Environmental Impact and Mitigation Benefits of Urban Heat Island Effect: A Systematic Review

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Abstract: The high temperature in city centres and urban areas than their surroundings, known as the Urban Heat Island (UHI) effect, which causes discomfort to city dwellers in the summer season, is gaining much attention worldwide as the world continues to urbanize. The Urban Heat Island (UHI) is a phenomenon where urban areas are experiencing high temperature than the surrounding rural areas. The current rapid urbanization in India cause of temperature rises, undeniable climatic changes etc. because of it heat island phenomenon occur which call for a need to address the issue of its consequences and awareness. To counterbalance this, various mitigation strategies has been introduced and new technologies are developed which helps in identifying the hot pockets in a city. Due to the seriousness of the problem, extensive research has been done and a lot of literature study of the subject is available. The literature in this domain provides the most up-to-date research methods, concepts, procedures, investigative tools, and mitigation strategies. The aim of this paper is to present state of the art on environmental benefits of UHI mitigation applied at city scale level like benefits of green roof, high albedo material, water body, modification in building envelope and also suggest that future study should concentrate on design and planning characteristics in order to minimize the level of urban heat island and, as a result, live in a better environment.
***Keywords*:** urbanisation, urban heat island effect, green roofs, natural cooling, sustainable design, high albedo material.

1. Introduction

It is continuously documented that around 45% of worldwide energy use is associated with construction, material and its maintenance (Gul, 2015). Now due to the undeniable climate changes high consumption of energy and resources in building is needed which deteriorates the balance of ecosystem, changes in Land cover Land use (LULC) and comfort conditions of population which raise the issues like increase of temperature, pollution, anthropogenic heat etc. Heat island effect is the most predictable phenomenon due to all these factors. This effect is mainly attributed to the degradation of urban landscape or loss of vegetation due to intensive development, including building density, size and orientation, open- built relation, use of heat absorbing construction material in regard of global warming trend, less impervious surface etc. It causes a disturbance in the thermal comfort of people outside at street level and worsens the discomfort caused by overheating of indoor spaces

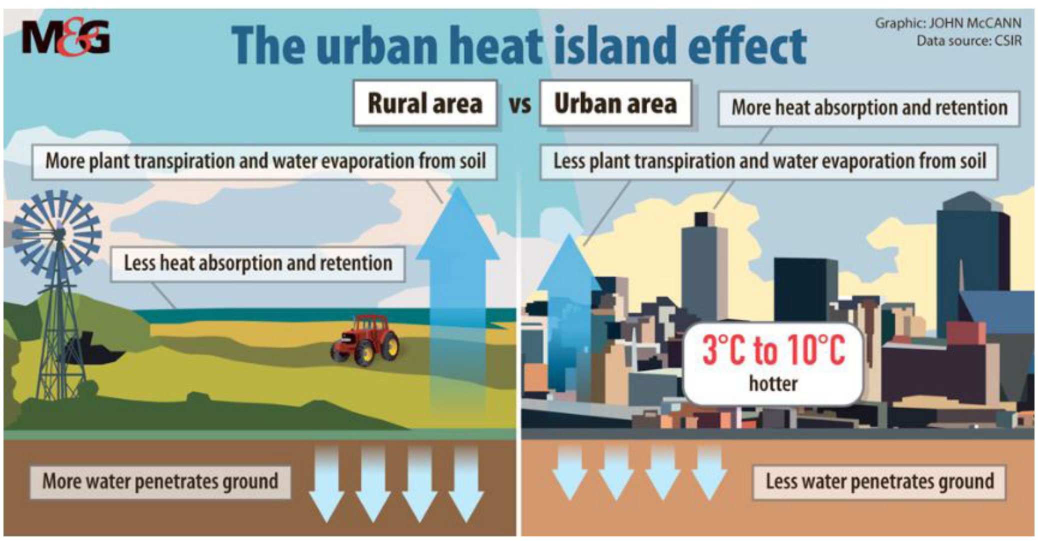

Figure 1. The urban heat island effect

The heat island effect increases the demand of energy in terms of air conditioning and adds strain to the power grid during peak hours, further increasing greenhouse gas emissions. For every 0.6 °C increase in summertime temperature, peak hour electricity demand rises 1.5 to 2% (Architects, 2014). The Intergovernmental Panel on Climate Change (IPCC) has widely planned that as global mean temperature rises, the risk of extreme events will climb as well (IPCC, 2013). This problem is worse more in metropolitan cities or having population more than a Million like Mumbai, Delhi, Bangalore, Hyderabad etc. who hits population about or more than 13.5 million (Census, 2011).

Hence, to reduce the high usage of energy in building, the advanced technologies or strategies, responsive energy efficient system or renewable sources or material should be incorporated. This paper has narrative review on UHI and aim of this paper is to focus on various parameters like water body, green scape, building envelope etc. incorporate in building design to mitigate UHI for this selection criteria is based on state of art paper, who discuss or explore the UHI types, methods and its mitigation.

2. Types of urban heat island effect

The UHI is of three types 1- Surface Urban heat island (SUHI) 2- Canopy Layer Urban heat island (CLUHI) 3- Boundary Layer Urban heat island (BLUHI)

SUHI- Surface urban heat island is formed by experiencing direct heat on surface of building, road, pavement, roof etc. parts of urban surfaces.

CLUHI- Air between street and roof level. Layer of air stuck between the two or more buildings area and measurements done on mobile platforms (using car or bicycle).

BLUHI- Layer of air above rooftop and trees extending upward as one mile.

CLUHI and BLUHI together form Atmospheric Urban heat island (AUHI). The comparison between SUHI & AUHI is summarised below through Table 1.

Table 1. Characteristics of SUHI & AUHI, EPA 2008

Feature		Surface UHI	Atmospheric UHI
Temporal development		Present at all time of day and night Most intense during day in summer	May be small or non-existent during day Mist intense at night
Peak Intensity (Most intense UHI conditions)		More spatial & temporal variation: Day-18 to 27 F (10° TO 15° C) Night- 9 to 18 F (5° to 10° C)	Less variation: Day: -1.8 to 5.4 F (-1° to 3°C) Night: 12.6 to 21.6 F (7° to 12° C)
Typical Identification Method		Indirect measurement: Remote Sensing	Direct measurement: - Fixed weather stations - Mobile traverses
Typical Depiction	Thermal Image	- Isotherm map - Temperature graph	

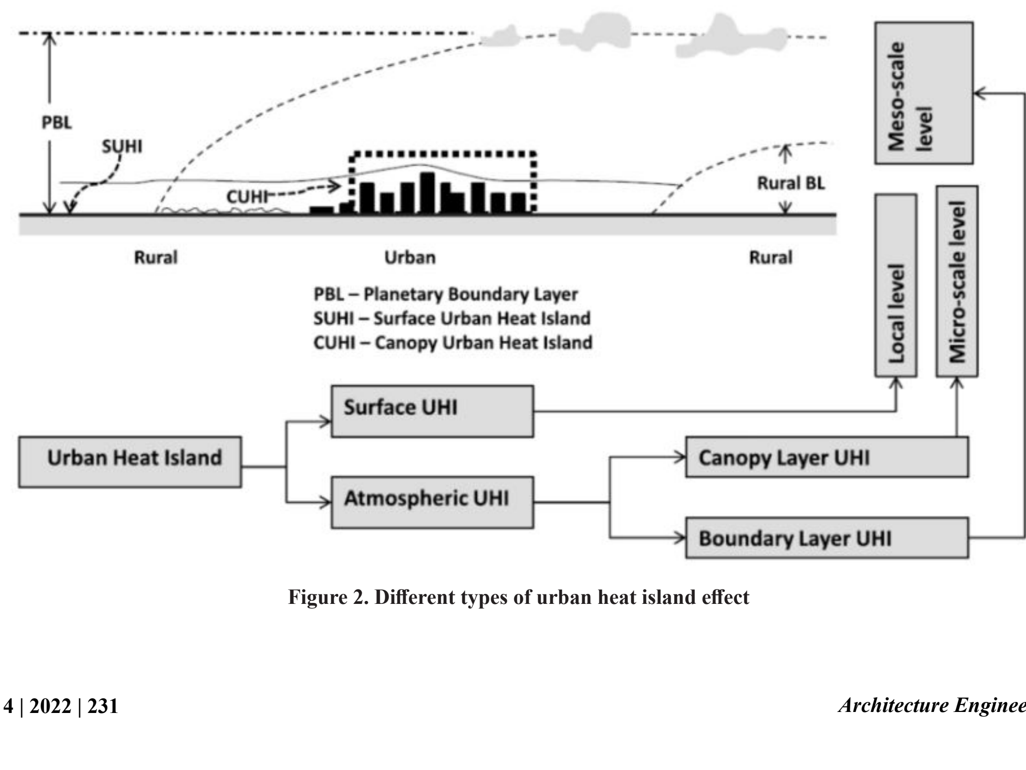

Figure 2. Different types of urban heat island effect

3. Methods of urban heat island study

Theoretical/empirical studies have been available since the beginning of recognising the importance of UHI research. However, observational, experimental, and computational methods are employed to estimate the existence of UHI in real time and to explore solutions to mitigate its impacts. Remote sensing, field measurements, and meteorological weather station data are examples of observational methodologies. The methods used in the UHI investigations in Indian cities have are summarized as below:

3.1 Satellite data

It has been found that most Urban Heat Island studies are done with the help of satellite imaging or remote sensing data to collect Land surface temperature (LST), Land cover land use (LULC), Normalized Difference Vegetation Index (NDVI) etc. with the variants of LANDSAT satellite and these satellites have various sensors like MODIS, TERRA, ASTER, TIRS, OLS, TM/ETM+ etc. In paper of (Chaohui, 2018), (Atasoy, 2019), (Kaveh, 2018)

3.2 Fixed weather station data

It is another method of collecting data or temperature through weather station or Indian Meteorological department (IMD) in rural and urban areas (Al-Saadi, 2020).

3.3 Field survey

It is of two types' Mobile survey and Station survey. In a stationary survey, a specific area is chosen and the temperature variation there is measured using devices such as thermometers. In Mobile survey, specified routes of various types of land are followed by a vehicle with temperature measuring sensors already connected for mobile surveys (Devi, 2006) (Mohan et al., 2012).

3.4 Numerical modelling

In a research by Gopalakrishnan et al., the researchers summarized that Indian research is still in its early stages in terms of numerically modelling and analysing heat island creation in metropolitan areas. This requires appropriate inputs as well as powerful computational resources (Gopalakrishnan et al., 2003)

4. Theoretical framework for mitigation of urban heat island effect

This section will shortly discuss about various possibility of mitigation parameters, how they are implemented, inter-related with each other and up-to which extent they are able to help in mitigation of UHI. As mentioned in above section that due to rapid urbanisation or change in size of city cause the global warming, health issues, raise in temperature etc. demand to do research in the field of mitigation and to examine how they help in mitigating the negative climate effect of urbanisation.

4.1 Mitigation types

In recent years, various researches have been done on UHI mitigation. (Al-Saadi, 2020) (AgneseSalvati, 2017) (Roxon, 2020) (Abbas, 2017), (Neil, 2015), (Ramamurthy & Bou-Zeid, 2017), (Mac Gregor-Fors, 2016), states that replacing vegetation cover by built surface and high concentration of pavement, change of land use and building with low albedo material, replacement of open spaces and trees with different types of infrastructure led to affect the ecosystem and modify the urban climate which cause rise in temperature, energy demand, air pollution, heat related illness (Sanchez, 2019); (Pearlmutter et al., 2009); (Saaroni et al., 2018); (Ohara, 2007); (Boris Bonn, 2016); (Memon et al., 2008); (Chakraborty et al., 2016); (Morakinyo, 2017). Due to heat stress, pollution particles are released into the urban environment by the combustion of fossil fuels in plants, automobiles, and other modes of transportation and because of design features like geometry and building material make urban canyon, heat is often trapped between streets and cause thermal stress in daytime energy demand increased, therefore low-income household are unable to afford their energy bills, they may expose to increased harm from extreme heat.

This is the reason, why the temperature in urban areas is higher in rural areas (Eun-Soon Im, 2017); (Aadhar, 2019); (Kumar, 2019); (Meerow, 2016); (Berardi et al., (Jensen, 2017); (Berardi, 2014); (Brien, 2017). Green initiatives in cities are seen as decorative or referred to as environmental, economic, and social benefits, or ecosystem services while also meeting tangible environmental and public health goals like green roofs, vegetated rooftops help to minimise UHI, as well as air pollution and energy usage, building energy consumption, storm water runoff, and noise pollution, as well as roof material lifespan. (Oke, 2012); (Virk et al., 2014); (Wang, 2016); (Kotharkar et al., 2020); (Santamouris, 2014); (Julia N. Georgi, 2010) (Zhifeng Wu, 2017). In sensitive local climate zones of an Indian region, a systemic solution for urban heat island mitigation strategies, 2020). Cool pavement and cool roofs with a high albedo come in the form of tiles, a sheet covering, and paint, both of which are low-maintenance and cost-effective, and have been shown to lower surface temperatures. Majorly mitigation measures are listed below in Table 3 (Or Aleksandrowicz, 2017).

4.2 Urban heat island mitigation measures

The urban heat island mitigation measure are summarized as below:

- Building envelope is basically a way to cool down the building structure by absorbing the heat through their building envelope.
- Urban landscaping is also one of method to mitigate the heat by providing various natural landscape elements.
- Pavement large part of urban cities is covered with these in form of asphalt or concrete etc. To provide thermal comfort in day time they are altered with cool or water retentive pavement.
- Street geometry is about the relation between open and built mass and by modifying it we can mitigate UHI.

The urban heat island mitigation measures related to cool building envelopes, green roofs and green facades have been studied by various researchers (Gartland, 2008); (Meyn and Oke, 2009); (Erell et al., 2011); (Santamouris et al., 2011); (Akbari and Matthews, 2012); (Kolokotroni and Kolokotsa, 2013); (Getter and Rowe, 2006); Oberndorfer et al. (2007); (Spala et al., 2008); (Castleton et al., 2010); (Chen, 2013); Saadatian et al., 2013); (Wong et al., 2010); (Pérez et al., 2011); (Perini et al., 2011); (Sheweka and Magdy, 2011); (Perini and Rosasco, 2013).

An extensive study on the urban heat island mitigation measures related to shade through trees, ground vegetation and water bodies have been studied by various researchers. (Gartland, 2008); (Shashua-Bar et al., 2009); (Bowler et al., 2010); (Erell et al., 2011); (Fintikakis et al., 2011); (Gaitani et al., 2011); (Shashua-Bar et al., 2011); (Berry et al., 2013); (Cohen et al., 2013); (Sawka et al., 2013); (Potchter et al., 2006); (Takebayashi and Moriyama, 2009); (Bowler et al., 2010); (Chow et al., 2011); (Hamada et al., 2013)

The urban heat island mitigation measures related to cool pavements and water retentive pavements have been studied by various researchers (Kinouchi et al., 2004); (Gartland, 2008); (Synnefa et al., 2011); (Akbari and Matthews, 2012); (Gago et al., 2013); (Karlessi et al., 2013); (Santamouris, 2013), (Scholz and Grabowiecki, 2007); (Nakayama and Fujita, 2010); (Qin, 2015).

The urban heat island mitigation measures related to built environment orientation, typical section with reference to prevailing wind and sun have been studied by various researchers (Ali-Toudert et al., 2005); (Erell et al., 2011); (Andreou and Axarli, 2012); (Gago et al., 2013); (Shishegar, 2013); (Yahia and Johansson, 2013); (Haeger-Eugensson and Holmer, 1999); (Erell et al., 2011)

4.3 Effects of heat island mitigation measures

Or Aleksandrowicz, presented the impact of climatic effect on each mitigation measure implied in various cities in different years. By following these measures we can mitigate UHI and able to create healthy microclimate (Or Aleksandrowicz, 2017). The effects of heat island mitigation measures are summarized as follows:

4.3.1 Cool building envelopes

Savio et al. studied through numerical simulation method in New York City, USA. They found that 0.18–0.36°K decrease of peak summer ambient air temperature at street level. An average 0.2K decreases per 0.1 increase of global roof albedo (Savio et al., 2006). Synnefa et al. researched through numerical simulation method in Athens, Greece. They found that 0.5–2.2°K decrease of peak summer ambient air temperature at street level. An average 0.2K decreases per 0.1 increase of global roof albedo (Synnefa et al., 2008). Bozonnet et al. studied through numerical simulation method in Poitiers, France. They found that overall reduction of roof surface temperature by around 10°K (Bozonnet et al., 2011). Romeo and Zinzi studied through monitoring numerical simulation method in Sicily, Italy. They found that the difference between roof surface temperature and ambient air temperature is around 5°K in a high-albedo roof surface (Romeo and Zinzi, 2013).

4.3.2 Green roofs

Wong et al. researched in Singapore that the maximum surface temperature difference of 18°K between green roof surface and conventionally exposed roof surface (Wong et al., 2007). Heusinger and Weber in Braunschweig, Germany studied through monitoring that the summer surface temperature of a green roof 17.4°K lower than of that of a bitumen roof, with a significant reduction of ambient air temperature 0.5m above roof level (Heusinger and Weber, 2015). Bevilacqua et al. researched in Cosenza, Italy that the green roof may reduce indoor temperature by 2.3°K during summer (Bevilacqua et al., 2016). Ouldboukhitine et al. studied through monitoring and numerical simulation in La Rochelle, France that the temperature between the exterior surface and the sealing membrane of a green roof layer may vary up to 10°K during hot summer days. The daily peak canyon air temperature next to the buildings with green roof was about 1°K lower than in buildings with cool roof (Ouldboukhitine et al., 2014).

4.3.3 Green facades

Chen et al. in Wuhan studied through monitoring that a reduction of up to 20.8°K in external surface wall temperature with the application of external layer of vegetation (Chen et al., 2013). Wong et al. studied through monitoring in Singapore that a reduction of wall surface temperature on clear days of up to 11.6°K (Wong et al., 2010). Eumorfopoulou and Kontoleon researched in Thessaloniki, Greece that the difference in the maximum surface temperature peak values between a bare wall and a plant-covered wall can reach 10–15°K on sunny days (Eumorfopoulou and Kontoleon, 2009). Mazzali et al. studied in Italy that the temperature difference of up to 20°K between the external surface of bare wall and the covered green wall (Mazzali et al., 2013)

4.3.4 Tree shades

Spronken-Smith and Oke studied through monitoring in Vancouver that urban parks rich of trees may reduce peak daytime outdoor temperature by up to 5°K (Spronken-Smith and Oke, 1998). Shashua-Bar and Hoffman researched in Tel-Aviv, Israel that the cooling effect of small urban green sites with trees may be 2.8°K on average (Shashua-Bar and Hoffman, 2000). Zoulia et al. studied through monitoring in Athens, Greece that the night-time temperature difference between a city park and densely built-up urban areas may be as high as 7°K (Zoulia et al., 2009). Johnson researched through site monitoring in Gaborone, Botswana researched that in comparison with their rural counterparts, irrigated vegetated urban areas are about 2°K cooler, while sparsely vegetated areas are as much as 2°K hotter (Johnson, 2004)

4.3.5 Ground vegetation

Oliveira et al. researched in Lisbon, Portugal that under summer conditions ambient air temperature in grass-covered urban parks was 1.7°K lower than in neighbouring non-shaded streets (Oliveira et al., 2011). Chatzidimitriou and Yannas studied in Thessaloniki, Greece that the grass surfaces were consistently (around 2°K) cooler than hard pavements when comparing shaded surfaces (Chatzidimitriou and Yannas, 2015). Vaz Monteiro et al. researched in a study in London, UK that the cooling impact of urban greenspace extends beyond its limits, and the magnitude of cooling was most strongly linked to grass coverage (Vaz Monteiro et al., 2016). Chatzidimitriou and Yannas studied that the mean surface temperature of flowing water in an urban fountain was significantly lower than that of asphalt surface (20°K less) and grass lesser by 12.9°K (Chatzidimitriou and Yannas, 2015)

4.3.6 Cool pavements

Karlessi et al. researched through monitoring that by replacing conventional asphalt with off-white thin layer asphalt (with higher reflectance) could lead to an average air temperature decrease of 2.3°K under low wind speed conditions (Karlessi et al., 2013). Fintikakis et al. studied through site monitoring that he use of cool pavements and additional vegetation can reduce the peak summer ambient air temperature in open urban spaces by 3°K (Fintikakis et al., 2011). Santamouris et al. researched through monitoring that the use of cool materials for pavements and streets, along with earth to air heat exchangers, solar control devices, photovoltaic panels and extensive use of green spaces and water, may reduce ambient urban temperatures by up to 3.4°K under peak summer climatic conditions (Santamouris et al., 2012b). Gaitani et al. studied that the use of passive cooling techniques (cool materials, green spaces, solar control and earth-to-air heat exchangers) can contribute to decrease in local temperatures of up to 2°K for summer conditions (Gaitani et al., 2011).

4.3.7 Water retentive pavements

Li et al. in a study in Oakland observed that a peak 5°K reduction in surface temperatures in permeable asphalt when compared to conventional asphalt 24h after irrigation stopped. During irrigation, the porous asphalt surface temperature was reduced by 30°K (Li et al., 2013b). Hendel et al. studied through monitoring in Paris, France that the pavement-watering technique to lower pavement summer surface temperatures for up to 13°K (Hendel et al., 2014)

4.3.8 Built environment orientation with reference to prevailing winds

Kagiya and Ashie observed through site monitoring in Tokyo, Japan that the recorded cooling effect of sea breezes entering the urban fabric through wide streets (Kagiya and Ashie, 2009). Ng et al. studied through monitoring in Hong Kong that the high-rise developments built directly on the waterfront may have a negative effect on the air temperatures of the adjacent streets due to impeded flow of fresh air coming from the seaside into the inner parts of the city (Ng et al., 2011). Johansson researched in Fez, Morocco that a constant difference in average winds speed between deep (H/W = 9.7, 0.4 m/s) and shallow (H/W = 0.6, 0.7 m/s during summer and 0.8 m/s during winter) street canyons (Johansson, 2006)

4.3.9 Built environment orientation with reference to sun

Krüger et al. observed through numerical simulation in Israel that N-S orientations in streets of relatively low aspect ratio (H/W b 0.5) tend to produce much higher summer cooling loads on buildings than E-W orientations, thus potentially conflicting with outdoor comfort needs (Krüger et al., 2010). Andreou studied through numerical simulation Tinos, Greece that the streets on E-W axis are found to have less solar gain in summer and thus lead to reduced cooling load in buildings (Andreou, 2014). Van Esch et al. researched through simulation in De Bilt, Netherlands, that the street orientation may influence the distribution of total radiation yield over the separate canyon surfaces-street, facades, and roof (Van Esch et al., 2012).

5. Relation between UHI mitigation strategies and their environmental benefits

As far of now we discussed UHI, its causes, types, various methods to find out its presence and various mitigation strategies. Table 2 discusses the relation between UHI mitigation strategies and their environmental benefits.

Table 2. Environmental benefits of urban heat island mitigations

Mitigation Strategy	Output	Environmental Benefit
Greenscape	- By providing green roofs - Green façade / wall - Ground vegetation - Shade trees	- Less use of energy - Decrease in surface temperature - Cooled up micro climate - Reduction in heat transmission - Impact on air flow movement - Effect on solar orientation - Day time urban temperature decrease
Waterbody	- Water retentive pavement - Fountain - Pond	
Material	- High albedo material - High thermal resistance	
Building Envelope	- Orientation - Passive design - Sustainable material - H/W ratio between streets	

6. Conclusion

In conclusion, it has been found that mitigation strategies have a great influence on environmental benefit and human health. Due to the negative impact on liveability, wellbeing, and health in urban contexts, there is a continuing need to mitigate the consequences of the UHI. The ever-expanding nature of cities, as well as the greater usage of hard, heat-absorbing materials, contributes significantly to the UHI. Reflective pavements, evaporative pavements, green roof making the surroundings greener, and utilising the cooling effects of wind and water have all been recommended in the literature as mitigating techniques. It is frequently discovered that combining numerous approaches to reduce the UHI effect is the most effective strategy. Many solutions are being studied, and more research is needed in all seasons of the year to find the optimum answer for UHI mitigation.

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