (℃)	Difference between Outside and Inside Temperatures (℃)
Cool roof + tree nearby	37.33	5.67
Cool roof + cross ventilation	37.65	3.90
Cool roof + open ground in neighborhood	35.50	4.75
Cool roof + no direct sun	38.06	5.44

* Measured with fan on.

We decided to run regressions to check which of the built environment factors influenced the temperatures within the sampled dwelling units (**Table 5**). The built environment characteristic of cross ventilation is statistically significant ($p < 0.05$) and significantly impacts the temperature inside the house. Other predictors, cool roofs, a tree adjoining the house, and open ground in the neighborhood did not display any significant impact on the temperatures inside the house.

Table 5. Regression results.

Built Environment Characteristics	Chi-Square	df: 26	*p*-value
Cool Roof	29.579	26	0.285
Cross Ventilation	56.908	26	0.000
Tree Adjoining	26.433	26	0.440
Open Ground in Neighborhood	32.991	26	0.162

Sample disaggregated by settlements does not give a clear advantage to the DUs with cool-roof the difference between outside DU and inside DU temperatures in all settlements except E-4 and C-1. The three settlements in west Ahmedabad did not have cool-roofs, and hence these have been excluded from **Table 6**. We do not see cool roofs alone having an advantage in reducing in-DU temperatures because other factors too have played a role in lowering temperatures within the DUs. These factors are availability of a storey above (where we have measured temperatures only on the ground floors), availability of cross ventilation, high roof (more than 10 feet), tree adjoining the DU, no direct sunlight on the walls, and shaded streets.

On average, the difference between the outside and inside temperatures in DUs with cool roofs is 5.39 ℃ (**Table 7**). This difference in the case of DUs without cool-roofs is lesser, 4.20 ℃. If the DUs had a storey above, cross-ventilation, a tree adjoining, a roof higher than 10 feet, and shaded street and DU-walls, these led to reducing temperature inside the DU compared to only ground-floor DUs, DUs without cross-ventilation, no adjoining tree, a roof lower than 10 feet, and direct sunlight hitting the streets and walls of the DU.

Table 6. Temperature (°C) difference with and without cool roofs.

Settlement	With Cool-roof			Without Cool-roof		
	Outside DU	**Inside DU**	**Difference**	**Outside DU**	**Inside DU**	**Difference**
	A	**B**	**A−B**	**A**	**B**	**A−B**
E-1	43.50	39.33	4.17	45.00	39.33	5.67
E-2	45.00	38.08	6.92	46.75	39.38	7.38
E-3	43.08	38.50	4.58	44.67	39.57	5.10
E-4	45.25	40.00	5.25	44.44	39.99	4.45
C-1	43.00	38.00	5.00	45.44	40.83	4.61

Source: Primary survey.

Table 7. Impact of housing related elements on average temperature inside DU, temperature reduction within DU as compared to outside DU and incidence of illness.

Housing Related Parameters	Temperature inside DU with fan on (°C)	Difference of temperature outside DU to temperature inside DU (°C)	Incidence of illness (%)
	Average	**Average**	
With cool-roof interventions	38.64	5.39	36.0
Without cool-roof interventions	38.83	4.20	40.0
Single storey DUs (Only ground floor)	38.89	4.38	35.5
Two-storey DUs (Ground + one) (only 4 DUs in sample) *	36.38	5.00	75.0
DUs with cross ventilation	37.89	4.43	34.8
DUs without cross ventilation	39.90	4.36	39.6
Roof 10ft or low	38.85	4.45	41.2
Roof above 10 ft	38.40	4.24	10.0
Roof GI/Asbestos/Cement Sheets	39.09	4.15	39.6
Roof Concrete	36.72	4.92	18.2
Open ground nearby	39.10	3.76	38.5
No open ground nearby	38.71	4.59	39.6
Tree adjoining DU	38.71	4.91	26.3
No tree adjoining DU	38.82	4.29	38.8
Direct sunlight on DU	38.93	4.12	32.1
No direct sunlight on DU	38.52	5.00	38.6
Shaded street adjoining DU	38.48	4.20	33.8
No shaded street adjoining DU	39.29	4.71	45.0

Source: Primary survey.
Notes: * Temperatures were measured only on the ground floor in two-storey DUs.

3.4. Health impacts

The reported heat-related illnesses are: stomach ache (1 person), blood pressure (1 person), chest pain (3 person), blood from the ear and nose (3 person), dizziness (16 person), dehydration (13 persons), vomiting (7 persons), and any other (3 persons). Two people did not state which illness they suffered. 43 of the 49 who reported illness stated that they fell ill due to heat.

Of those who reported illness, 6 percent were children below age 15 years, 26 percent were in age 15–30 years, the largest 61 percent were in age 30 to 60 years (the working age), and 6 percent were elderly above 60 years. Of the seven senior citizens in the survey, three have fallen ill. Of 207 children, only three reported illness. 65 percent of those who reported illness were women.

Mainly, the illness is among the adults expected to go out of the house. 23 of those who reported illness were employed in work that required them to go outside the house, such as labor work, street vending, manufacturing, etc. 16 of those who reported illness either did not work as they were elderly or children or did not report their work. Among 10 who reported they fell ill were either home-based workers (5 of them) or were housewives or worked indoors. Sixteen of those who reported illness had co-morbidity such as diabetes (3 people), kidney ailment (1 person), heart-related issues such as high or low blood pressure, and others (12). Those with heart-related ailments also reported diabetes.

Table 8. Reported morbidity and mortality incidence by settlements.

	Incidence of illness (per 1000 pop)	Incidence of death (per 1000 pop)	% age women among ill
E-1	200.0		33.3
E-2	73.2		66.7
E-3	74.1		50.0
E-4	39.2		75.0
C-1	114.3		100.0
W-1	125.0		80.0
W-2	84.5		83.3
W-3	166.7	23.8*	57.1
Overall	88.6	1.8	65.3

Source: Primary survey.
* Should be mindful of small sample size in interpreting this data.

The incidence of illnesses reported is a combined effect of employment conditions (as seen above), co-morbidities, and housing conditions, which we analyze next. Of the 49 who reported illness, only eight reported using any method to cool the roof to reduce the effect inside the house. Of these eight, five had painted their roofs with a white coat. Except for three, all those who reported illness stayed in a house with GI/Asbestos/Cement sheets, i.e., houses that had reported higher internal temperatures. Further, 40 percent of the DUs with GI/Asbestos/Cement sheets reported someone ill. This number for those staying in DUs with concrete roofs was 18 percent. While 84 percent of DUs had ceilings below 10 feet (**Table 8**), 95 percent of those reporting illness stayed in such houses. These DUs had registered slightly higher internal average temperatures at the time of the survey than the DUs with higher ceilings. DUs having cross ventilation did report relatively lower internal temperatures at the time of the survey and hence reduced the incidence of illness among their residents. The same with regards to the shaded adjoining street, which reduced internal temperature (**Table 5**) and hence reduced the incidence of illness. A tree adjoining the DU did reduce internal temperature (**Table 5**), and hence also had an impact on reducing the incidence of illness among the residents; 26 percent of DUs with a tree adjoining reported illness, while this number for DUs not having any tree adjacent is

39 percent. Shaded streets too made a difference; the incidence of illness among the residents of DU on shaded streets was 33.8 percent, and for those living in DUs that did not have a shaded street, it was 45.0 percent. The inside DU temperatures in the latter were higher than in the former. Thus, we find that micro-level factors discussed above not only influenced the temperature experienced within the DU but also influenced the incidence of morbidity. Hence, the incidence of illness is an outcome of compounded factors: employment conditions, the presence of co-morbidities, housing conditions, including the presence of cool roofs, and street characteristics.

4. Discussion

This exploratory research started by assuming that cool roofs lower indoor temperatures, leading to an increase in thermal comfort and fewer illnesses. While on the field, we realized that other local built environments (physical dimensions of a DU) work to reduce indoor temperatures. Our research was conducted during the peak summer period when none of the DUs surveyed reported inside temperatures within the thermal comfort band. However, other built environment characteristics made a difference of a few degrees within the DU. The internal temperatures experienced also impacted the incidence of illness.

The research broadly finds that the cool roof reduced internal temperatures. The DUs with cool roofs experienced 1.19 ℃ less inside than the ones without cool roofs. This is reflected in the incidence of illness reported as well; in the DUs with cool roofs, the proportion of residents reporting illness was 36 percent, whereas in DUs without cool roofs, this number was 40 percent. The DUs with a storey above recorded lower internal temperatures and also a lower incidence of illness than only single-storey DUs. However, two-storey DUs in our sample were only four in number, and hence we cannot draw any significant conclusions from the data. The DUs with cross ventilation recorded lower inside DU temperatures, a higher difference between the outside and inside DU temperatures, and a lower incidence of illness. DUs with low ceiling height (10 ft or low) recorded higher inside temperatures than the DUs with higher ceiling height (above 10 ft), and the former also registered a higher incidence of illness compared to the latter. Roofs of GI/Asbestos/Cement sheets reported higher inside DU temperatures and also a higher incidence of illness compared to the DUs with concrete roofs. In this study, open ground nearby a DU did not influence the internal temperatures as well as the incidence of illness. A tree adjoining the DU reduced internal experience of temperature and also larger difference between the outside DU and inside DU temperatures as compared to a DU not having a tree abutting it. The former DUs also reported a lower incidence of illness compared to the latter. Shaded streets matter. The presence of shaded streets in a built form that is predominantly low-rise, single- or two-storey, has the potential to reduce temperatures experienced inside the DUs and thus also reduce the incidence of illness. However, the regression analysis does not establish any of these characteristics as significant predictors of temperatures experienced inside the dwelling units in the informal settlements.

For physical adaptive actions, a combination of micro-level built environment characteristics, including the roof material, influence temperatures experienced within a DU in informal housing. The heat-adaptation efforts within the informal housing in the cities of the global south, which may not be able to transit to formal housing in the short and medium term, will need to tackle local-level built environment characteristics, which include immediate neighborhood-level interventions as well as individual DU-level interventions to adapt to increasing temperatures and urban heat island impacts. The emphasis on cool roofs alone may not lead to effective adaptive interventions.

Urban Heat Island (UHI) has become a reality in Ahmedabad and cities in India. Adaptation to it requires small interventions at the individual house and local neighborhood levels, which in turn has the potential to reduce heat-induced morbidity and mortality. These efforts would be predominantly at the individual household level, however, with the assistance of the communities, non-governmental organizations, and local governments. This study is of housing in the informal settlements, which as an urban form is expected to persist and even expand in rapidly urbanizing India as well as the cities of the global South. Thus, the efforts to build resilience to heat will have to pay attention to the informal housing units. We cannot wait till the residents of all the informal settlements transit to the formal housing, which is a long way ahead. At the same time, longitudinal and large-scale surveys or participatory research on a long-term basis is required to establish housing upgrading efforts in the informal settlements to ensure adaptation to increasing heat on account of climate change.

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