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Article

Sustainable Mitigation Strategies for Urban Heat Island Effects

in Urban Areas

Abdul Munaf Mohamed Irfeey 1 Cheuk Yin Wai 2,3 , Nitin Muttil 2,3 , Hing-Wah Chau 2,3,\* and Elmira Jamei 2,3

, Mohamed Mahusoon Fathima Sumaiya 4

,

1 Technology Stream, Advanced Level Section, Zahira College Colombo, Orabi Pasha Street, Maradana,

Colombo 01000, Sri Lanka

2 College of Sport, Health and Engineering, Victoria University, P.O. Box 14428, Melbourne, VIC 8001, Australia

3 Institute for Sustainable Industries & Livable Cities, Victoria University, P.O. Box 14428,

Melbourne, VIC 8001, Australia

4 Department of Food Science and Technology, Faculty of Applied Sciences, University of Sri Jayewardenepura,

Gangodawila, Nugegoda 10250, Sri Lanka

\* Correspondence: hing-wah.chau@vu.edu.au; Tel.: +61-3-9919-4784

Abstract: The globe is at a crossroads in terms of the urban heat island effect, with rising surface tem-

peratures due to urbanization and an expanding built environment. This cause-and-effect connection

may be linked to weather-related dangers, natural disasters, and disease outbreaks. Urbanization and

industrialization will not lead to a secure and sustainable future. Finding solutions to problems such

as the heat island effect is at the forefront of scientific research and policy development. Sustainable

ways to decrease urban heat island impacts are a core principle for urban planners. This literature

study examines the benefits of adding green infrastructure and sustainable materials in built-up areas

to reduce the urban heat island effect. Materials such as reflective street pavements, coating materials

including light-colored paint, phase-change materials, color-changing paint, fluorescence paint, and

energy-efficient appliances are considered sustainable materials, whereas green infrastructure like

green roofs, green walls, green parking and pavements, and shaded streets are considered to mitigate

the urban heat island effect. The hurdles to the widespread adoption of such practices include a

lack of governmental legislation, insufficient technological development, an erroneous estimation of

economic gains, and unwillingness on the part of impacted parties.

Keywords: built environment; green urban infrastructure; sustainable building materials; urban

development; climate change

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1. Introduction

Rapid advancement in the built environment and increasing urbanization are alter-

ing ecosystems and climates, with surface temperature being one of the most influential

factors [1], and increased energy consumption in the urban environment contributes di-

rectly to the rise in surface temperature [2]. Due to urbanization and human activities, the

urban heat island (UHI) effect, which is caused by an increase in surface temperature, is

one of the most severe problems in urban areas [3]. The impact of UHI can be measured by

using the heat and humidity index (THI), the related stress index (RSI), and the number of

Beer Garden days [4]. The UHI effect has a negative influence not only on the environment

but also on the health of the inhabitants. Multiple studies indicate that indigestion is a

common problem, as well as nervous system disorders such as memory loss, depression,

irritability, and sleeplessness [5].

In addition to that, the UHI’s thermal impact may cause a significant circulation of

pollution, resulting in local winds that migrate from suburban to urban areas, bringing city-

contaminated air that is now present in rural areas back to urban areas, worsening urban

air pollution and also increasing the financial burden on city dwellers. The solar radiation

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captured by urban surfaces is influenced by factors such as the number of buildings,

their orientation, and the distance between them [6]. The arrangement of buildings has a

significant impact on the distribution of shadows and temperature differences throughout

a city. The canyon-like shape of streetscapes surrounded by high-rise buildings has an

effect on wind patterns in urban canyons due to the intricate heat exchange between the

mass of the buildings and the surrounding atmosphere [7]. Urban heat exchange is affected

by a number of factors, including the thermal characteristics of urban surface materials,

color, texture, and coverage [8].

The lack of vegetation in urban areas increases the amount of heat absorbed by different

components such as buildings, pavement, and roads. Human activities such as driving and

HVAC (heat, ventilation, and air conditioning) systems are also major contributors to heat

accumulation in the atmosphere. Basically, the UHI effect is measured on three different

levels: the ground level, the canopy level, and the urban level [9]. Specifically, the thermal

behavior of surface materials and their exposure to solar radiation impact the UHI effect.

The atmosphere over urban areas can be affected by the emission of heat and subsequent

convectional mixing of the heat [10]. The amount of heat accumulated in the canopy layer

is affected by a number of factors, including the geometry and orientation of open spaces,

the aspect ratio, the sky view factor, the land cover materials, and the direction and velocity

of the wind [11,12].

The urban surface layer’s emitted heat is blended together by turbulence in the air

above the canopy layer of the urban areas [13]. Above the canopy layer, local air is mixed,

leading to the formation of a warm air dome over inhabited areas [14]. Due to the convective

nature of the atmosphere, the urban boundary layer tends to be at its thickest at midnight.

Due to its high heat resistance, the air has a relatively thin surface layer that only goes down

a few centimeters [15]. By late afternoon, when the urban canopy has been heating in the

sun for several hours, the air temperature in the canopy layer has reached its maximum [16].

Although the urban boundary layer is at its thickest in the evening, when warm air is pulled

into the lower atmosphere, it forms a dome of warm air above the urban zone. The rural

boundary layer fluctuates throughout the day, reaching its highest point at the same time

as the day’s highest surface temperature [17].

Responses to the effect of UHIs can be categorized as either adaptation or mitigation.

Adaptations are made to decrease the harm, whereas mitigation is an activity performed to

lessen the intensity or amount of the effect. The UHI effect can be adapted to and mitigated

at the building, neighborhood, municipal, and regional levels. This study is an attempt to

fill a need in the existing literature by offering a synoptic perspective of sustainable green

infrastructure and materials that may be used in urban areas to reduce the UHI impact.

Table 1 presents the background of the strategies reviewed in this study for the mitigation

of UHIs. According to prior research by Shishegar 2014, increasing urban green spaces

like parks, street trees, and green roofs may help reduce the UHI impact [18]. Petzold

and Mose 2023 also undertook a study that investigated the economic and social factors

around urban greening infrastructure [19]. Hence, the results from this study and ensuing

suggestions aim to benefit the built environment in its pursuit of UHI mitigation strategies.

Consequently, presented herein is the specific scope of the study:

• Identifying suitable green infrastructure that can be incorporated within the built-up

areas in the urban setting.

• The identification of sustainable materials that can be integrated with building compo-

nents to reduce the UHI effect.

• Examining the principle behind those identified techniques and their effectiveness in

implementation.

• Identifying the most prevalent obstacles to the widespread implementation of the

identified UHI mitigation strategies in urban areas and proposing solutions to

these problems.

The next section describes the methodology implemented in this review. Section 3

describes the green infrastructure and sustainable materials that could be incorporated intoSustainability 2023, 15, 10767 3 of 26

the urban environment. Section 4 examines the obstacles to applying these sustainable

strategies in urban settings. Finally, a summary of the study is presented and conclusions

are drawn in the last section.

Table 1. Background of the strategies incorporated in this study on UHI mitigation.

No UHI Mitigation Strategies Description

Green roofs Rooftop of a building that is partially or fully covered with vegetation and a substrate

for plant growth.

Green walls Vertical walls that are either completely or partially covered in plants. Consists of

panels attached to an internal or external vertical structure.

1 Green infrastructure

Green façades Natural climber plants are grown on the exterior of a building with the help of an

auxiliary framework.

Green parking,

Pavements, and

shaded streets

The amount of solar energy absorbed decreases as the percentage of vegetative cover

increases, allowing for the use of evaporative cooling on roads, parking areas, and

sidewalks using water-retentive pavements and permeable porous pavers.

Reflective street

pavements

In order to reduce the surface temperature and sensible heat emissions, reflective

pavements that have a higher albedo (than regular pavements) are used.

Various materials can be integrated into the interior or exterior of building structures,

as well as other urban components, with the aim of mitigating the impacts of UHIs.

The ability of retro-reflective materials to redirect light to their original source is a

useful and unique attribute.

2 Sustainable materials

Coating materials

Materials that store and release latent heat to boost the apparent thermal capacity of

buildings and urban structures and lower their peak surface temperatures.

Materials that undergo a thermochromic color change in response to temperature.

Capture the photovoltaic energy of solar radiation, release the light emission, and aid

in increasing the surface’s ability to reflect light.

Reducing energy consumption and running costs and lowering greenhouse

gas emissions.

2. Materials and Methods

The issue of UHIs and sustainable mitigation practices is gaining relevance among

individuals residing in densely populated urban areas. Global industrial and development

activities have led to an increased emphasis on environmental sustainability, which marks

a departure from past practices. Given the escalating expenses associated with the UHI

phenomenon, it is imperative to prioritize the identification of sustainable measures aimed

at mitigating its adverse impacts. Despite the fact that a number of studies have already

been conducted to identify sustainable green strategies, this study will concentrate on

a variety of urban-specific strategies that incorporate the built environment. This study

reviewed over 315 documents to gather the recent literature; however, 163 were irrelevant to

the study’s objectives and out-of-date. Consequently, they were excluded. Table 2 presents

detailed descriptions of the reviewed articles and the details from various academic sources

(ScienceDirect, PubMed, Scopus, Google Scholar, etc.). UHI, UHI mitigation methods, the

built environment and green infrastructure, and climate change were all used as search

keywords for relevant papers.

Figure 1 describes the methodology undertaken to conduct this study. First, a literature

study was conducted in order to bring to light many problems that have been associated

with the UHI. Extensive explanations are given of global sustainable programs that have

adopted innovative methods in lieu of more conventional ones. Methods for protecting

against solar heating are explored, such as using green roofs, living walls, green façades,

innovative road and pavement designs, coatings made from paint, phase-change materials,

color-change materials, fluorescence materials, and sun shade. The adoption of more

energy-efficient appliances in favor of older, less efficient models is another method of

reducing the UHI’s impact on the environment. Finally, the limitations and constraints of

commonly used solutions for mitigating the effects of UHIs have been highlighted.Sustainability 2023, 15, 10767 p p

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çades, innovative road and pavement designs, coatings made from paint, phase-change

materials, color-change materials, fluorescence materials, and sun shade. The adoption of

more energy-efficient appliances in favor of older, less efficient models is another method

4 of 26

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Figure 1. Methodology undertaken for conducting this study.

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Table 2. Description of articles referred to for the study.

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Journal Name

(Short Form)

Journal Name

(Short Form)

No. of

Reviewed

No. of

Papers

Reviewed

Papers

J. Build. Eng. 1 1 1 2

Green Parking, Pavements, and

Energy-Efficient Appliances

J. Alloys Compd 2 1 1 2

Green Parking, Pavements, and

Shaded Streets

Shaded Streets

Color-Changing Materials

Color-Changing Materials

Infrastructure Sustainable Materials

Green

Green Infrastructure Sustainable Materials

Energy-Efficient Appliances

Green Roofs

Green Roofs

Green Walls

Green Walls

Innovative Streets

Innovative Streets and

and Pavements

Pavements

Light-Colored Paint

Light-Colored Paint

PCM

PCM

Fluorescence Materials

Fluorescence Materials

No. of

No. of

Times

Times

Cited in

Cited in

Other

Other

Sections of

This Paper

Sections

of this

Paper

Total

Total no. of

Times

no. of

Cited in

Times

This Paper

Cited in

this

Paper

J. Nanomater 1 1 1

J. Alloys Compd 2 1 1 2

J. Vis. Exp 1 1 1

J. Build. Eng. 1 1 1 2

Sustain. Cities Soc 1 1 1

J. Nanomater 1 1 1

Woodhead Publishing 1 1 1

ACS Appl. Mater. Interfaces 2 2 2

J. Vis. Exp 1 1 1

ACS Sustain. Chem. Eng 1 1 1

Sustain. Cities Soc 1 1 1

Adv. Exp. Med. Biol. 1 1 1 2

Woodhead Publishing 1 1 1

Adv. Intell. Syst. 1 1 1

Adv. Mater 1 1 1

ACS Appl. Mater.

Adv. Mater. Sci. Eng. 1 1 1

Interfaces 2 2 2

Adv. Opt. Mater 1 1 1

ACS Sustain. Chem. Eng 1 1 1

Adv. Photonics Res 1 1 1

Adv. Sci 1 2 1 3

Adv. Exp. Med. Biol. 1 1 1 2

Agric. For. Meteorol 1 1 1

Ain Shams Eng. J 2 1 1 2

Appl. Acoust 1 1 1

Appl. Sci 1 1 1

Appl. Therm. Eng 2 1 1 2

Archit. South Africa 1 1 1

Architecture 1 1

Atmos. Chem. Phys 3 2 2

Atmos. Meas. Tech 1 1

Atmosphere 2 1 1 2Sustainability 2023, 15, 10767 5 of 26

Table 2. Cont.

Green Infrastructure Sustainable Materials

Journal Name

(Short Form)

No. of

Reviewed

Papers

Green Roofs

Green Walls

Green Parking, Pavements, and

Shaded Streets

Innovative Streets

and Pavements

Light-Colored Paint

PCM

Color-Changing Materials

Fluorescence Materials

Energy-Efficient Appliances

No. of

Times

Cited in

Other

Sections of

This Paper

Total no. of

Times

Cited in

This Paper

Biomater. Sci. 1 1 1

Build. Environ. 7 1 1 1 1 4

Buildings 4 2 2 4

Chem. Eng. J 1 1 1

City Environ. Interact 1 1

CivilEng 1 1 1

Color Res. Appl. 1 1 1

Concr. Int. 1 1 1

Conference Proceedings 3 1 1 3 1 5

Constr. Build. Mater 9 2 4 1 3 10

Elsevier book chapters 3 1 1 1 3

Energy 1 1 1

Energy Build 3 1 3 4

Energy Procedia 1 1 1

Energy Res. Soc. Sci. 1 1

Energy Rev. 1 1

Eng. Technol. Appl. Sci. Res 1 1 1

Environ. Fluid Mech 1 1

Environ. Plan. B Plan. Des. 1 1

Environ. Res. Lett. 1 1

Environ. Sci. Pollut. Res 1 1 1

Epoch book chapter 1 1

Fresenius Environ. Bull 1 1 1

Ind. Eng. Chem. Res 1 1 1

Indoor Environment,

Berkely Lab 1 1 1

Int. J. Eng. Res. Technol 1 1 1

Int. J. Environ. Res.

Public Health 1 1 1

Int. J. Environ. Sustain 1 1

Int. J. Pavement Eng 1 1 1

InTech 1 1 1

IOP Conf. Ser. Mater.

Sci. Eng 1 1 1 2

J. Am. Soc. Farm Manag.

Rural Apprais 1 1

J. Build. Eng 1 1 1

J. Clean. Prod 3 2 2

J. Energy Storage 1 1 1 2

J. Environ. Eng. 1 1 1

J. Environ. Manage 2 1 1 2

J. Road Eng 1 1 1

J. Text. Inst. 1 1 1

Mater. Horizons 1 1 1

Mater. Today Proc 1 1 1

Materials 3 1 2 1 4

Polymers 1 1 1

Proc. Natl. Acad. Sci. USA 1 1 1

Procedia Eng. 1 1

Prog. Plann 1 1 1

Transportation Res. Rec. 1 2 2

Remote Sens 1 1 1

Remote Sens. Environ 1 1 1

Renew. Energy 1 1 1 1 1 4Sustainability 2023, 15, 10767 6 of 26

Table 2. Cont.

Green Infrastructure Sustainable Materials

Journal Name

(Short Form)

No. of

Reviewed

Papers

Green Roofs

Green Walls

Green Parking, Pavements, and

Shaded Streets

Innovative Streets

and Pavements

Light-Colored Paint

PCM

Color-Changing Materials

Fluorescence Materials

Energy-Efficient Appliances

No. of

Times

Cited in

Other

Sections of

This Paper

Total no. of

Times

Cited in

This Paper

Renew. Sustain. Energy Rev 7 2 3 2 1 1 1 10

Resources 1 1 1 2

Sci. Rep 1 1 1

Sci. Total Environ 2 1 1

Sol. Energy 3 3 3

Sol. Energy Mater. Sol. Cells 2 1 1 1 3

Surf. Coatings Technol. 2 1 1 2

Sustain. Cities Soc 2 1 1

Sustain. Energy Rev 1 1 1

Sustainability 15 2 1 2 3 1 9

Sustainable Cities

and Innovation 1 1

Urban Clim 2 1 1

Urban Ecosyst 1 1 1

Urban Stud. Res 1 1 1

Total references 152

3. Incorporation of Green Infrastructure into Buildings

Green infrastructure is the addition of blue (water) and green (vegetation) components

in contrast to the constructed environment to improve and manage environmental systems

to enhance the quality of life in the ecosystem [20]. These green assets, if well-planned

and designed, could mitigate the negative impacts of urban heat islands (UHIs) and

climate change while also improving residents’ quality of life. Green infrastructure is

the strategic approach to developing and optimizing sustainable management systems

of urban natural ecosystems in the face of climate change challenges. Innovative and

well-developed potential practices can be considered by urban planners inside the built

environment, including the implementation of green strategies into the main components,

such as rooftops, façades, parking areas for buildings, pavements, walls, and landscaping

areas to reduce the UHI effect with sustainable green and blue concepts.

Given the limited land resources, significantly increasing the density of green space is

a challenging task. As a result, enhancing the spatial arrangement of green space could be

a viable option. The significance of green space in mitigating urban heat islands (UHIs) is

attributed to its spatial characteristics, including size, composition, and configuration [21].

As such, it is important that the unique qualities and characteristics be taken into account

throughout planning, construction, and maintenance [22]. The environmental sector is

put to the test by green infrastructure, which calls for a holistic and environmentally

friendly strategy that integrates more concerns. Pressures may also be felt regarding the

growing concerns of energy demand, consumption, and production, all of which have

direct and indirect effects on the environmental facet of developing building infrastructure.

Heat gain and loss are major factors on roofs since they represent the greatest exposed

space. Traditional roofing practices using a variety of materials have contributed to the

excessive heat buildup within structures and in the immediate vicinity [23]. As a result,

many regions of the globe are becoming familiar with the practice of initiating green

roofing approaches by using greenery techniques and regulating the excessive heat and

heat variations surrounding the plants.Sustainability 2023, 15, 10767 7 of 26

Façades are huge potential vertical spaces on structures, and these areas will expand

as the buildings rise in height. Despite the vertical openness to the surroundings, the UHI

effect is significantly impacted by façades due to the solar heat absorption potential and

heat release from nearby buildings [24]. The streets and paving systems around a structure

are essential in making it accessible to the public. The UHI impact is influenced by the

layout of streets and pavement, including whether they are exposed to or sheltered from

the sun, as well as by nearby buildings and other factors. The right planning of roadways

and pavements, as well as the inclusion of sustainable flora, is crucial. As a result, the

introduction of novel green infrastructure techniques into high-rise buildings and a full

investigation of the seriousness of all these components via past literature studies are

required for the present situation. Each facet of green infrastructure is examined in depth

in this section.

3.1. Green Roofing Techniques

A green roofing system is one of the useful tools for reducing the UHI effect by cooling

the surrounding atmosphere. The built environment is being built at the expense of parks

and other green spaces as a result of rapid urbanization [25]. This leads to a scarcity of

vegetation, which reduces canopy interception and transpiration within the city, raising

temperatures and lowering humidity [26]. Changing the characteristics of rooftops can help

alleviate some of these issues. The addition of vegetation and soil to unused rooftop spaces

is typically seen as a good method for making buildings more environmentally friendly [27].

Hence, green roofs are just rooftops that have had vegetation transplanted onto a growing

medium. Benefits to the buildings’ aesthetics, the environment, and the economy can be

gained by encouraging the development of green roofs. Vegetation, substrate, filter fabric,

drainage material, a root barrier, and insulation are the components that comprise a green

roof [28]. Figure 2 shows the typical layers of a green roof system.

Substituting man-made, impermeable surfaces in built environment areas is the pri-

mary driver of UHIs [29]. Vegetation holds water in order for it to be evaporated back

into the air through evapotranspiration, which not only cools the vegetated surface and

low-level atmosphere but also lowers the amount of energy held in urban materials and

released as heat [30]. Latent heat results from the transformation of evapotranspiration

energy into the cooling of water vapor molecules in the higher atmosphere [31]. Rainwater

evaporation converts some of the solar energy into latent heat, but hard, non-porous sur-

faces still collect most of the solar radiation and radiate them as heat. Roofs that are too

warm boost the UHI but also allow more heat into a building, leading to higher indoor

temperatures [10].

Rising temperatures also raise the peak loads required to meet the requirements for air

conditioning and refrigeration, which can result in increased emissions of greenhouse gases

(GHGs), and other pollutants [32]. Green roofs may provide additional benefits to building

occupants and city dwellers, including reduced heating and cooling costs and increased

durability of roof membranes due to temperature fluctuations [33]. Reduced stormwater

runoff and combined sewage overflow, which occurs when the sewer system is flushed

during extreme rainfall events, are also added benefits of green roofing. Green roofs can

be either intensive or extensive. Intensive green roofs have a thick substrate layer, a large

diversity of plants, high upkeep, high capital cost, and a higher weight; therefore, they

usually require a lot of maintenance in the form of fertilizing, weeding, and watering [34].

However, extensive green roofs have a thin substrate layer, low capital cost, low weight,

and minimal upkeep. Extensive green roof systems are often employed when no further

structural support is required [34].

Part of the water that falls on a green roof is absorbed by the developing substrate or is

held in pore spaces. Vegetation can take water in and either store it in their tissues or release

it back into the air through a process called transpiration. The remaining water is sent into

the drainage system after passing through the filter cloth. Water will be held back since it

can be stored in the granules’ pores or the drainage modules’ compartments. One of theSustainability 2023, 15, 10767 and watering [34]. However, extensive green roofs have a thin substrate layer, low capital

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8 of 26

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most critical factors is the growth medium, which must be able to retain water for the plant

One of the most critical factors is the growth medium, which must be able to retain water

to thrive. Substrate for green roofs often consists of lightweight volcanic rocks, making

for the plant to thrive. Substrate for green roofs often consists of lightweight volcanic

it excellent at retaining moisture [35]. Energy savings from green roofs are an enticing

rocks, making it excellent at retaining moisture [35]. Energy savings from green roofs are

prospect in the construction industry. By increasing the efficiency of a building’s insulation,

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they help cut down on the amount of energy needed to heat and cool them [36]. A green

ing’s insulation, they help cut down on the amount of energy needed to heat and cool

roof can lower indoor temperatures which depend on the roof’s green area. Increases in

them [36]. A green roof can lower indoor temperatures which depend on the roof’s green

shading, improved insulation, and a larger thermal mass of the roof system are mostly

area. Increases in shading, improved insulation, and a larger thermal mass of the roof

responsible for the noticeable rise in thermal performance.

system are mostly responsible for the noticeable rise in thermal performance.

Figure 2. The typical layers of a green roof system [37].

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3.2. Green Wall Techniques

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One alternative to using traditional wall construction to reduce the UHI effect is to

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use green walls, which are covered in plants. When compared to low-rise buildings, high-

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rises have a greater expanse of wall surface area and thus a greater potential for greenery

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implementations, increasing the effectiveness of such practices. The execution makes use

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of vertical walls that are either completely or partially covered in plants, resulting in an

of vertical walls that are either completely or partially covered in plants, resulting in an

extravagantly verdant aesthetic [38]. Despite centering on UHI mitigation techniques, it

extravagantly verdant aesthetic [38]. Despite centering on UHI mitigation techniques, it

provides a pleasant perspective and contributes to a livelier environment. Green walls

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improve air quality and aesthetics by removing carbon dioxide (CO2), which is a GHG,

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from the air, therefore reducing temperatures inside and out [39].

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Living walls and green façades are the two main types of green walls. A living wall

Living walls and green façades are the two main types of green walls. A living wall

consists of panels attached to an internal or external vertical structure (Figure 3), whereas

consists of panels attached to an internal or external vertical structure (Figure 3), whereas

a green façade is a system in which a natural climber plant is grown on the exterior of a

a green façade is a system in which a natural climber plant is grown on the exterior of a

building with the help of an auxiliary framework (Figure 4) [40]. The panels are ideal for

building with the help of an auxiliary framework (Figure 4) [40]. The panels are ideal for

growing upholstery plants. A green façade is a wall that has been grown over by plants

growing upholstery plants. A green façade is a wall that has been grown over by plants that

that either climb or cascade over the wall. Initially, the constructors had climbing plants

either climb or cascade over the wall. Initially, the constructors had climbing plants attach

attach themselves directly to the walls [41]. However, green façade practices nowadays

themselves directly to the walls [41]. However, green façade practices nowadays have

shifted toward constructing structural frames and enabling plants to climb them rather

than planting them directly on the walls because of the concern that the root systems of

the climbers could potentially cause damage. Plants can be established anywhere from

the foundations to intermediate planters to the roofs of buildings. Within a short period

of time, these plants completely colonize the walls, changing them into lush, verdant

green walls [42].Sustainability 2023, 15, 10767 have shifted toward constructing structural frames and enabling plants to climb them ra-

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Figure 3. Sample structure of a living wall.

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Figure 3. Sample structure of a living wall.

Figure 4. Sample structure of a green façade.

Figure 4. Sample structure of a green façade.

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A green façade can either be added to an existing wall or stand alone. Living walls are

A green façade can either be added to an existing wall or stand alone. Living walls

A green façade can either be added to an existing wall or stand alone. Living walls

composed of a metal framework, a PVC layer, and an air layer [43]. Due to its relatively low

are composed of a metal framework, a PVC layer, and an air layer [43]. Due to its relatively

are composed of a metal framework, a PVC layer, and an air layer [43]. Due to its relatively

weight, it may be constructed virtually anywhere and in any size. This system supports

low weight, it may be constructed virtually anywhere and in any size. This system sup-

low weight, it may be constructed virtually anywhere and in any size. This system sup-

numerous plant species, including a combination of vegetation, perennial flowers, low

ports numerous plant species, including a combination of vegetation, perennial flowers,

shrubs, and ferns, among others [44]. It performs effectively in a variety of climatic

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The success of a green wall relies on several aspects, including the growth rate of the

plants used in the design, the temperature they can tolerate, and the amount of light they

get, all of which must be taken into account when selecting a plant species [45]. Due to a

plants used in the design, the temperature they can tolerate, and the amount of light they

confluence of factors, a poorly thought-out planting scheme might result in an overgrown

wall, inadequate sunlight exposure, insufficient water absorption, or even inappropriate

plant species selection [46]. Therefore, vertical greening systems, if implemented properly,

have the potential to have long-lasting, positive effects on the immediate functional area of

the inside building and the greater surrounding area as well as on the health and quality

of life of humans in the vicinity. The following Table 3 provides a comparison of the

description, benefits, and limitations of different types of green wall.Sustainability 2023, 15, 10767 10 of 26

Table 3. Different types of green wall.

No Type of Green Wall Description Benefits Limitations

1 Modular

Panel Façade

2 Modular

Trellis Panel Façade

3 Cable–Tensile

Façade System

Made of steel,

box arrangement,

panel depth between 6 and

25 cm based on plants and

planting shrubs

Strong, 3D galvanized steel

wire; plants not attached

directly to the green façade.

limited growth with multiple

tendril supports

Cable system,

planting is possible in ground

or between floors or on roof

4 Cable Façade System

5 Wire Net Façade System

6 Stainless Steel

Frame Façade

7 Living Felt Wall

8 Active Living Wall System

9 Passive Living Wall System

Cable

Suitable for

rapid-growing plants

Ground/cable base

Cable

Suitable for

slow-growing plants

Needs support

Less weight-bearing wall

Independent structures

Gap between façade and frame

Felt made of non-decaying

materials, placing plants in felt

pumps and picker irrigation

plant in the ground, then

transferred to the location

Biological filter

mechanical ventilation

Pull fresh air through a vent

Places plant roots between

two layers

Fertilize through water

Light systems

Modular panels

Drip irrigation system

No air circulation needed

Planting in containers

Long irrigation interval

Ease of moving boxes

Quick growth

Drip irrigation

No need for ground support

Large area

Can make curved shapes

Less stress on the plant

Normal irrigation

Suitable for public spaces

Stress depends on

planting location

Normal irrigation

Air corridor on

the wall

Can construct in

many directions

Wire net system

Wall support

Less stress on the

plant

Normal irrigation

Air corridor on

the wall

Integrate with

cable systems

Easy installation

Ability to create different sizes

and patterns

More flexible

Less stress on plants

Normal irrigation

Firmly on the ground

Airflow to wall

Normal irrigation

Weight-bearing

Allowing airflow

Quick growth

Similar to green roof system

Increase in air

purification capacity

Hydroponic system

Less possibility of plasticity

stress to the plant with height

from earth

Certain plants only

Concrete wall is needed

Speed of growth depends on

wall size

Ground base needed

Short distance to the hub

Long duration of growth

Short distance to the hub

Long duration of growth

Ground base needed

Less distance to grids

Long duration of growth

Long duration for growth

Pump for irrigation of plants

Ventilation system needed

Frequent maintenance

Using of hydroponic

system Air purification capacity low

3.3. Green Parking, Pavements and Shaded Streets

One such method of reducing UHIs is through increasing tree cover and creating

shade. Trees’ leaf density, leaf area, and evapotranspiration all have a role, as do their

geometric qualities. Urban temperatures and land surface elevations may be stabilized to

some degree by the careful planning and design of urban landscaping and green areas [47].

During the summer, the amount of solar energy absorbed is decreased as the percent-

age of vegetative cover increases, especially if the canopy index is high [48]. Trees in

urban regions face a number of challenges due to impervious cover, poor soil moisture,

nutritional scarcity, a lack of rooting volume, water/air pollution, and transport-related

toxicity [49]. The longevity of tree populations in cities is further affected by factors such

as low-temperature pressures, anthropogenic heat sources, air turbulence, and high windSustainability 2023, 15, 10767 11 of 26

speed owing to urban canyons [50]. Tree species vary in their evapotranspiration rates, heat,

and drought tolerance based on a number of factors including morphology, physiology,

local water supply, and wind velocity. Although pavement surface temperatures are raised

by direct solar radiation, they are lowered by tree canopies. As the amount of asphalt,

concrete, and other impermeable surfaces grows, the overnight temperatures rise [51].

Improvements in nighttime urban warming mitigation may be achieved by the elimination

of non-permeable surfaces.

Increasing the ratio of impervious surfaces to canopy cover is an important mitigating

technique. Solar radiation through the canopy helps keep the ground below at a constant

temperature. Pavement undergoes a freezing and thawing cycle as a result of nighttime

heat loss and temperature drops. Cracks in the pavement form as a result of the pavement’s

exposure to repeated cycles of freezing and thawing [52]. As the rate of pavement degrada-

tion rises, the pavement’s useful life decreases. Trees may reduce daytime temperatures,

which in turn reduces the temperature gradients between the road and the surrounding

landscape. The pavement’s durability is increased as a result of this [53]. The UHI may be

mitigated by urban shade because it lowers local temperatures and slows down the rate at

which heat is conducted away from surfaces. The geometry, structure, leaf size, and canopy

cover density of trees are all quantifiable factors in urban shade.

Creating tree-shaded areas improves occupants’ thermal comfort inside the built

environment in hot climates [5]. Trees with a wide canopy may block solar radiation and

the rays reflected off concrete, asphalt, glass, and other man-made surfaces. The quality

of shade may be enhanced by increasing canopy leaf area, size, density, projection, and

transmissivity [54]. Shade may cut down on heat intake from buildings and other structures,

as well as on heat exchange and surface temperatures. Leaf structure, epidermal features,

and angle all have a role in reflectance. A foliar canopy affects absorption, and it is most

often assessed by calculating the leaf-area index, chlorophyll content, and water content of

the plant [55]. The quantity of solar radiation that penetrates a canopy may be measured

using a dimensionless ratio such as transmissivity, which is affected by the structure of

the canopy [56].

A variety of mechanisms, including reflection, absorption, and transmission, allow

trees and other plants to diffuse solar radiation. Part of the solar energy that is taken in

is used for photosynthesis, while the rest is transformed into heat [57]. This is because

the leaves warm up as they absorb more heat. Water from the leaf is turned into water

vapor and exhaled into the atmosphere via the stomata. Water vapor is converted during

the conversion process, which results in the leaf cooling as a result of the loss of latent

heat [58]. Plants are able to chill the air around them by taking in carbon dioxide during

photosynthesis and exhaling it during transpiration. When combined with shade, this

technique causes an overall cooling of the environment throughout the summer [59].

The peak air temperature is higher in open terrain than in vegetative areas. Suburbs

devoid of mature trees tend to be warmer than their tree-lined counterparts [59]. It is

warmer on barren ground than in irrigated areas and it is warmer on artificial turf pitches

than on grass grounds. The Leaf Area Index (LAI) is a metric for measuring the impact of

trees on urban surface temperatures. This establishes a connection between the amount of

greenery present and the amount of water lost to evaporation in urban settings [60]. Several

factors, including tree species, age, hydraulic state, vapor pressure deficit, soil nutrient

availability, seasonal changes, groundwater conditions, and wind speed, all play a part in

determining the LAI [61].

There are techniques to include water storage in paving systems, allowing for the use

of evaporative cooling on roads, parking areas, and sidewalks [62]. Cooler temperatures

are maintained on water-retentive pavements because less solar energy is converted to

heat through conduction. There are several types of water-repellent pavements, including

porous pavers, permeable pavers, and pervious pavers [63]. Water permeates porous

pavers through tiny holes in their surface. These pavers typically include a cellular grid

design, and the holes within the grid are filled with moisture-retaining materials [64]. GrassSustainability 2023, 15, 10767 12 of 26

is a great choice for infill because it promotes transpiration from the root to the shoot of

the plant and brings moisture from the ground up to the surface, where it can evaporate

and cool the pavements below [65]. In contrast to previous and porous choices, permeable

pavers allow water to flow over their surface rather than through them and are made from

concrete or kiln-fired clay bricks [66]. In order to facilitate the evaporation of surface water,

a path is made between pavers by the use of spacer lugs or small holes. It was about as

warm as concrete during the day and about as cool as asphalt at night, making this paver

an ideal alternative. It follows that the evaporative cooling effect of permeable pavers

is marginal.

4. Sustainable Materials for UHI Effect Mitigation

The incorporation of sustainable building materials into the built environment is

another key contributor to the UHI impact. The building’s preconstruction, construction,

and finishing materials all contribute considerably. Streets and pavements composed of

impermeable and highly heat-absorbent materials, painting materials with high thermal

effects, and utility efficiency appliances that release high heat and GHGs contribute sig-

nificantly to UHI effects. Sustainable construction materials are not only economically

feasible but also minimize harmful emissions and UHI effects, hence minimizing the total

environmental impact. Buildings should make use of environmentally friendly building

materials and technologies in a manner that is suitable and contextual. Locally made or

obtained construction materials qualify as sustainable. These items comprise recycled and

industrial byproducts and waste materials. Sustainable materials are thermally efficient

and have a lesser environmental effect. The manufacturing of these building materials takes

much less energy than the production of contemporary or conventional building materials.

4.1. Innovative Streets and Pavement Systems

The idea of adopting novel pavements to reduce the UHI effect has gained popu-

larity in recent years in highly populated regions. In order to produce cool pavements,

conventional pavements may make use of already available pavement technologies by

modifying the materials, implementing sustainable strategies, or introducing brand-new

materials [67,68]. If a pavement increases solar reflectance ability, increases the evapora-

tion process, or decreases the release of sensible heat into the urban atmosphere, then it

will remain cooler than traditional pavement [53]. Cool pavements are categorized into

reflective, evaporative, and heat-harvesting pavements [62]. In order to reduce the surface

temperature and sensible heat emission, reflective pavements have a higher albedo than

regular pavements. Evaporative pavements are those that retain water at the surface or in

the subsurface for the purpose of evaporative cooling. Subduing the surface temperature,

heat-harvesting pavements collect energy from the sun and use it for other purposes. The

topic of cool pavements has expanded beyond pavement cooling technology to include the

impact of such pavements on the weather in cities [69].

Paving materials that are designed to keep temperatures down, such as those that

are reflective of light, increase the rate at which water evaporates or have some other

cooling effect [70]. It will always be colder than standard asphalt, and it will radiate

less heat into the atmosphere. Since the hottest time of the day typically occurs in the

summer, when the release of sensible heat is crucial to the formation of the UHI, a cool

pavement must be able to reduce its daily maximum temperature [29]. Pavements that

have been sealed with a material that is reflective of light will have less of an impact on the

environment [71]. A sealed surface is created by pressing finely graded aggregates into a

thin layer of hot bitumen that has been spread over an existing pavement [61]. Due to the

aggregates being partly exposed, the surface albedo should be somewhere between that

of the asphalt binder and that of the aggregates themselves [72]. Solar reflection is shown

to be highly dependent on the aggregate’s color and the pavement’s age [73]. Chip seal

pavement’s albedo is observed to decline with age yet remains higher than that of regular

asphalt concrete [74]. Although generating white slurry seal requires re-formulating theSustainability 2023, 15, 10767 13 of 26

emulsifier and increasing the price, it has limited applications because of the increased

albedo the pavement receives from it [75]. It is also possible to greatly improve asphalt

pavement’s reflectivity by the use of other methods, such as painting with light colors or

micro surfacing with light-colored materials [76].

Incorporating white cementitious materials and light-colored pebbles into concrete

mixes can create highly reflective pavements [77]. The albedo of hydrated concrete is

principally determined by the cement’s solar reflectance, with other ingredients playing a

supporting role. Although the addition of fly ash, which reacts with calcium hydroxide to

produce stronger concrete, can decrease albedo slightly, it can also increase longevity [78].

The solar reflecting ability can be altered by a wetting, soiling, and abrasion process after

being exposed [79]. The reflectivity of the fine aggregates and paste is what primarily

determines the albedo in the aged state. High reflectivity can also be seen in white topping

and roller-compacted pavements. Streets with minimal traffic in urban areas may have a

white overlay of only two to four inches thick [80].

Although reflective pavements keep the heat off in the summer, they can have the

opposite effect in the winter by making the road surface colder [81]. During the summer, a

pavement surface with high reflection is preferable, while a surface with low reflectance

during the winter is preferable. Due to a reversible molecular structure transition that

occurs at elevated temperatures, the albedo of thermochromic materials shifts when their

surfaces warm and cool [82]. Thermochromic substances and their doses can affect the

transition temperature. Adding TiO2 to this thermochromic coating could increase its

reflectivity [83]. When thermochromic pigments were added to asphalt binder, it was

discovered that the binder retained its temperature more effectively in both hot and cold

climates [84]. Similarly, it was discovered that cement paste with thermochromic pigments

could maintain a colder temperature in hot conditions and a warmer temperature in cold

environments than plain concrete paste [65]. Thermochromic materials can be impregnated

into concrete; however, this process may reduce the concrete’s strength.

Therefore, the ability of permeable pavement to maintain a low temperature depends

on whether or not the evaporative flux is greater than the extra heat uptake brought about

by the pavement’s low thermal inertia [85]. A pervious paver is a porous concrete that

allows water to flow through it instead of collecting and pooling on the surface. Large,

uniform-sized aggregates are coated with a concrete paste or asphalt binder to create

pervious concrete [86]. Since the pavement systems drain easily, the permeable pavers in

this concrete do not collect or hold too much percolating water. Pervious pavements have

been found to be as hot as black asphalt pavements on sunny summer days because of their

higher solar radiation absorption and lower heat inertia than conventional pavements [87].

Pervious pavements may be considered cool pavements due to their lower temperature at

night and their ability to cool faster than regular concrete. This is because the roughness

of the pervious surface reduces its albedo, allowing it to soak up more solar energy than

regular concrete would. When compared to conventional concrete pavement, pervious

concrete pavement has a lower solar reflectance index [88]. When compared to regular

concrete, pervious concrete is reported to have a lower thermal inertia. The texture of

pervious concrete is coarser than that of regular concrete. With a higher heat convective

coefficient, this concrete could be more effective in dissipating heat in breezy conditions [89].

Unless the pervious concrete is re-wetted at a suitable time, the evaporation of the

preceding concrete adds relatively little to the decrease in surface temperature [90]. Too

much water seeps through pervious concrete too quickly for it to be effective at prevent-

ing evaporation. Adequate water is required for evaporative cooling and water-holding

pavements, which retain most of their moisture in the surface layer [76]. Water-retentive

pavements differ from permeable pavements in their pore structure and evaporative ca-

pacity. Water-retentive fillers are often incorporated into concrete to increase its capacity

to store water. A water-retentive pavement is one that, when saturated, can hold onto

rainwater for a period of time by using specific filler materials [91]. In addition, when the

evaporated water close to the surface is gone, the water-retentive filler’s pore structureSustainability 2023, 15, 10767 14 of 26

can draw water from the base via capillary force. After being watered, the dry surface of a

water-retentive block can absorb water at a rate greater than its absorptivity [65]. Refilling

water-retentive pavements with wastewater is one strategy for increasing their resistance

to evaporation [92]. Wastewater is sprinkled on water-retentive pavements in some places

to extend the cooling effect of evaporation. The use of high absorptive infill and recycled

water for irrigation both assist keep pavements at a more comfortable temperature than the

vegetation around them [93].

4.2. Various Coating Materials

4.2.1. Painting with Light-Colored Materials

One potential solution to the UHI effect is the use of solar-reflective coatings for the

building envelope [94]. Extensive global modeling and field studies have confirmed that

highly reflective materials, when combined with thermal energy storage and conservation

measures, are an effective strategy to combat the UHI effect [95]. Traditional cool materials

with diffuse reflectance do not appear to resolve concerns connected to rising urban density,

such as the proximity of buildings and canyon phenomena [96]. As a matter of fact, with a

diffusive nature, some of the reflection will be absorbed by nearby structures. The favorable

effect they have on UHIs is also mitigated since reflected radiation from diffuse vertical

surfaces is absorbed more strongly by pavements and roads [97]. The ability of retro-

reflective (RR) materials to redirect light to their original source is a useful and unique

attribute. RR materials are now used for traffic safety applications such as road signs and

work clothing but are not commercially available for use as building coatings [98]. Coating

urban patterns with RR materials may mitigate UHIs by reducing the amount of sunlight

that is reflected to nearby structures and roads [99].

Currently, high reflectance coatings made from acrylic materials, elastomeric, sili-

cone, fluoropolymer, or mixtures thereof, are widely utilized globally to mitigate the UHI

impact [8]. Several highly reflective artificial coatings may be far cooler than naturally oc-

curring white materials but still a few degrees warmer than the ambient temperature [100].

The solar reflectance, emissivity value, and thermal capacity of white reflective materials

all contribute to the surface temperature range that these materials exhibit. Hence, most

white reflective coatings deteriorate and lose their luster, which is a major issue for the

industry [101]. A further problem with white coatings is that they allow bacteria to multiply

rapidly on the surface [102]. Roof washing can restore some of the roofing material’s optical

qualities but may reduce its reflectivity. White reflective coatings lose their reflectivity

months to years after they are applied.

Many factors, including the coatings’ composition and treatment, as well as the sur-

rounding environment, affect optical performance and the likelihood of an increase in

optical durability [103]. Compared to white paints made with organic binders, those made

with inorganic components are more optically stable and have higher solar reflectance and

emissivity. It has been discovered that doping titanium dioxide with Al, Li, or K signifi-

cantly improves the photostability of the coatings without affecting their reflectance [8].

The coatings’ self-cleaning characteristics and optical performance are both improved by

the incorporation of photocatalytic technology. When titanium dioxide (TiO2) nanoparticles

are incorporated into a coating, the deposited organic substances are broken down into

sulfate, water, nitrate, and carbon dioxide, which are then washed off by water cleaning

or rain [104].

This drastically reduces the adhesion of bacteria to the coating’s surface. The surface

temperatures of white, man-made materials with high reflectivity and emissivity are only

slightly higher than the surrounding air temperature. Since they dramatically lower the

emission of sensible heat into the atmosphere, they are very helpful in preventing cities from

becoming uncomfortably hot. An important downside of highly reflecting white materials

is that their optical and thermal performance may degrade significantly with age [105].

There are a variety of mitigation solutions that make use of commercially available colored,

spectrally selective materials with high spectral reflectivity in the near-infrared wavelengthSustainability 2023, 15, 10767 15 of 26

range and a high emissivity value. Materials that reflect infrared rays have a much higher

solar reflectance compared to materials of the same color and type [106].

To boost reflectivity, scientists have turned to polymeric inorganic hybrid materials and

organic or inorganic pigments with near-infrared spectrum reflectivity [107]. Pigments that

reflect infrared light and are made from inorganic materials have superior optical stability,

great durability, and high temperature stability. Heavy metals in pigments could be bad for

the environment. For the most part, the melt blending procedures of polymeric inorganic

hybrid materials are less harmful to the environment [108]. Infrared-reflecting pigments

can be used with any solvent, including those used to dissolve polyesters, fluoropolymers,

and acrylics, as well as those used in water-based coating chemistry [109]. When pigments

are combined with binders and other compounds, a coating can be created. It is reflective

because the coating’s pigment has a different refractive index in the infrared spectrum than

the binder.

On the other hand, if the coating’s transparency to infrared (IR) radiation is not af-

fected by the difference between the IR refractive indexes of the pigment and binder, then

the coating will be transparent to IR radiation [110]. When trying to generate a reflective

surface, infrared reflective coatings can be put directly over any material, while infrared-

transmitting coatings require a near-infrared reflecting background. A near-infrared trans-

mission coating can be applied when the substrate has a high IR reflectance; however, a

white basecoat and an IR-transmitting coating can be applied instead when the substrate is

absorbing [111]. The reflectance of the substrate, the thickness of the coating, the roughness

of the surface, and the possible backscattering of the pigments all play major roles in

determining the composite material’s spectral reflectance [112].

The optical properties of the pigments, binder refractive index, pigment volume

concentration, and particle size all have a role in regulating this. However, the near-infrared

(NIR) and solar reflectance of cool coatings are observed to increase with the thickness of

the white base coat and can reach a maximum constant value above a specific thickness,

suggesting that smoothing the rough surface of the materials boosts reflectivity across

all wavelengths. Roofing and paving materials can receive IR reflective coatings [113].

IR--reflecting materials have a far lower surface temperature than traditional materials

of the same color, allowing for less sensible heat to be released and significantly less

urban hyperthermia as a result [114]. The emittance and solar reflectance of IR-reflecting

materials exposed to the external environment are diminished due to weathering, aging,

and soiling [115].

4.2.2. Phase-Change Materials (PCMs)

Another tactic for minimizing the UHI effect is the use of PCMs that store and re-

lease latent heat to boost the apparent thermal capacity of buildings and urban structures

and lower their peak surface temperatures. Most PCMs are noncorrosive, nontoxic, and

compatible with a wide range of other materials used in asphalt and concrete pavement

and roofing goods, and they can be categorized as either organic, inorganic, or eutectic

mixes [116]. With the help of PCMs, asphaltic pavements are less likely to experience

thermally-induced rutting and cracking, and the viscoelastic qualities of asphalt binders

are less likely to degrade [8]. Concrete pavements’ resistance to cracking, curling strains,

hydration processes, and thermal shrinkage can all be enhanced by using PCMs [117]. It is

feasible to reduce the surface temperature of pavements and release the stored energy at a

later time by including PCMs within the pavement’s mass [118].

The amount of PCMs in the entire mixture, the phase-change materials employed, the

method used to incorporate PCMs into the pavement, the thermal and optical characteristics

of the pavement materials, and the local climatic circumstances all influence how much the

surface temperature can be lowered [119]. The thermal capacity and the heat transmission

quality of the pavements are both affected by the volume percentage of the PCMs [120].

Because of the low conductivity in the liquid phase, PCMs impede heat transfer in the mass

of the pavement, leading to higher surface temperatures even as their presence in the mixSustainability 2023, 15, 10767 16 of 26

increases the possibility for latent heat storage and hence reduces surface temperatures [94].

Choosing the PCM melting point is important because it determines how long it takes to

heat up the pavement to its maximum temperature and how fast it cools down again [121].

The melting temperature selection should be based on the local climate and the thermal

balance of the pavement [122]. It is possible to use many PCMs, some of which have quite

varied melting points. When used in construction or urban planning materials, PCMs

pose a serious leakage danger when in their molten condition [123]. Micro-encapsulation,

macro-encapsulation, and porous inclusion are among the preferred ways of putting them

into construction materials [119].

4.2.3. Color-Changing Materials

Materials that undergo a thermochromic color change in response to temperature can,

for example, be bright and reflective in the summer and dark and absorbing in the win-

ter. A wide variety of thermochromic materials, including thermochromic combinations,

with a wide range of color-changing mechanisms, are known. Sol-gel films’ lumines-

cence shifts [124], surface plasmon absorption [125], liquid–crystal phase transitions [126],

dye–dye and dye–polymer aggregation and disaggregation mechanisms [127], photonic

crystals’ refractive index modulation [128], and pH changes [129] are the most common ex-

amples of the many known mechanisms. Thermochromic pigments and leuco dyes require

the use of three distinct components: a solvent that regulates the color-change temperature;

a color former such as spirolactone, spiropyran, triphenylmethane, or fluorane; and a color

developer [130]. At the melting point of the thermochromic substance, the solvent turns

from a solid to a liquid, allowing the developer and the color former to dissolve into it [131].

Thermochromic systems lose their color when the hydrogen bonds between the solvent

and the color former are severed [132]. In thermochromic materials, the solvent reverts to

the solid phase and the color former regains its original color when the temperature drops

below the freezing point [133]. Leuco dyes’ color transition temperature is easily modifiable

by experimenting with various dyes and solvents. By combining different thermochromic

ingredients, it is possible to create thermochromic mixes with more than one color change.

Without damaging their color-changing characteristics, the composites can change from

gray to pink, green to blue, and white at temperatures close to 24◦C [8]. It is the molar

ratios of the three components in the thermochromic mixture, as well as their chemical

properties, that determine the color quality and thermochromic qualities of leuco dye-based

materials [134]. Important issues with aging arise with thermochromic materials based on

the use of leuco dyes because of fading and the loss of reversibility. Molecular oxygen is

reduced and reactive oxygen species are produced in an irreversible photochemical process

triggered by ultraviolet (UV) radiation [135]. There is a great possibility for mitigation in

the built environment from thermochromic materials.

4.2.4. Fluorescence Materials

One of the creative strategies that may be used in UHI impact mitigation procedures

is to capture the photovoltaic energy of solar radiation, release the light emission, and

aid in increasing the surface’s ability to reflect light [8]. There are two different kinds

of fluorescent substances: bulk fluorescent substances like ruby and nano-fluorescent

substances like quantum dots [134]. Combining a polymer with a colloidal quantum dot

solution is an alternate method for depositing quantum dots on a substrate. By using this

method, the danger of luminous deterioration brought on by the aggregation of quantum

dots is reduced [136]. Quantum dots and fluorescent materials offer a great opportunity to

reduce the UHI effect.

Some pigments have shown promise for effective fluorescence and look to be econom-

ically and enduringly viable. Ruby, an aluminum oxide pigment with chromium added,

was the first of its kind. It is useful for making things in shades of red and pink [137].

Another option is calcium copper tetra-silicate with either barium (Ba) or strontium (Sr) in

place of the calcium, the finest results to yet have been obtained with calcium and strontiumSustainability 2023, 15, 10767 17 of 26

compounds [138]. The near-infrared fluorescence is preserved throughout the mixing pro-

cess. A coating of synthetic rubies, with its rich dark red hue and fluorescence advantage,

is a positive sight [139]. These pigments are alkaline earth copper silicates, which are often

manufactured using solid-state chemical methods. In a nutshell, the oxides or carbonates of

the component metals are well mixed and then heated in air to a temperature approaching

900 ◦C for a few hours [140]. It is common for the dark compound copper oxide to remain

as an impurity after the synthesis. The pigment will be gray instead of blue if there is an

excess of copper oxide [141].

4.3. Use of Energy-Efficient Appliances

The energy used by buildings and the one-third of all GHG emissions they account for

are both significant contributors to UHIs. Reducing energy consumption and running costs

and lowering greenhouse gas emissions across the life cycle of buildings requires proper

building design and construction, the sufficient use of energy sources, and the discovery of

innovative materials [142]. Climate parameters and climate zones are crucial in adjusting

to and minimizing the impacts of UHIs since they influence so many elements of building

design and operation [143]. New energy budgets must be established, and the energy

efficiency of buildings and whole cities must be improved. Taking climate dynamism into

consideration throughout the building design process is crucial because it allows for more

accurate sizing of residential hot water, heating, and cooling systems, as well as more

thoughtful material selection [144]. To achieve a building design that reduces the negative

impacts of UHI while still adapting to the urban environment, codes and standards must

be flexible enough to accommodate changing circumstances.

Thus, it is important to establish new climatic zones and formulate suggestions to

provide appropriate thermal conditions for future epochs. The construction industry

has a unique potential to cut down on waste disposal and resource consumption via

the development of economically and ecologically sustainable materials based on the

integration of secondary materials as alternatives. Appliances that reduce energy use have

an enormous impact on these two important environmental goals. Materials that quickly

disperse energy are highly valued in the quest for efficiency and the mitigation of carbon

emissions. However, domestic energy savings are reliant on users’ technical and habitual

behavior; in fact, energy-efficient home appliances provide better energy efficiency and

sustainability than the habitual adjustment of turning off appliances when not in use [145].

5. Challenges in Implementing UHI Mitigation Strategies

Despite the fact that a great deal of work is being done to find solutions to the problem

of the UHI in highly urbanized regions where environmental concerns are paramount,

there are still certain practical limitations that are encountered by the initiators. The lack of

government legislation, inadequate technology, an inaccurate estimate of the economic ad-

vantages, and reluctance on the part of individuals are all examples of these limitations. The

largest problem is the government’s lack of policies aimed at reducing UHIs and providing

direction to those who would want to implement such efforts. As previously indicated,

government policies are the single most effective tool for advancing urban sustainability

programs [146]. Yet, ineffective government initiatives may dampen public excitement.

However, while being aware of the environmental, economic, and social advantages

of implementing sustainable initiatives in a voluntary manner, developers and private

sectors sometimes find it difficult to use newly offered technology. The failure to regularly

update the local experience and feedback report is also cited as a serious challenge. Despite

the obvious advantages to business, local governments in certain nations continue to

enact policies that are harmful to the environment [147]. Companies in the private sector

are often hesitant to take on such initiatives because they fear failure in the absence of

adequate government oversight and funding [148]. Although there has been a lot of

attention on innovation and technical progress in the research studies, there are still several

technological roadblocks that prevent widespread implementation. While each city hasSustainability 2023, 15, 10767 18 of 26

its own unique characteristics from its climate to its high concentration of urban features,

different applications must be adapted to work in each one.

Building characteristics, roof pitches, plant types, and other accessibility variables

all put constraints on the available options. To provide one example, the roofs of older

buildings are not designed to support considerable weight; therefore, only a large system

with low structural loading may be employed. However, the lightweight and expansive

mechanism is unable to withstand much wind. Furthermore, urban floods, the UHI phe-

nomena, and the diminishment of urban landscapes are all primarily driven by the growth

in buildings and pavement. Numerous cities are dominated by skyscrapers; however, these

structures almost never have any roof space left over for greenery because of the presence

of expensive and necessary construction services. In addition, green roof plants may attract

mosquitoes and other pests, which can cause problems for nearby households. Metals

like aluminum, copper, zinc, and iron, used in roofing, may contribute to environmental

degradation if they are not used appropriately [149].

Many advantages, including those related to protecting the environment, enhancing

biodiversity, and enhancing occupants’ quality of life, cannot be evaluated in terms of

economic returns and hence act as a barrier to adoption by developers and the private sector.

However, there are challenges in calculating the economic advantages of UHI reduction

owing to a lack of appropriate resources and improper auditing methods. Meanwhile,

prices increase. The upfront costs of designing, building, maintaining, and watering

such a roof might be more than conventional roofs [34]. Dislike might emerge from

a lack of understanding and knowledge about the repayment time frame. Economic

gains are complicated by the widely varying lengths of time it takes to get a return on

investment [150]. The time it takes to recoup the investment made in a large project is a

drawback despite the fact that it may ultimately save money [151]. A major roadblock is the

reluctance of designers and developers to implement new tactics, mostly due to concerns

that locals will not like them and the resulting excess of unnecessary space. This issue

emphasizes the need for a more informed and supportive public.

6. Discussion

The UHI effect and its harmful effects from built environments inside urban areas

were detailed in this study. It is obvious that the conventional methods of construction

and the rapidly rising number of buildings in urban areas have exacerbated environmental

challenges. Multiple initiatives are now conducting research and development to identify

the optimal solution for low-impact architecture and design of buildings and built envi-

ronments that will also minimize the UHI effect. This research focused on two primary

strategies: the incorporation of green infrastructure into the built environment and its

components and the use of sustainable materials in buildings. Green infrastructure, such as

green roofs, green façades, green parking, green roadways, and green pavements, were con-

sidered and examined. Incorporating plants and the evapotranspiration of plants, reducing

the heat impact and increasing the cooling nature of the environment, and also adding

value to the green space and protecting the ecosystem, green roofing has been identified as

a potential solution to conventional roofing systems by attaching plants and regulating the

thermal effect within the building interior and the near surroundings of the building.

However, this has also brought about some unfavorable outcomes, such as providing a

safe haven for insects and certain dangerous reptiles and necessitating the implementation

of remedies to problems like water leaks and root penetration in the structure. In contrast,

green façades use the vertical surface area of the structure and may be used without

affecting the building’s performance. Similar to green roofs, green walls and living walls

are a kind of vertical garden seen on high-rise buildings. Others are framed and connected

to the buildings rather than the façades themselves. Green roofing and other forms of direct

façade attachment have been linked to structural damage and water leakage, although

these problems may be mitigated if the right preventative measures and repair methodsSustainability 2023, 15, 10767 19 of 26

are used [152]. However, such damage caused by plants may be avoided in the case of

frame-supported façades, although doing so may lead to increased expenses.

It is true that the designers of sustainable green buildings are being urged to cut

down on parking spaces in an effort to limit the number of individual vehicles used.

However, in certain circumstances, parking spaces are essential and the number of vehicles

is unavoidable due to insufficient public transit options. With the use of tree canopies

and highly reflecting indexing paint, parking lots may be made more environmentally

friendly and less detrimental to the environment. This will cause plants to produce a

cooling action known as evapotranspiration. Pavement and road designs that include

vegetation to minimize heat gain, promote water infiltration and percolation, and decrease

the UHI impact are preferable from an environmental and economic perspective. The heat

absorption of a building and the UHI effect are both largely attributable to the materials

used in construction [143]. The thermal impact of the materials, including their absorption

and reflection of heat, must be carefully examined throughout the construction process.

Using sustainable construction practices and sustainable building materials in high-rise

structures is the most effective way to mitigate the UHI impact. By using highly reflective

paint, you may limit the amount of heat absorbed by a building’s exterior.

Incorporating phase-change materials into construction allows for the absorption

and storage of thermal energy through a phase transition. Because of this, the ambient

temperature drops. Color-changing materials can be white during times of high solar

radiation, increasing reflectivity and decreasing heat gain, and black during times of low

solar radiation and low temperatures inside the building, absorbing heat and lowering the

need for heating, both of which help to lower GHG emissions and the UHI. By doing so,

the fluorescence effect is achieved and the heat gain of the building is decreased thanks to

the incorporation of fluorescence materials into the building components. GHG emissions

may be lowered and energy use can be lowered by using appliances that are more energy-

efficient. In this way, it is not only worthwhile but also economically useful, and it helps

to mitigate the UHI impact. While all of these green infrastructures and materials have

helped with UHI reduction and mitigation measures, there are several obstacles to their

widespread use in tall buildings that must be overcome. A lack of government regulation,

poor technology, an overestimation of economic benefits, and individual hesitation are all

factors holding progress back. Sustainable built environments in dense urban settings will

pave the way for environmental friendliness, a lesser UHI effect, and comfort for occupants

and other living beings and integrated ecosystems in the future by fixing the problems and

making it accessible to anyone, anywhere in the globe.

7. Conclusions

This article compares and analyzes many cutting-edge strategies for decreasing the

negative impacts of UHIs. The use of green roofing systems, green façades, and green

parking, pavement, and streets in place of traditional nature enhances the amount of green

space, aids in the implementation of heat reduction measures, and lessens the impact on

the environment through the cooling effect of metabolic processes. Green walls provide a

viable alternative and a large canvas on which to grow vegetation vertically. Sustainable

greenery mitigation measures will be bolstered by the replacement of roads and pavements

for walkers in highly urbanized areas with green installations. To further minimize solar

radiation absorption and boost surface heat, shading arrangements and coating materials

with specialized functions like white coloring, PCMs, color changes, and fluorescence need

to be implemented.

The adoption of energy-efficient appliances is an important step in mitigating the

effects of global warming caused by the production of GHGs and limiting the rise in global

surface temperature. The buildings, parks, water features, roadways, and recreational

spaces that make up urban areas will vary from one location to the other. Depending

on the type of building (such as residential, hotel, industrial, office, and retail complex

buildings), many greening initiatives and methods may be viable to execute. This study’sSustainability 2023, 15, 10767 20 of 26

main limitation is that it only took into account typical buildings and their accompanying

subcomponents like parking lots, pavements, and roadways. Hence, there are numerous

challenges that must be overcome before this idea can be used on a global scale, but doing

so will help to move closer to an environment where UHIs have less of an impact and,

hopefully, eventually have no effect at all. This is true on a local as well as global scale, and

it may be achieved via the implementation of efficient laws and regulations, the discovery

of new methods for handling existing problems, and the sharing of the findings of relevant

research and development initiatives.

The key findings from this review are listed below:

• The rapidly urbanizing cities around the world necessitate ecologically mindful and

sustainable ways to build.

• The UHI effect is a critical urban phenomenon; however, adequate mitigation efforts will

lessen the effects on the environment as well as on the safety and health of inhabitants.

• Infrastructure and building materials as well as greening the built environment are

crucial in managing UHIs.

• New and existing buildings should include infrastructure with green roofs, walls,

façades, green parking, water retaining pavements, and shaded roadways, which have

proven benefits toward mitigating UHIs.

• The incorporation of sustainable and environmentally friendly materials into the built

environment, such as innovative street and pavement systems, a variety of coating

materials, and the use of energy-efficient appliances, has provided a number of benefits

and been proven to be highly effective in lowering the UHI effect.

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Article

Evaluation of Urban Heat Island (UHI) Using Satellite Images

in Densely Populated Cities of South Asia

Manisha Maharjan 1, Anil Aryal 2, Bijay Man Shakya 2,3 and Saurav Kumar 4

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, Rocky Talchabhadel 3,4,\* , Bhesh Raj Thapa 3,5

1 Department of Environmental Engineering, Kyoto University, Katsura, Nishikyo-ku 615-8510, Japan;

maharjan.manisha.67a@kyoto-u.jp

2 Interdisciplinary Centre for River Basin Environment, University of Yamanashi, 4-3-11 Takeda,

Kofu 400-8510, Japan; aanil@yamanashi.ac.jp (A.A.); bijay@smartphones4water.org (B.M.S.)

3 Smartphones For Water Nepal (S4W-Nepal), Lalitpur 44700, Nepal; bhesh@smartphones4water.org

4 Texas A&M AgriLife Research, Texas A&M University, El Paso, TX 79927, USA; saurav.kumar@ag.tamu.edu

5 Universal Engineering and Science College, Lalitpur 44700, Nepal

\* Correspondence: rocky.talchabhadel@ag.tamu.edu

Abstract: Rapid Urbanization, and other anthropogenic activities, have amplified the change in

land-use transition from green space to heat emission in built-up areas globally. As a result, there

has been an increase in the land surface temperature (LST) causing the Urban Heat Island (UHI)

effect, particularly in large cities. The UHI effect poses a serious risk to human health and well-being,

magnified in large developing cities with limited resources to cope with such issues. This study

focuses on understanding the UHI effect in Kathmandu Valley (KV), Delhi, and Dhaka, three growing

cities in South Asia. The UHI effect was evaluated by analyzing the UHI intensity of the city with

respect to the surroundings. We found that the central urban area, of all three cities, experienced more

heat zones compared to the peri-urban areas. The estimated average surface temperature ranged

from 21.1 ◦C in March 2014 to 32.0 ◦C in June 2015 in KV, while Delhi and Dhaka experienced surface

temperature variation from 29.7◦C in June 2017 to 40.2◦C in June 2019 and 23.6◦C in March 2017

to 33.2 ◦C in March 2014, respectively. Based on magnitude and variation of LST, highly built-up

central KV showed heat island characteristics. In both Delhi and Dhaka, the western regions showed

the UHI effect. Overall, this study finds that the UHI zones are more concentrated near the urban

business centers with high population density. The results suggest that most areas in these cities have

a rising LST trend and are on the verge of being UHI regions. Therefore, it is essential that further

detailed assessment is conducted to understand and abate the impact of the temperature variations.

Keywords: land surface temperature; normalized difference vegetation index; normalized difference

built-up index; South Asia; urban heat island

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1. Introduction

The frequency and magnitude of extreme weather events, such as heatwaves, are ex-

pected to rise with an increase in air temperature [1]. Such events are exacerbated when

coupled with Urban Heat Island (UHI) effect. UHI is the phenomenon where urban air

temperatures are higher than the surrounding rural areas [2]. Several factors, such as an

increase in anthropogenic heat flux’s emission [3], change in urban geometry, and pop-

ulation density [4], and change in land-use and land cover LULC [5], results in the UHI

phenomenon. With the rapid increase in urbanization, the green land cover is replaced by

impervious land surfaces, such as concrete buildings and bituminous roads [6,7]. Change in

land cover properties alters the thermal properties, surface radiation, and humidity of the

urban area [8], leading to the UHI effect. Evaluation of UHI in urbanized and populated

cities is crucial to analyze the change in surface albedo, emissivity, and evapotranspira-

tion [6]. The UHI phenomenon has been widely studied [9–11] since its first observation by

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Howard in London [12]. The rise in UHI has affected both the natural and human systems

by changing rainfall patterns [13], worsening air quality [14], increasing flood risk, and

decreasing water quality [15], among others. Thus, UHI’s quantification is essential to

inform the potential direct and indirect risks exerted by rising temperatures [16,17]. Fur-

ther, extreme heatwaves and the related heat stress could be evaluated by analyzing UHI

intensity [18].

While there is evidence in the literature of land surface temperature (LST) link with

the UHI, a thorough examination of UHI is required to attribute the surface temperature

changes to local climate and anthropogenic disturbances e.g., rapid urbanization. Satellite-

based indices, such as Normalized Difference Vegetation Index (NDVI) and Normalized

Difference Built-up Index (NDBI), may provide critical information on relationships be-

tween annual surface temperature, LST and UHI. The association between LST, NDVI,

and NDBI can provide crucial information for urban land managers and planners [19].

There is evidence that changes in LULC pattern has increased the frequency and inten-

sity of surface urban heat island (SUHI) thereby impacting the quality of life [20]. Thus,

quantification of UHI and LST will also help assess the impact on human health and

environmental changes [21].

Globally, there is significant evidence for urbanization and LST rise [22–25]. LST is a

vital step for the quantification of the UHI effect [26]. Dissanayake et al. [27], using Landsat

data, reported that the impervious area at Kanda City, Sri Lanka increased from 2.3% (1996)

to 6.7% (2006) to 23.9% (2017). With such an increase in impervious areas and changing

climate [28], an increase in LST has a greater influence on UHI [29]. With the advancement

in remote sensing techniques, the concept of SUHI has been used for the quantification of

UHI. SUHI relies on measuring the surface temperature through remote sensing imageries.

Limitations and shortcomings of the ground-based meteorological observations, such as

sparse gauge network and limited data availability, justifies the application of remote

sensing techniques. Liu et al. [30] reported that the SUHI, defined as an UHI quantified

by the difference in LST [31,32], was found to be more prevalent from May to October in

Beijing. They further stressed that SUHI intensity was more pronounced during July and

August. Another study across 419 global big cities, Peng et al. [33] showed that the average

annual daytime SUHI intensity was higher than that in the annual nighttime. Vegetation

clearance during urbanization has also been shown to cause an increase in LST and has

induced UHI effect. The surface temperature analysis showed that the minimum and

maximum temperatures at Skopje, Macedonia were 15◦C and 37 ◦C for 2013, and 24◦C

and 49 ◦C for 2017 [34]. Population density also has been shown to affect UHI. The spatial

variability of UHI showed higher intensity in densely populated areas compared to less

dense and peripheral urban areas at Sargoda City in Pakistan [35].

The spatial and temporal characteristics of LST, NDVI, and NDBI and their relationship

has been quantified at the global and regional scale. However, these association differ

between cities due to their unique geophysical, climate, and urban growth characteristics.

Research has been carried out in understanding the local climate of some cities in India,

however, no such study has been done for countries like Nepal. Understanding of the

urban climate behavior using the satellite images in major populated and urbanized cities

of South Asia is still lacking. This study aims to evaluate LST, NDVI, and NDBI and

explore their associations to fill the gap and advance our understanding for the region.

We have chosen three capital cities with growing populations-Kathmandu Valley (KV),

Delhi, and Dhaka-to represent the region. However, such quantification of LST and

SUHI (hereafter referred to as UHI) should help in planning other smart resilient cities in

the region.Earth 2021, 2 88

2. Materials and Methods

2.1. Materials

2.1.1. Landsat–8 Data

We used Landsat 8 satellite images, OLI (Operational Land Imager) and TIRS (Thermal

Infrared Sensor) 15 to 30-m multispectral data from Landsat–8 C1 Level-1, downloaded

from United States Geological Survey (USGS). Thermal band, Band 10, is provided as

the atmospheric brightness temperature in Kelvin (K), and the multispectral-bands of

Landsat–8 OLI is provided as surface reflectance. Band 10 is available at 100m horizontal

resolution. Since the UHI effect is weakened by cloud cover [36], the satellite imagery with

cloud coverage <10% were selected (cloud-free). Cloud cover in the entire study area is not

similar. Data was selected to maintain temporal uniformity over the study period (Table 1).

This data selection should not be hindered as our study focused on LST variations and

UHI over modified land use rather than the absolute value of LST. A comprehensive

outline of the necessary metadata is outlined in Table 1. Data required were downloaded

from Earth Explorer [37] and masked to the study area. Then, the LST map for each study

area was generated for different data acquisition dates as shown in Table 1. The extracted

images for most of the years were obtained for summer (March-August) so that the high

surface temperatures could be captured. Since we filtered the cloud cover to be less than

10%, the downloaded satellite image could not coincide for the same day in each year and

most of the images were acquired for March. The scaling-factors used for determining LST

and UHI were extracted from metadata (K1 = 774.4483, K2 = 1321.0789, ML = 0.0003342,

AL = 0.1, please refer to Section 2.3.1 for details).

Table 1. Acquisition properties of Landsat satellite images.

SN Acquisition Year Kathmandu Valley

(Cloud Coverage %)

Delhi

(Cloud Coverage %)

Dhaka

(Cloud Coverage %)

1 2013 26-March

(4.51)

2 2014 26-March

(3.21)

3 2015 01-June

(7.27)

4 2016 15-March

(7.97)

5 2017 02-March

(6.82)

6 2018 08-May

(5.59)

7 2019 24-March

(1.88)

21-June

(0.31)

10-July

(0.00)

DNA \*

30-March

(0.00)

DNA \* 17-March

(2.97)

16-August

(4.04)

25-June

(3.30)

03-March

(10.75)

22-March

(3.88)

DNA \* 12-May

(1.90)

15-June

(0.00)

28-March

(0.28)

\* Data Not Available.

2.1.2. Population Distribution

The annual population distribution in the KV, Delhi and Dhaka is shown in Table 2 [38].

The increase in average rates of the population for KV, Delhi and Dhaka were found to

be 3.97%, 3.25%, and 3.61% respectively, the highest being in KV. The rate of population

change increased until 2014, then decreased until 2017, and again increased in the year

2018 for KV whilst remained constant throughout the study period for Delhi and Dhaka

except in the year 2019. The rate of population change is expected to drop to 3.49% for

KV, 3.03% for Delhi and 3.56% for Dhaka in the year 2020. Table 2 shows the increasing

population trend for all study areas which could eventually impact the land use pattern

and the surface temperature. The rapid increase in the urban population in two decades

has led to the rise in the rate of urbanization too in these cities.Earth 2021, 2 89

Table 2. Annual population of Kathmandu Valley, Delhi and Dhaka cities [Millions \*\*]. The change (%) in population

represents the change in number of population in consecutive years.

Year Kathmandu Valley Delhi Dhaka

Population Change (%) population Change (%) Population Change (%)

2010 0.965 - 21.988 - 14.731 -

2011 1.004 4.04 22.714 3.30 15.264 3.62

2012 1.045 4.08 23.464 3.30 15.816 3.62

2013 1.088 4.11 24.239 3.30 16.389 3.62

2014 1.133 4.14 25.039 3.30 16.982 3.62

2015 1.179 4.06 25.866 3.30 17.597 3.62

2016 1.227 4.07 26.720 3.30 18.234 3.62

2017 1.277 4.07 27.602 3.30 18.894 3.62

2018 1.330 4.15 28.514 3.30 19.578 3.62

2019 1.376 3.46 29.399 3.10 20.284 3.61

2020 1.424 3.49 30.291 3.03 21.006 3.56

\*\* World Population Prospects, UN.

2.1.3. Observed Air Temperature

The average observed air temperature acquired [39] for all the study areas is shown

in Table 3. The observed temperature for the missing satellite data acquisition months

in 2015 and 2018 for Delhi were obtained on 28 July 2015 and 20 June 2018 respectively.

Likewise, the observed air temperature for Dhaka in 2013 was obtained on the day of 20

March 2013. Meanwhile, the missing temperature data on the satellite data acquisition day

were obtained by averaging the temperature from the previous day and the following day

of the missing date.

Table 3. Average daily observed air temperature for the data acquisition day in Kathmandu Valley,

Delhi and Dhaka for different years [◦C].

2013 2014 2015 2016 2017 2018 2019

KV 24.0 23.5 30.5 20.5 16.5 29.0 17.5

Delhi 40.0 40.5 33.0 33.5 39.0 40.0 42.5

Dhaka 30.0 32.0 30.0 30.5 28.5 31.0 32.0

2.2. Study Area

South Asian (SA) nations, namely: Afghanistan, Pakistan, India, Nepal, Maldives,

Bhutan, Sri Lanka and Bangladesh combined have more than 18 billion population [40]

where 31% resides in the urban area [41]. The capitals of SA nations are economically rich,

urbanized, and highly populated. Delhi (30.2 million) and Dhaka (21.0 million) are the

top 10 most populated capital cities in SA, while KV is the most populated and emerging

urbanized city in Nepal. The rising population has induced urbanization in all these

capitals. The rate of urbanization is increasing rapidly with the increase in population to

130 million in just a span of 10 years (2001 to 2011) and is expected to reach 250 million

by 2025 [42] in SA. A brief description of each study area is discussed below under each

sub-sections. The section deals with the physiography and climate of each study area.

2.2.1. Kathmandu Valley

KV is one of the biggest cities, in terms of population and economic development,

in Nepal comprising an area of approximately 664 km2 (Figure 1). The bowl-shaped

valley is located at 85◦11′E 27◦32′N inscribing the major cities Kathmandu, Lalitpur and

Bhaktapur [43,44]. KV lies in the warm temperate zone [45] with a fair climate varying from

2.4 ◦C to 37 ◦C in the period of 1981–2010 [46]. Geographically, the central lower part of the

valley is situated at an elevation of 1425 m above mean sea level MSL and is surroundedEarth 2021, 2 90

by four mountain ranges namely Shivapuri, Phulchowki, Nagarjun, and Chandragiri Hills.

KV is the most developed city in Nepal with a greater portion occupied by the built-up

area. On the contrary, KV has some open spaces namely Tundikhel, Tribhuvan park,

Sankha park, etc., which are expected to serve as green space thereby reducing the rising

daytime temperature.

**Kathmandu**

**Valley**

**Delhi**

¹

**Nepal India**

0 4 8 12

Km

0 4 8 12

Km

**Dhaka**

**Bangladesh**

**Bangladesh**

0 4 8 12

Km

**Maldives**

0 800 1,600 2,400

Km

**Kathmandu**

**Valley**

Nagarjun

Chandragiri

Kirtipur

Dakshinkali

0 4 8 12

Km

**Delhi**

Tarakeshwor

Tokha

Budhanilakantha

Gokarneshwor

Shankharapur

Kageshwori Manahora

Kathmandu

Changunarayan

Madhyapur Thimi

Lalitpur

Bhaktapur

Mahalaxmi

Suryabinayak

Godawari

Konjyosom

¹

Delhi

**Nepal India**

0 4 8 12

Km

**Dhaka**

Dhamrai

Nawabganj

Dohar

Savar

**Bangladesh**

**Bangladesh**

Tejgaon

Keraniganj

0 4 8 12

Km

**Maldives**

0 800 1,600 2,400

Km

Figure 1. The three study areas in Nepal (Kathmandu Valley), India (Delhi), and Bangladesh (Dhaka). The top panel shows

the international boundary while the bottom panel shows the respective administrative units of the focal study area.Earth 2021, 2 91

2.2.2. Delhi

Delhi located in Northern India, at 77◦14′E 28◦36′N is bordered by Uttar Pradesh

in the East and by the states of Haryana on the West, North and South (Figure 1). It

covers an area of 1484 km2, of which 783 km2 is designated as rural, and 700 km2 as urban

therefore making it the largest city in terms of area in India. It has a length of 51.9 km and

a width of 48.48 km. Delhi has a dry subtropical and semi-arid type of climate [47]. The

annual average temperature is 25◦C with monthly means varying from 13◦C to 32 ◦C.

The warm season begins in early April and peaks in late May or early June with an average

temperature of about 38◦C but occasional heat waves may result in high temperatures of

over 45 ◦C on some days. Per capita availability of green space in Delhi is about 20 m2

whereas that of open space is 30 m2 [48].

2.2.3. Dhaka

Dhaka is located in central Bangladesh at 90◦22′E 23◦42′N (Figure 1) along the eastern

banks of the Buriganga River. The city lies on the lower reaches of the Ganges Delta and

covers a total area of 306.38 km2. Dhaka has a tropical savanna climate. The city has a dis-

tinct monsoonal season, with an annual average temperature of 26◦C and monthly means

varying between 19◦C in January and 29◦C in May [49]. There are many parks within

Dhaka city, including Ramna Park, Suhrawardy Udyan, Shishu Park, National Botanical

Garden, Baldha Garden, Chandrima Uddan, Gulshan Park, and Dhaka Zoo. There are

lakes within the city, such as Crescent lake, Dhanmondi lake, Baridhara-Gulshan lake,

Banani lake, Uttara lake, and Hatirjheel-Begunbari lake. These parks and lakes act as green

space and help in minimizing the rising surface temperature.

2.3. Methodology

Figure 2 shows the flowchart of methodologies adopted in this study. A step-wise

description is discussed below:

2.3.1. Step-Wise Methodologies to Estimate UHI

Conversion of Spectral Radiance to Top of Atmospheric Brightness Temperature

Landsat 8 satellite imagery obtained was processed using 32-bit floating-point calcu-

lations. These values were then converted to 16-bit integer values in the finished level 1

product. Conversion to spectral radiance was done using the radiance scaling factors

provided in the metadata file [37] using Equation (1).

Lλ = ML ∗Qcal + AL (1)

The calculated spectral radiance was then converted to brightness temperature which

was often determined as the effective temperature under unit emissivity. Top of Atmo-

sphere (TOA) Brightness Temperature was obtained from spectral radiance in degree

Celsius using Equation (2).

K2

TB =

−273.15 (2)

Ln K2

Lλ + 1

where,

Lλ = TOA spectral reflectance (watts/(m2 \* sr \* µm)),

ML = Band specific multiplicative rescaling factor,

Qcal = Quantized and calibrated standard product pixel values (DN),

AL = Band specific additive rescaling factor,

TB = Effective temperature in◦CEarth 2021, 2 92

Band 10 Band 4 Band 5

Landsat-8

Bands

Top of

Atmospheric

Spectral

Radiance

Normalized

Difference

Vegetation

Index (NDVI)

Proportion of

vegetation

(Pv)

Step 1

Radians to

At-sensor

temperature

Ground

Emissivity

Step 2

Land Surface

Temperature

(LST)

Step 3

Urban Heat Island (UHI)

Step 4

Figure 2. Overall methodological outline to estimate Land Surface Temperature (LST), Normalized Difference Vege-

tation Index (NDVI), Ground Emissivity and Urban Heat Island (UHI) effect in the considered study area using the

satellite imageries.

Landsat Surface Temperature Generation

OLI and TIRS band data were converted to radiance using the radiance scaling factors

provided in the metadata file using Equation (1) and then to TOA brightness temperature

using Equation (2). After acquiring brightness temperature, LST for Landsat–8 was esti-

mated using Equations (3)–(7). Parameters such as NDVI, proportion of vegetation (Pv),

and ground emissivity (e) were required to estimate the LST. Each parameters NDVI,

Pv and e were calculated using Equations (4), (6), and (7) respectively. NDVI was calcu-

lated using Near InfraRed Band (B5) and Red Band (B4) of Landsat imagery. Normalized

Difference Built-up Index (NDBI) was calculated using 6th (Middle InfraRed) and 5th

(Near InfraRed) of Landsat 8 bands using Equation (5).

LST=

TB

TB

C2 ) ∗Ln(e) (3)

1 + (λ ∗

NDVI=

B5−B4

B5 + B4

B6−B5

NDBI=

(4)

(5)

B6 + B5Earth 2021, 2 93

Pv =

NDVI−NDVImin

NDVImax−NDVImin

e = 0.004 ∗Pv + 0.986 2

(6)

(7)

where,

LST = Land Surface Temperature (◦C),

TB = Effective temperature (◦C),

NDVI = Normalized Difference Vegetation Index calculated using Equation (4),

NDBI = Normalized Difference Built-up Index calculated using Equation (5),

Pv = Proportion of vegetation calculated using Equation (6),

e = Ground Emissivity calculated from Equation (7),

λ and C2 are constants having values of 10.8 and 14,388 respectively.

Urban Heat Island

After obtaining LST, Equations (8) and (9) were used for determining UHI used by

Kaplan et al. [34]. Here, µ is the mean LST value for the study area, and σ is the standard

deviation of the LST.

UHI= LST > µ + 0.5 ∗σ UHI= 0 < LST ≤µ + 0.5 ∗σ (8)

(9)

3. Results

3.1. LST, NDVI, and NDBI for Each Study Area

3.1.1. Kathmandu Valley

The estimated spatial distribution of LST for KV is shown in Figures 3 and 4 for the

dates reported in Table 1. We observed an increase in surface temperature up to more

than 30 ◦C for 2015 and 2018. In the year 2015, LST was estimated for June so most

of the region in KV had higher temperature compared to other years. Kathmandu and

Lalitpur Metropolitan City (referred to as Kathmandu and Lalitpur) showed higher surface

temperature compared to other nearby municipalities (Madhyapur Thimi, Kirtipur etc.)

and rural municipalities (Konjyosom) (refer Figure 1 for the locations of administrative

units). It may be noted that in June 2015, Konjyosom rural municipality exhibited higher

temperature than in other years.

The peri-urban municipalities like Nagarjun, and the higher region of Budhanilkantha,

and Godawari had the temperatures ranging from 15◦C to 25 ◦C most of the years.

These regions also had surface temperature higher than 27◦C during 1 June 2015, 22 April

2018, and 8 May 2018. This might be due to the rise in air temperature as a result of

reflectance in the urban and barren land. Kathmandu and Lalitpur experienced higher

temperature most of the summer time. However, the boundaries of KV such as Chandragiri,

Dakshinkali, Nagarjun, Gokarneshwor, Budhanilkantha, and Konjyosom experienced

temperatures less than 10◦C.

The second and third columns of Figures 3 and 4 show the temporal and spatial distri-

bution of NDVI and NDBI for KV. The figures depicted that vegetative area (NDVI > 0)

was higher in the peri-urban area compared to central KV which had NDVI < 0, negative

NDVI for March 2013 and 2014. NDVI values for central KV were negative which support

the presence of non-vegetative areas usually barren land or built-up area. It was observed,

as expected, that the built-up area increased with the increase in population.Earth 2021, 2 94

**LST NDVI NDBI**

**March 2013**

¸

**March 2014**

**LST NDVI NDBI**

**LST** < 10

**June 2015**

10 - 15 15 - 20 20 - 25

25 - 30 30 - 35 > 35

**NDVI**

**NDBI**

0.6

0 10 20 30

Km

High : 0.4

Low : -0.4

-0.2

**March 2016**

**LST** < 10

**NDVI**

**NDBI**

10 - 15 15 - 20 20 - 25

0.6

0 10 20 30

Km

25 - 30 30 - 35 > 35

High : 0.4

Low : -0.4

-0.2

Figure 3. Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up

Index (NDBI) estimated for Kathmandu Valley study area using Landsat–8 satellite image for the year March 2013–2014

(top two panels) and March 2015–2016 (bottom two panels).Earth 2021, 2 95

**LST NDVI NDBI**

**March 2017**

¸

**LST NDVI NDBI**

**March 2014**

**April 2018**

**LST** < 10

**March 2019**

**NDVI**

**NDBI**

10 - 15 15 - 20 20 - 25

25 - 30 30 - 35 > 35

0.6

-0.2

0 10 20 30

Km

High : 0.4

Low : -0.4

**NDVI**

**NDBI**

0 10 20 30

Km

High : 0.4

Low : -0.4

**LST** < 10

10 - 15 15 - 20 20 - 25

0.6

25 - 30 30 - 35 > 35

-0.2

Figure 4. LST, NDVI, NDBI estimated for Kathmandu Valley study area using Landsat–8 satellite imagery for the year

March 2017, April 2018 and March 2019.

Further, the result of NDBI confirmed that the built-up area (NDBI < 0) was con-

centrated in the central KV, mainly in Kathmandu, compared to peri-urban areas of KV

such as Godawari and Nagarjun municipalities. Central KV, including Kathmandu and

Lalitpur, had lower values of NDVI and higher values of NDBI which states that it KV

was less vegetative compared to other regions. NDVI ranged from−0.1 (March 2016) to

+0.6 (June 2015) during the study period in KV. Most of the peri-urban regions within

KV had higher values of NDVI during 2015 while central KV showed a lower value of

NDVI. Similarly, NDBI in KV ranged from−0.2 to +0.4. Most of the built-up areas were

concentrated in central KV while the peri-urban areas had lesser built-up areas as shown

in the third column of Figures 3 and 4. Expansion of NDBI further demonstrates that the

built-up areas in the eastern KV were increasing. Change in the land cover pattern such asEarth 2021, 2 96

the increase in impervious areas (attributed by increase in NDBI values) has limited the

recharge capacity of the groundwater in central KV [50,51] which eventually reduces the

soil moisture.

The estimated average surface temperature ranged from 20◦C in 2016 to 32 ◦C in 2015

(Table 4). The higher discrepancy in observed and estimated temperature occurred in the

year 2017 and 2019 resulting in higher differences of 5.04 and 5.3◦C, respectively. While

the discrepancies in other years were found to be comparatively less as shown in Table 4.

Table 4. Comparison of estimated LST with the observed air temperature and difference between the

two at Kathmandu Valley.

SN Acquisition Date EstimatedLST ObservedAir Temperature Difference

1 26-March-2013 26.48 24.00 2.48

2 26-March-2014 21.08 23.50−2.42

3 1-June-2015 31.98 30.50 1.48

4 15-March-2016 19.97 20.50−0.53

5 2-March-2017 21.54 16.50 5.04

6 8-May-2018 28.32 29.00−0.68

7 24-March-2019 22.82 17.50 5.32

3.1.2. Delhi

Spatial and temporal distribution of LST, NDVI, and NDBI for Delhi is shown in

Figures 5 and 6. In the eastern end of Delhi two areas were not well characterized by the

satellite imagery, dark blue color on the right side for the year 2013–2016 and lower left

for the years 2017 and 2019. We did not consider and these two areas for the analysis. LST

for Delhi ranged from 15 to 30◦C in most of the regions during 2013–2017 while very few

areas experienced LST > 35 ◦C. However, the reverse was the case for the year 2019 where

most of Delhi received surface temperature > 35 ◦C, except for the Yamuna river ranging

from 25 to 30 ◦C. The comparison of observed and estimated LST Table 5 showed that the

maximum difference in the temperature was 9.3◦C in the year 2017, whereas the least bias

of 2.3 ◦C found in the year 2019.

LST in Delhi was found to be inconsistent intra-annually. During the year 2013, June

was considered for the evaluation purpose and the mean surface temperature was found to

be 32.8 ◦C with minimum and maximum LST being 14.7◦C and 42.9 ◦C, respectively. Areas

in the north of Delhi experienced the minimum temperature while the south-west region

exhibited the maximum temperature. Most of the regions in Delhi had LST ranging from 30

to 35 ◦C as shown in the upper panel under the LST column in Figure 5. However, in 2019,

mean LST was estimated to be 40.2 ◦C with minimum and maximum LST to be 29.8 and

47.7 ◦C respectively. The higher LST may be attributed to the increase in the built-up area,

also demonstrated by the NDBI. In contrast, the south-east part of Delhi shows reduction

in the LST values which may be an artifact of data processing. The maximum value of

NDBI in 2019 was found to be 0.51 which increased from 0.29 in 2013. Similarly, the result

of NDVI showed a decrease in the maximum vegetative index from 0.47 in 2013 to 0.44

in 2019.

The result of NDVI portrayed that vegetative area was less compared to non-vegetative

areas. The non-vegetative area increased with the increase in LST. The vegetative area

was more in south Delhi compared to north Delhi which holds more built-up towns and

industrial areas. However, in, 2016, NDVI map showed that Delhi has a more vegetative

area compared to non-vegetative which might be the result of lesser air temperature

(observed 33.5◦C) and higher relative humidity (RH) compared to 2015 and 2017 for the

same month. RH was found to be 21% in the data acquisition day in 2019.Earth 2021, 2 97

**June 2013**

**LST**

¸**NDVI NDBI**

**July 2014**

**LST**

**NDBI**

**NDVI**

< 10

10 - 15

15 - 20

20 - 25

25 - 30

30 - 35

> 35

0.4

-0.4

0.6

-0.2

Figure 5. LST, NDVI, NDBI estimated for Delhi using Landsat–8 satellite image for 2013 and 2014.The dark blue section

represents the missing data because of not overlapping the satellite image. The dark blue portion is not considered in

the analysis.

Table 5. Comparison of estimated LST with the observed air temperature and difference between the

two at Delhi.

SN Acquisition Date LST Observed Air Temperature Difference

1 21-June-2013 40.0 32.8 7.2

2 10-July-2014 40.5 34.1 6.4

3 16-August-2016 33.5 25.7 7.8

4 25-June-2017 39.0 29.7 9.3

5 15-June-2019 42.5 40.2 2.3

Similarly, 40◦C observed temperature and 30% RH, was observed in 2013. NDVI

values ranged from−0.09 in 2013 to 0.52 in 2016 (August). This suggested that Delhi

has a lesser vegetative area compared to the non-vegetative area. A similar pattern was

observed from NDBI. Most regions in Delhi have NDBI value ranging from−0.3 to 0.51,

the distribution shows higher percentage of the built-up area than the non-built-up area.

The NDBI values suggest that more areas in Delhi radiate the incoming sunlight thereby

increasing the temperature of the study area.

3.1.3. Dhaka

The spatial and temporal distribution of LST, NDVI, and NDBI were plotted for Dhaka

district as shown in Figures 7 and 8. The spatial distribution of LST over Dhaka showed

the temperature distribution in March 2014 was higher than 35◦C, a few areas have a

temperature less than 35◦C. This was validated by the observed temperature as shownEarth 2021, 2 98

in Table 6. The bias in observed air temperature and estimated surface temperature was

found to be−1.23 ◦C in the year 2014. The maximum bias of +5.5◦C was found in 2018.

The spatial distribution of NDVI showed that most of the western districts in Dhaka

such as Dhamari, Savar, Nawabgang and Dohar are vegetative compared to eastern districts

such as Tejgaon and Keraniganj. It further showed that during the years 2016 and 2017,

the non-vegetative area has increased in the eastern districts. The similar pattern was

observed from the NDBI too. The eastern districts are highly built-up in comparison with

the western. The NDBI values ranged from−0.10 in the year 2019 to +0.55 in the year 2018.

Negative values of NDBI showed a non-built-up region while the positive value reflected

the built-up area of the study area.

**LST**

**August 2016**

¸**NDVI NDBI**

**June 2017**

**LST**

**NDBI**

**NDVI**

< 10

10 - 15

15 - 20

20 - 25

25 - 30

30 - 35

> 35

0.4

-0.4

0.6

-0.2

**June 2019**

**June 2017**

Figure 6. LST, NDVI, NDBI estimated for Delhi using Landsat–8 satellite image for the year 2016, 2017 (top panel), and

**LST**

2019 (bottom panel). The dark blue section represents the missing overlapping of satellite images. The dark blue portion is

not considered in the analysis.¸**NDVI NDBI**Earth 2021, 2 99

**LST March 2014**

¸**NDVI NDBI**

**March 2015**

**March 2016**

**LST**

**March 2017**

< 10

10 - 15

15 - 20

20 - 25

25 - 30

30 - 35

> 35

**NDBI**

0.4

-0.4

**NDVI**

0.6

-0.2

Figure 7. LST, NDVI, NDBI estimated for Dhaka using Landsat–8 satellite image for March 2014, 2015 (top panel) and 2016,

2017 (bottom panel).Earth 2021, 2 100

**LST**

**NDVI NDBI**

**May 2018**

¸

**LST**

**March 2019**

**NDBI**

**NDVI**

< 10

10 - 15

15 - 20

20 - 25

25 - 30

30 - 35

> 35

0.4

-0.4

0.6

-0.2

Figure 8. LST, NDVI, NDBI estimated for Dhaka using Landsat–8 satellite image for 2018 and March 2019.

Table 6. Comparison of estimated LST with the observed air temperature and the difference between

the two at Dhaka.

SN Acquisition Date Estimated Observed Difference

1 30-March-2014 32.00 33.23−1.23

2 17-March-2015 30.00 26.12 3.88

3 3-March-2016 30.50 26.46 4.04

4 22-March-2017 28.50 23.64 4.86

5 12-May-2018 31.00 25.55 5.45

6 28-March-2019 32.00 26.87 5.13

3.2. Relationship between LST, NDVI and NDBI

The relationship between LST, NDVI and NDBI is necessary to understand the UHI

phenomenon in urban cities. Increase in the LST values is governed by the climatic (rainfall,

air temperature, humidity) and non-climatic (land use and land cover, aerosols, air particles

in the atmosphere, built-up area) variables. Spatial average values of LST, NDVI, and NDBI

were used to understand the relationship between them.

3.2.1. Kathmandu Valley

The relationship between LST and NDVI showed a mixed relation trend for KV.

The negative linear trend exists for temperature less than 25◦C and the parabolic relation-

ship for higher values with p-value = 0.08 (p-value > 0.05) and R2 = 0.05. The statistical

performance of p-value shows that there is no statistically significant relation between

mean LST and mean NDVI. The non-vegetative area increased with increment in the sur-

face temperature (Figure 9). This implies that likely the increase in non-vegetative areas isEarth 2021, 2 101

directly associated with the change in surface temperature and built-up area [26]. For the

surface temperature ranging from 22.5◦C to 30.0 ◦C, the NDVI increased. This indicates

an increase in greenness together with an increase in surface temperature. This variation

might be attributed to rainfall days before the measurement was taken.

Figure 9. Relationship between LST and NDVI at different administrative units of Kathmandu Valley

(KV) region in 2013–2019.

3.2.2. Delhi

The relationship between mean LST and mean NDVI was established for the study

period 2013–2019 as shown in Figure 10. The statistical performance of the relationship

among mean LST and mean NDVI shows a negative linear trend with R2 value of 0.79 and

p-value = 0.043 (p-value < 0.05). This shows a statistically significant relationship between

mean LST and mean NDVI. Since Delhi is often viewed as a single administrative unit, we

have used only 5 temporal data points to develop the relationship. The Figure 10 shows

the well-distributed relationship between mean LST and NDVI (R2 = 0.79). The increase

in mean LST was concomitant in the decrease in vegetative area for Delhi. Thus with

the increase in the surface temperature, the number of UHI regions are likely to increase.

This situation might exacerbate the risk of heat-stroke in Delhi.

Figure 10. Relationship between LST and NDVI at Delhi in 2013–2019.

3.2.3. Dhaka

Relationships between mean LST and mean NDVI were studied for Dhaka district

and found that NDVI value increased slightly with the increase in LST. The statistical

result shows very low correlation exists between mean LST and mean NDVI (R2 ∼0).

The p-value is equal to 0.75 (p > 0.05) is not statistically significant and cannot provideEarth 2021, 2 102

enough evidence for rejecting the null hypothesis of similarity. During data acquisition

day in 2014–2019, most of the administrative units had mean LST ranging from 24.0◦C to

28.0 ◦C with the variation of NDVI ranging from 0.0 to 0.35 (Figure 11).

Figure 11. Relationship between LST and NDVI at different administrative units of Dhaka during

data acquisition day in the year 2014–2019.

3.3. UHI for the Study Area

UHI was calculated based on mean and standard deviation (SD) of LST. Green color

shows the non-UHIs while red color shows the UHI regions for each of the study areas.

The threshold value of UHI ranged from 21.6◦C to 24.2 ◦C for KV, from 26.2◦C to 41.3 ◦C

for Delhi and from 24.6 ◦C to 34.9 ◦C for Dhaka (Figures 12–14 respectively). The variation

in the UHIs was governed by the LST each land cover type had in the study area. Further,

the availability of green space (as seen from NDVI) and clustering of the built-up area (as

seen from NDBI) have a significant impact on the UHI for each study area.

3.3.1. Kathmandu Valley

The spatial and temporal distribution of UHI for the KV was developed for each

year using the surface temperature for the same month (Figure 12). Distribution of UHI

showed that for all the years, central KV experienced higher temperature and thus may

be considered as heat islands which were further supported by LST, NDVI and NDBI in

earlier sections. Compared to southern regions, the Northern region is highly populated

(as can be seen from NDBI maps) and thus these regions experienced higher temperatures.

On 26 March 2013, the central and Northern region experienced temperatures higher than

28.3 ◦C. The boundary administrative such as Budhanilkantha, Gorkarneshwor, Changu-

narayan, Godavari, Chandragiri, etc. had comparatively lesser UHI effects throughout the

study period. The result of UHI analysis also show an increasing trend in UHI especially in

the peri-urban areas. Spatial analysis revealed that the UHI zones were more concentrated

in the central and northern regions of the KV. UHI at the different administrative units of

KV reflected the increasing trend of UHI zones which might be the impact of increasing

population and intensified urbanization. Developing the new greener space might help in

reducing the impact of increasing UHI in the densely populated urban cities like KV [52].Earth 2021, 2 103

¹

**March 2013**

< 23.0

23.0 - 39.9

**March 2014**

< 22.4

22.4 - 39.9

**March 2016**

< 21.6

21.6 - 39.9

**March 2017**

< 23.0

23.0 - 39.9

**March 2019**

< 24.2

24.2 - 39.9

Tarakeshwor

Budhanilakantha

Tokha

Gokarneshwor

Nagarjun

Shankharapur

Kageshwori Manahora

Kathmandu

Chandragiri

Changunarayan

Madhyapur Thimi

Kirtipur

Lalitpur

Bhaktapur

Suryabinayak

Mahalaxmi

Dakshinkali

Godawari

Konjyosom

0 10 20 30

Km

Metropolitan City

**Adminstrative type**

Municipality

Rural Municipality

Figure 12. Monthly Urban Heat Island (UHI) estimated for different administrative units of KV in◦C during March

2013–2019. Green color shows the non-UHI zones and red color shows the UHI zones.

3.3.2. Delhi

Figure 13 showed the spatio-temporal distribution of UHI for Delhi. The minimum

threshold of UHI for Delhi was found to be 26.2 ◦C in the year 2016 on the data acquisition

date. The maximum threshold of UHI was estimated to be 41.3 ◦C for the year 2019.

With the higher values of mean LST and the least value of SD, most of the areas in Delhi

are estimated to behave non-UHI. Since the UHI threshold is less and the temperature

range is small, more UHI areas were observed in Delhi in 2016 compared to other high

UHI threshold years. This point to a limitation of UHI threshold for cities like Delhi.

Residential or mixed regions have a higher potential risk of UHI in Delhi as portrayed

by Mohan et al. [53]. Researchers [53] further stressed that UHI in summer is expected to

increase and become more dominant in the densely urbanized built-up areas.

3.3.3. Dhaka

The minimum and maximum threshold of UHI for Dhaka were found to be 24.6 ◦C

and 34.9 ◦C respectively (Figure 14). The result showed that western districts such as Dohar,

Nawabganj, Dhamrai behave as non-UHI while the eastern districts such as Tejgaon, Savar,

and Kernaiganj behave as UHI zones. The North-West region of Dhaka was less impacted

by the rising surface temperature and is thus identified as non-UHI regions throughout

the temporal study period. Eastern parts of Tejgaon and Keraniganj were identified as

UHI regions for each year is associated with a higher density of impervious structures

such as concrete buildings and paved roads in the region. The potential impact of UHI

is increased by the rising surface temperature in the Dhaka city from 28.5◦C in 2002 to

40.1 ◦C in 2014 [54].Earth 2021, 2 104

¹

**June 2013**

< 34.6

34.6 - 42.9

**July 2014**

< 34.9

34.9 - 39.1

**August 2016**

< 26.2

26.2 - 31.0

**Delhi**

**June 2017**

< 30.4

30.4 - 35.3

**June 2019**

< 41.3

41.3 - 47.7

0 20 40 60

Km

Figure 13. Monthly UHI estimated for Delhi in◦C during June, July and August 2013–2019. Green color shows the non-UHI

zones and red color shows the UHI zones.

¹

**March 2014**

< 34.9

35 - 36.3

**March 2015**

< 27.3

27.4 - 36.3

**March 2016**

< 27.2

27.3 - 36.3

**Dhamrai**

**Savar**

**Tejgaon**

**Keraniganj**

**Nawabganj**

**Dohar**

**March 2017**

< 24.6

24.7 - 36.3

**March 2019**

< 27.9

28 - 36.3

0 20 40 60

Km

Figure 14. UHI estimated at different administrative units of Dhaka district in ◦C unit for the period March 2014–2019.

Green color shows the non-UHI zones and red color shows the UHI zones.Earth 2021, 2 105

4. Discussions

Satellite imageries provide an appropriate platform to evaluate LST and UHI at any

spatial and temporal scale. The primary objective of the study is to evaluate the UHIs

in densely populated cities of South Asia namely, Kathmandu, Delhi, and Dhaka using

satellite imageries. Also, we examined the LST, NDVI, and NDBI for the same to observe

the state of surface temperature, wetness, and dryness of the land and Built-up intensity

for the temporal period of 2013–2019.

4.1. Relationship between LST, NDVI and NDBI

Visual analysis of the LST showed that June 2015 was the most hottest month during

the temporal study period in KV. In 2014 and 2016, the month of March was found to have

less warm days in the high elevated regions where the LST is <10◦C (Figures 3 and 4).

In the case of Delhi, high LST was observed in 2019 followed by 2013 and 2014. Simi-

lar trends of the LST variation were observed in Dhaka. NDVI values for KV and Dhaka

were found to increase at the rate of 0.007 and 0.004 respectively while a negative trend

was observed in Delhi (Figure 15). The negative trend in Delhi might be the result of the

presence of a relatively higher amount of the open spaces as compared to KV and Dhaka.

The results depict an increasing trend of NDBI values for Delhi; almost no trend for Dhaka

and decreasing trend for KV (Figure 15). The spatio-temporal variation in the NDVI and

NDBI values might be the consequences of the local climatic conditions [55] of the study

area. The spatio-temporal variation over the different topographical regions has been well

established in the study domains. Climates of the study area have an important role in

governing LST, NDVI, NDBI, and UHI as computed in this study. The large orographic

differences over a short latitude change could be responsible for lesser LST and higher

NDVI values in the KV [45,56,57]. The differences in spatio-temporal LST retrieval in the

study domain might have been affected by the biophysical effects, evapotranspiration,

and albedo that are eventually influenced by precipitation and local climate [58]. Densely

populated zones in the study areas are found to have higher LST values compared to

surrounding areas. The higher values of LST in the central zone of the study area is likely

due to the densely built-up area and paved roads [26,59]. Pan et al. [60] found that

the LST values at built-up areas are higher than 40◦C in the humid subtropical climate.

The variation in LST was also attenuated by the change in elevation. Increase in the LST

values was also concomitant with increased population in all the cities of South Asia [61].

Kathmandu Valley

Delhi

Dhaka

NDBI, NDVI

0.4

0.3

0.2

0.1

0.0

-0.1

-0.2

y = 0.007x + 0.069

y = 0.004x + 0.1264

y = -0.0068x + 0.3994

NDVI

NDBI

y = 0.0071x - 0.2899

y = -0.0023x - 0.0062

y = 0.0008x - 0.1472

18 20 22 24 26 28 30 32 34

24 26 28 30 32 34 36 38 40 42

22 24 26 28 30 32 34 36

LST oC

Figure 15. Linear trend analysis among LST, NDVI and NDBI retrieval at the study area (KV, Delhi and Dhaka) for the

temporal study period of 2013–2019.

4.2. Quantification of UHI from Retrieved LST

UHI values retrieved for the study areas showed the increment in UHI zones with

the passage of time. In KV, the lower UHI values ranged from 21.6◦C in 2016 to 24.2 ◦C

in 2019 while the maximum reached 40 ◦C. The lower UHI values for Delhi varied fromEarth 2021, 2 106

26.2 ◦C in 2016 to 41.3 ◦C in 2019. Similarly, the lower UHI values for Dhaka varied

from 24.6 ◦C in 2017 to 34.9 ◦C in 2014. The business centers attributed by economic

conditions [62] and increased population [63] in each study area were found to have higher

UHI values compared to surrounding areas. The increased built-up areas and the paved

roads might be the driving factors that alter the spatio-temporal alteration of UHI zones.

Further, the reduced open spaces (green areas) and current development works such as

the construction of roads, buildings might have aggravated the increase in the UHI zones.

Growth and development activities increases the impervious surfaces, resulting in reduced

evapotranspiration and lesser soil moisture [64], which ultimately have a direct impact

on the LST of the urban areas. The spatio-temporal variation in UHI values across the

study area has been impacted by increased NDBI index [34]. UHI magnitudes increased

across the regions with increased NDBI and decreased NDVI. El Niño might also have

contributed to the wider variability of UHI effects in the study regions [65].

4.3. Impact of UHIs and Mitigation Strategies to Minimize Rising Surface Temperature

The UHIs has diverse impacts on different elements of the society such as energy

consumption, human health, biodiversity, agriculture, water availability and others [66].

With the increase in the urban population (Table 2) and urbanization, the intensity and

frequency of the heatwaves have increased. Further, an increase in the frequency and

magnitude of hotter days attributed by the rise in LST and UHI zones have a direct impact

on the energy consumption. The urban population tends to consume more electricity to

make themselves more comfortable against the increasing heat. In recent years, the trend

of electricity consumption in SA region is increasing [67,68]. The increase in electricity

consumption might be the cumulative impact of the increasing population, rising urban-

ization, growing wealth, and climate extremities. Further, the increased climate extremes

(such as heat strokes, UHI, increased LST) has also impacted the health of the people in SA.

The comfort level induced by the climatic extremes in the health of the residents of any city

is measured in terms of discomfort index (DI) and physiological equivalent temperature

(PET) index. The previous research in SA and West Bengal (India) showed that the area with

shades due to high rise buildings and trees have comfortable conditions compared to the

one with no shades [66,69]. The increase in surface temperature has increased the number

of heat strokes in urban cities of SA [70]. The number of patients suffering from heat stroke

was found to be comparatively higher in the urban centers than in the peri-urban areas of

SA. This supports the idea that increasing UHI and LST has increased the risk of heatwave

globally and regionally [71,72]. The increased surface temperature has a significant impact

on diarrheal disease and heat stress in Bangladesh [73]. The policy makers and planners of

each study region now need to focus on the proper mitigation and adaptation strategies to

cope against the rising LST and increasing UHIs. This study shows that more planning and

perhaps enforcement are required to reduce the impact of the rising surface temperature.

Increase in the green land area and afforestation activities can reduce the impact of excess

heating from the solar radiation. This also enhances the asthetics of the city. Few mitigation

strategies have been considered by the local government in Kathmandu valley such as

cleaning of the Bagmati river corridor and increasing the number of new recreational parks.

In India, Niti Aayog has proposed to ban the diesel vehicle and sell the electric vehicle

by 2030 to reduce the air pollution. Such major mitigation measures are necessary for

reduction of UHI too for the region to be better prepared for climate extremities.

4.4. Limitations of the Research

The current study has limitations in the spatial and temporal domains. Temporally,

we only focused on the summer days to assess the summer surface temperature and

subsequent heat island. Spatially we focused on the highly urbanized and rapidly rising

cities at SA. The study focused on three major cities, however several smaller cities in SA

may face similar problems. A coordinated effort is needed to understand the regional LSTEarth 2021, 2 107

and UHI in detail. Also, understanding of antecedent conditions coupled with on ground

sensing may be beneficial for future work.

5. Conclusions

This study evaluated the UHI using the Landsat-8 satellite images in three densely

populated cities of South Asia namely, Kathmandu Valley, Delhi, and Dhaka. These are

the growing cities in terms of economic development, urbanization and population rise.

The spatial and temporal variations of LST, NDVI, NDBI, and UHI were analyzed in these

three cities to assess the impact of urbanization on the surface temperatures. An increase in

the impervious areas, such as concrete buildings and paved roads reduces the recharge

capacity of the soils thereby reducing the soil moisture. This leads to an increase in barren

and non-vegetative lands in these urban cities. The analysis of LST and UHI in these

urban cities demonstrate the importance of urban planning to mitigate the effects of future

climate. The analysis was focused from 2013–2019 when the cloud cover is less than 10%.

The following conclusions are drawn from the research:

1. Results of LST showed the surface temperature is more in the Kathmandu and

Lalitpur Metropolitan City while the regions that are situated at the boundaries

of KV experienced LST less than 10◦C, below that of KV. Similarly, for Delhi higher

LST is observed in the western region of Delhi and the eastern region of Dhaka. It can

be inferred that the zones which are densely populated experience higher LST.

2. Like LST, NDVI of the study area shows more vegetative regions in peri-urban areas

and less in the central KV. NDVI result of Delhi shows a lesser vegetative area than

the non-vegetative area. In the case of Dhaka, the eastern district (Tejgaon) has less

vegetative area compared to the western region.

3. NDBI shows the concentration of built-up areas in most regions of the KV (NDBI > 0).

Regions with NDBI < 0 are concentrated in the peripheries of KV. Similarly, NDBI re-

sult exhibits that the built-up area is concentrated in the western region for Delhi and

the eastern region for Dhaka.

4. The results of this study imply that the spatial distribution of LST magnitude and

UHI zones are greater in Delhi and Dhaka compared to KV. However, the core center

of the KV has a higher rate of LST magnitude and UHI effects are increasing faster

annually.

5. The results of the research provide insights into urban microclimates and changes in

the environment that may be used for drafting the city planning legislation to mitigate

the rising LST.

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Abbreviations

The following abbreviations are used in this manuscript:

KV Kathmandu Valley

LST Land Surface Temperature

LULC Land-use and land cover

NDVI Normalized Difference Vegetation Index

NDBI Normalized Difference Built-up Index

OLI Operational Land Imager

SA South Asian

SD Standard Deviation

SUHI Surface Urban Heat Island

TIRS Thermal Infrared Sensor

TOA Top Of Atmosphere

UHI Urban Heat Island

USGS United States Geological Survey

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ORIGINAL ARTICLE

Analysis of Urban Heat Island and Heat Waves Using Sentinel‑3

Images: a Study of Andalusian Cities in Spain

David Hidalgo García1

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Abstract

At present, understanding the synergies between the Surface Urban Heat Island (SUHI) phenomenon and extreme climatic

events entailing high mortality, i.e., heat waves, is a great challenge that must be faced to improve the quality of life in urban

zones. The implementation of new mitigation and resilience measures in cities would serve to lessen the effects of heat waves

and the economic cost they entail. In this research, the Land Surface Temperature (LST) and the SUHI were determined

through Sentinel-3A and 3B images of the eight capitals of Andalusia (southern Spain) during the months of July and August

of years 2019 and 2020. The objective was to determine possible synergies or interaction between the LST and SUHI, as

well as between SUHI and heat waves, in a region classified as highly vulnerable to the effects of climate change. For each

Andalusian city, the atmospheric variables of ambient temperature, solar radiation, wind speed and direction were obtained

from stations of the Spanish State Meteorological Agency (AEMET); the data were quantified and classified both in periods

of normal environmental conditions and during heat waves. By means of Data Panel statistical analysis, the multivariate

relationships were derived, determining which ones statistically influence the SUHI during heat wave periods. The results

indicate that the LST and the mean SUHI obtained are statistically interacted and intensify under heat wave conditions. The

greatest increases in daytime temperatures were seen for Sentinel-3A in cities by the coast (LST

=

3.90 °C, SUHI

=

1.44 °C)

and for Sentinel-3B in cities located inland (LST

=

2.85 °C, SUHI

=

0.52 °C). The existence of statistically significant posi-

tive relationships above 99% (p < 0.000) between the SUHI and solar radiation, and between the SUHI and the direction of

the wind, intensified in periods of heat wave, could be verified. An increase in the urban area affected by the SUHI under

heat wave conditions is reported.

\* David Hidalgo García

dhidalgo@ugr.es

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Technical Superior School of Building Engineering,

University of Granada, Fuentenueva Campus,

18071 Granada, Spain

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Graphical Abstract

Keywords Surface Urban Heat Island · Heat waves · Sentinel-3 imagery · Land surface temperature · Heat Resilience and

Urban Resilience

1 Introduction

In recent decades, numerous studies warn that the transfor-

mation of the landscape owing to the expansion of urban

areas is one of the processes that contributes most to climate

change (Li et al. 2011; Carvalho et al. 2017; Jiang et al.

2019; Yang et al. 2019; Song et al. 2020). Changes in land

cover increase the surfaces of impermeable materials, such

as asphalt and concrete, reducing evapotranspiration (Stew-

art and Oke 2012). These materials are known to store the

heat coming from solar radiation and subsequently release

it into the atmosphere (Arnfield 2003; Zhou et al. 2015; An

et al. 2020).

The greatest increases in temperature occur in cities,

mainly due to a phenomenon of urban climate altera-

tion (Li et al. 2011; Zhou et al. 2015; Wang et al. 2016;

Luo and Lau 2018; Zhao et al. 2018; Tewari et al. 2019;

Anjos et al. 2020) called Urban Heat Island (UHI), whose

intensity is heightened by multiple human activities (Lai

et al. 2018; Huang et al. 2020; Santamouris 2020) and by

extreme weather events such as droughts or heat waves.

The positive interaction between UHI and heat waves is

well documented: in Baltimore and Maryland (Li and

Bou-Zeid 2013), Beijing (Li et al. 2015; Jiang et al. 2019),

New York (Ramamurthy and Bou-Zeid 2017), Shanghai

and Guangzhou (Jiang et al. 2019) and Athens (Founda

and Santamouris 2017).

Research shows that heat waves are becoming more

intense, lasting longer, and occurring more frequently

(Meehl and Tebaldi 2004; Sun et al. 2014). It is anticipated

that by the end of the twenty-first century they will affect

larger land areas (Meehl and Tebaldi 2004; Lau and Nath

2012; Coumou et al. 2013). Episodes of increased anthro-

pogenic heat are known to be among the natural phenom-

ena having the greatest social, economic and environmen-

tal impact (An et al. 2020). They imply more consumption

of electricity and water in homes (Valor et al. 2001), and

increased morbidity and mortality (Semenza et al. 1996;

Poumadère et al. 2005; Jiang et al. 2019; An et al. 2020).

Proof can be found in the heat wave of Chicago in 1995,

which caused 800 deaths (Semenza et al. 1996), that of

the summer of 2003 in Europe, when 70,000 people died

(Robine et al. 2008), the one occurring in Russia dur-

ing the summer of 2010 (Grumm 2011), that of eastern

China in 2013 (Xia et al. 2016), or Northwestern USA and

Western Canada (Lytton) in 2021, with temperatures over

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45.0 °C on consecutive days and extremely warm nights in

between, causing some 500 deaths (UNO 2021).

While a positive interaction between SUHI and heat

waves has been demonstrated, the type of climate or particu-

lar climatic conditions (wind speed and direction, solar radi-

ation) and geomorphological factors of cities are contribute

substantially to this interaction (Zhao et al. 2014; Yoon et al.

2018; Jiang et al. 2019; An et al. 2020; Qiu et al. 2020; Ven-

ter et al. 2020). Studies of cities in Oklahoma (Basara et al.

2010), several European cities (Founda et al. 2015), London

(Gregor et al. 2007) or Beijing and Guangzhou (Jiang et al.

2019) report increases in SUHI that are stronger during the

night. In contrast, studies of Athens and Parma (House and

Santamouris 2011) and Shanghai (Ao et al. 2019; Jiang et al.

2019) found that the SUHI rise was stronger during the day.

Other studies found no significant amplification of the SUHI

(Ramamurthy and Bou-Zeid 2017; Scott et al. 2018; Zhao

et al. 2018).

Among the different methodologies used to determine

this phenomenon, thermal remote sensing stands out because

of its capacity to allow large-scale urban studies of LST

and SUHI using satellite images with Thermal Infrared

Sensor (TIRS) sensors. Studies involving these systems and

the dynamics of urban climate have become consolidated

as an important field of research (Ramamurthy and Bou-

Zeid 2017) with an extensive body of literature (Wang and

Ouyang 2017; Song et al. 2018; Yao et al. 2018; Sejati et al.

2019; Guo et al. 2020; Hu et al. 2020; Roy et al. 2020; Shafi-

zadeh et al. 2020; Yang et al. 2020a). A relatively recent but

highly accurate product used in many studies is Sentinel-3

imaging. All Sentinels have 3 TIRS channels—bands 7, 8

and 9—that provide LST estimates at a resolution of 1000 m.

Their use for this type of research lends an important advan-

tage over satellites such as Landsat or NOAA, since they

orbit twice a day over the same point on the planet—once

during the day and again at night. The use of Sentinel-3

is widely documented in the literature, e.g., through SUHI

studies of the cities of Daman (India) and Huazhaizi (China)

(Yang et al. 2020b), Oklahoma City (USA) and Dahra (Sen-

egal) (Sobrino et al. 2016).

The space–time variability of the SUHI in cities under

Heat Wave conditions is largely unknown, and very few

studies have focused on cities in the Mediterranean Basin.

Recent estimates are that the mean air temperature will be

1–3 °C higher in the near future (compared to 1961–1990),

3–5 °C higher by the middle of the century (2040–2069)

and approximately 3.5–7 °C higher by the end of the century

(2070–2100) (Founda et al. 2015; Founda and Santamouris

2017); values for the Mediterranean Sea basin may be even

higher (Ward et al. 2016; Cramer et al. 2018).

The fact that temperature in the Mediterranean region is

increasing at a faster rate than elsewhere in the world leads it

to be considered an area of high vulnerability due to climate

change. Such potentially dire circumstances, together with

the variability of the data, accentuate the need for detailed

research efforts. In this case, a quantitative and systematic

study of the existence of synergies between SUHI and heat

waves in the cities of Andalusia (Spain) was undertaken.

This adverse meteorological phenomenon is a problem

that tends to affect urban populations in particular. The syn-

ergies between SUHI and heat waves may be questioned,

however, owing to disparate results reported to date, and

insufficient knowledge about the factors affecting their

intensity, properties, and activation flow. Such information

is crucial for the establishment of adequate mitigation or

resilience measures for urban planning in attempts to limit

the effects and economic cost of heat waves (Emmanuel and

Krüger 2012). This research aims to analyze the relationship

between heat wave and three outstanding factors: solar radia-

tion, wind speed and direction.

Our study was intended to characterize and quantify the

variability of the LST and the day and night SUHIs of all

eight Andalusian (southern Spain) capital cities using Sen-

tinel-3 images, throughout the months of July and August of

2019 and 2020, when five heat waves occurred. The factors

involved were statistically analyzed using the Data Panel

method. The methodology entailed an open source envi-

ronment allowing one to monitor SUHI the variations in

a precise, urgent and economic way, providing for a more

comprehensive understanding of the space–time variability

of the SUHI during Heat Wave periods, and of underlying

factors.

2 Materials and Methods

2.1 Study Area and Data Source

The area under study comprises the eight provincial capi-

tals of the region of Andalusia, located in southern Spain

(Fig. 1).

Four of them are inland cities: Sevilla, Cordoba, Granada

and Jaen. The other four are coastal cities: Huelva, Cadiz,

Málaga and Almería. Characteristics of the population, sur-

face area, climate, rainfall, altitude and UTM coordinates

are found in Table 1.

According to Spain´s National Institute of Statistics

(INE), Andalusia covers an area of 87,268 ­ km2 and has a

population of 8,427,325, being the second largest region

and the most populated one in all of Spain. The region

shows different local background climates. According

to the Koppen-Geiger climate classification, the cities

of Cadiz and Huelva share a Mediterranean Oceanic cli-

mate (Csb), the cities of Sevilla, Malaga, Cordoba and

Jaen feature a Mediterranean climate (Csa), and Granada

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Fig. 1 Study area, Andalusia, Spain

Table 1 Characteristics of inland cities of Andalusia

Geographic informa-

tion

Inland cities Coastal cities

Sevilla Cordoba Jaen Granada Huelva Cadiz Malaga Almeria

Downtown location

37.375 N, −

UTM

6.025 W

37.891 N,

− 4.819 W

37.780 N, −

3.831 W

37.111 N, − 3.362 W 37.270 N, −

6.974 W

36.516 N, −

6.317 W

36.765 N, −

4.564 W

36.841 N, −

2.492 W

Climate Zone Csa Csa Csa Csa—Bsk Csb Csb Csa Bsk

Mean annual T. (°C) 18.6 17.8 16.9 15.5 17.8 17.9 18.4 17.9

576 612 552 450 467 597 520 228

Average annual rain-

fall (mm)

Total area ­ (km2) 140.8 1253 424 88.8 151.3 13.3 398 296.2

Total urban area ­ (km2) 68.69 31.35 9.43 21.78 14.87 7.34 58.6 14.95

Population in 2019

688,592 325,701 112,999 232,462 143,663 116,027 574,654 198,533

(hab)

Urban mean elevation

11 106 570 680 24 13 8 16

(masl)

Climate Zones: Csa Mediterranean Climate, Csb Mediterranean Oceanic Climate, Bsk Cold Semi-Arid Climate

and Almería have a cold semi-arid climate (Bsk). Such

typologies imply mild, humid winters and hot, dry sum-

mers (De Castro et al. 2007). The region is bordered by

mountains to the north, while the Mediterranean Sea lies

to the south. This circumstance makes the sea and land

breezes strongly impact coastal cities. The average altitude

is 503 m above sea level; the annual average temperature

fluctuates between 11 °C in January and 26.5 °C in July,

with minima in winter of − 3 °C and extremes in summer

of 44 °C. The approximate number of hours of sunshine

per year ranges between 2800 and 3200, giving an average

between 7.67 and 8.76 h of sunshine per day, depending

on the area within the Andalusian region.

2.2 Methodology

The methodology carried out in this research called for

obtaining the LST using Sentinel-3 images and validating

them by comparison with the ambient temperatures recorded

by AEMET (Srivastava et al. 2009; Gallo et al. 2011; Li et al.

2013; Avdan and Jovanovska 2016; Rongali et al. 2018). They

were classified in periods of normal environmental conditions

and in periods under heat wave. Next, the LST and SUHI

values were obtained for statistical analysis, as seen in Fig. 2.

The Data Panel statistical method was used for data

analysis. Unlike more traditional methods of analysis, it

admits a greater number of data, including the individual

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Fig. 2 Methodology of our

research

effects of each city in the overall result, while eliminat-

ing the problem of collinearity between variables. Using

this method allowed us to reflect possible variations in the

conditions of each city contemplated in the final results,

which makes it a unique and powerful approach. It has

been validated by studies (Chen et al. 2011; Alcock et al.

2015; Fang and Tian 2020) similar to ours, accounting for

time series of multiple cities or areas, as well as quantita-

tive variables when the conditions may vary among the

cities analyzed.

2.3 Identification of Heat Waves

According to the AEMET, during 2019 three episodes clas-

sified as heat waves in Andalusia, and in 2020 just two.

Table 2 indicates their onset, end date and duration, along

with the thermal anomaly they produced in room temper-

ature and the maximum temperature reached. Although

numerous studies cite decreased environmental pollution,

LST and SUHI as a consequence of the lockdown situa-

tion caused by COVID-19 (Ali et al. 2021; Das et al. 2021;

Table 2 Characteristics of the

heat waves studied in Andalusia

Heat waves 2019 2020

1st 2nd 3rd 4th 5th

Start date 26/06/2019 20/07/2019 06/08/2019 30/07/2020 05/08/2020

End date 01/07/2019 25/07/2019 10/08/2019 01/08/2020 08/08/2020

Duration (days) 6 6 5 3 4

Air thermal anomaly (C) 4 2 3.3 4 5

Maximum air temperature

38.8 36.8 37.9 38.5 39.4

reached (C)

Source: State Meteorological Agency (AEMET)

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Ghosh et al. 2020; Jiang et al. 2021; Mandal and Pal 2020;

Nakajima et al. 2021; Pani et al. 2020; Srivastava et al. 2021;

Toro et al. 2021), no scientific evidence stands to indicate a

decrease in heat waves due to or during this situation.

To facilitate comparison of the LST and SUHI of peri-

ods under heat wave conditions with periods of “normal”

environmental conditions, the 2 days before and after each

heat wave period were taken into account. In total, the envi-

ronmental parameters of the eight cities were studied for

20 days under normal conditions and 24 days under heat

wave conditions.

2.4 Sentinel‑3 Images. Land Surface Temperature

Estimation

Sentinel-3 satellites are equipped with the high-resolution

scanning instrument LST Radiometer, enabling LSTs of the

Earth's surface to be obtained. Its thermal products have

three levels of processing (levels 0, 1 and 2), although only

the last two are available for download. Those of level 1

present radiance and brightness temperatures that require

split window (SW) algorithms to obtain the LST. Level 2

products directly and automatically include the LST together

with associated parameters such as the Normalized Vegeta-

tion Index (NDVI), Vegetation Type (Biome), Vegetable

Fraction (Pv) and Normalized Difference Index (NDBI).

The existing SW algorithms that serve to gauge LST are

based on the concept of differential absorption (McMillin

1975), whereby the difference between the two TIRS band

wavelengths allows for correction of the atmospheric effects

produced on the signal. Abundant studies report on the vali-

dation, use and precision of these algorithms in Sentinel-3

images (Coppo et al. 2010; Wan 2013; Ruescas et al. 2016;

Sobrino et al. 2016; Prikaziuk and van der Tol 2019; Chiang

and Ivan 2020; Yang et al. 2020b).

The SW algorithm of the official Sentinel-3A and 3B

level 2 SLSTR product implicitly incorporates soil emis-

sivity by means of the following equation (Remedios and

Emsley 2012):

1

*LST*= *af*,*i*,*pw* + *bf*,*i*(*T*11− *T*12)

cos(𝜃

*m* ) + (*bf*,*i* + *cf*,*i*)*T*12− 273.15,

(1)

where LST is the surface temperature in degrees C; a, b and

c are coefficients dependent on the vegetation cover and the

biome; and ­ T11 and ­ T12 are the brightness temperatures of

bands 8 and 9 of Sentinel-3, respectively. θ is the zenith

angle of view of the satellite and m is a dependent variable

of θ (Remedios and Emsley 2012; Yang et al. 2020a).

Andalusia lies below the route of the Sentinel-3A and

3B satellites. The usual daytime hours of passage over the

region are between 9:00 and 11:00 a.m.; nighttime passage

is between 20:00 and 22:00 h (8:00–10:00 p.m.). The images

1 3 chosen for the study correspond to 44 days in the months of

July and August of 2019 and 2020. Throughout this time

interval, a total of 88 images were used, 44 corresponding

to Sentinel-3A (day) and 44 corresponding to Sentinel-3B

(night). All of them have a cloudiness index of less than 15%

to ensure accuracy in obtaining the LST and subsequently

calculate the SUHI. The images used were acquired through

the European Space Agency (ESA) Copernicus Open Access

Hub for level 2.

After downloading the images, they were reclassified and

corrected using the Toolbox (S3TBX) under the Sentinel

Application Platform (SNAP) open-source software environ-

ment, version 7.0.0. With the help of SNAP 7.0.0 and using

level 2 products, the day and night LST of each investigated

day were recovered for each city. The LST images were sub-

sequently exported in Geotiff format to QGIS open-source

software, version 3.10.5.

2.5 Rural Stations and Meteorological Data

The ambient temperature was obtained from AEMET. This

national weather agency has multiple rural observation sta-

tions in Andalusia that hourly collect the environmental

parameters of the site where they are located. The ambient

temperature was needed to subsequently validate the satel-

lite data, as indicated in the methodology section. So as to

minimize the impact of the rural environment on calcula-

tion of the SUHI with Sentinel-3 images, the ones located

in rural areas—surrounded by farmland and with few

impervious surfaces—were selected for each city studied.

This selection criterion has given statistically significant

impacts in similar investigations (Wang et al. 2017; Jiang

et al. 2019).

The rural stations of reference were selected taking

into account the following considerations (Wang et al.

2017): (1) The % of impervious surfaces around the sta-

tion is roughly 10% and the proportion of farmland must

be greater than 65%; (2) the difference in surface eleva-

tion between the station and the city would be approxi-

mately 30 m; (3) rural stations had to be outside the

main urban areas; (4) An approximate area of 1000 ×

1000 ­ m2 of equal coverage should surround the station.

Given these prerequisites, a rural meteorological station

was chosen for each city, its characteristics and location

shown in Table 3.

Heat waves in Spain are often associated with strong

anticyclonic conditions and large-scale subsidence with

warm advection from North Africa in the lower atmosphere

(Xoplaki et al. 2003). For the days and hours selected in this

research, and from each rural meteorological station, the

following data were obtained: ambient temperature, solar

radiation, wind speed and direction.

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Table 3 Characteristics of rural meteorological stations in inland cities

Geographic

information

Inland cities Coastal cities

Sevilla Cordoba Jaen Granada Huelva Cadiz Malaga Almeria

Name of

the rural

temperature

station

Sevilla Air-

port

Distance from

the station

to the city

center (Km)

Impervious

surface

nearby (%)

Altitude

(masl)

UTM 37.250 N, −

5.524 W

Cordoba

Airport

Jaen City Granada

Airport

Huelva City Rota Naval

base

Malaga Air-

port

Almeria

Airport

8.2 10.8 3 16 4 8.5 7 12

16 12 15 10 23 20 15 3

34 90 580 567 19 2 5 21

37.505 N, −

4.504 W

37.463 N, −

3.483 W

37.112 N, −

3.472 W

37.164 N, −

6.544 W

36.300 N, −

6.195 W

36.395 N, −

4.285 W

36.50 N, −

2.212 W

Source: State Meteorological Agency (AEMET)

Previous research (van Hove et al. 2015; Gaur et al. 2018;

Jiang et al. 2019) indicates that solar radiation and wind

speed and direction are elements that condition the inten-

sity of SUHI in cities. The high pressures associated with

heat waves decrease wind speed and cloud cover, which

causes the earth's surface to receive more solar radiation.

An increase in solar radiation produced by high pressure

and low cloud cover increases environmental temperatures.

Such circumstances reduce cooling and amplify the SUHI

phenomenon (Oke 1987; Ackerman and Knox 2012; Li and

Bou-Zeid 2013). Accordingly, certain studies (De Boeck

et al. 2010; Wang et al. 2017; Jiang et al. 2019) report that

during heat wave periods, solar radiation may be 2.5 times

higher than under normal conditions, a fact related to SUHI

amplification in many cities.

2.6 Surface Urban Heat Island estimation

In the literature, UHI and SUHI are defined in terms of dif-

ferent temperatures measured within an urban area and in

rural areas surrounding the city, taken at the same time (Oke

1987). UHI refers to ambient temperatures and SUHI to ter-

restrial surface temperatures. Therefore, the SUHI can be

determined according to Eq. 2:

SUHI= LSTurban− LSTrural.

(2)

Having exported the LST images of Sentinel day and

night to QGIS software, version 3.10.5, and with the help

of the raster calculator command, the SUHI of the city was

determined by means of Eq. 2.

2.7 Analytical Strategy

Introducing the Data Panel method of statistical analysis in

the model entailed two phases (Chen et al. 2011). Firstly,

by means of the Hausman proof, the effects of analysis

were determined to be either fixed or random. Then the

model was assessed in view of the results obtained in

Wooldridge and Wald Tests. There are three options for

calculation: Method of Ordinary Squares (MOS), General-

ized Least Squares (GLS) and the Method of Intragroup

Estimators (MIE) (Labra 2014).

The first of the three, while widely used for years, does

not enable the effects of every individual to be analyzed

over the course of time, which can give rise to biased

estimators.

The second is considered to be a more efficient exten-

sion of the first. It is assumed that individual effects are

not reflected in the explanatory variables of the model;

instead, they contribute to the error term, following the

expression:

Yit = 𝛽Xit + (𝛼i + 𝜇it),

(3)

where 𝛼i represents the individual effects, 𝜇it is the error of

the model, X would represent explanatory variables, i

=

indi-

vidual and t

=

time.

The third method cited above assumes that individual

effects are in line with the explanatory variables, so that

the individual effect is separated after error, under the fol-

lowing calculation:

Yit = 𝛼i + 𝛽Xit + 𝜇it,

(4)

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where, again, 𝛼i are the individual effects, 𝜇it is the error of

the model, X are explanatory variables, i

=

individual and

t

=

time.

3 Results

3.1 Land Surface Temperature by Sentinel day

and night versus Rural Weather Stations

Overall, the Sentinel day and night products present higher

mean values than those obtained from the AEMET rural

meteorological stations for the study periods in 2019 and

2020. The two temperatures are different but correlated,

meaning they will serve later to validate the LST data

obtained by satellite. Specifically, in the morning the high-

est mean LST values are obtained using the official product

Sentinel day (39.46 °C), while the mean environmental tem-

perature of the rural station was lower (35.87 °C). At night,

the highest mean LST values are obtained with the official

Sentinel product (24.05 °C), and the mean environmental

temperature of rural stations was again lower (21.10 °C).

The mean differences obtained between the LSTs with sat-

ellite images and the rural stations amounted to 3.59 °C for

Sentinel Day, and 2.95 °C for Sentinel night. Findings of

increased LST with Sentinel-3 images are reproduced for

both inland cities and coastal cities: the former show LST

differences of 3.70 °C with Sentinel day and 3.10 °C with

Sentinel night, while coastal cities show LST differences of

3.48 ºC with Sentinel day and 2.84 °C with Sentinel night.

3.2 LST Amplified Under Heat Waves

The statistics of the daytime and nighttime LST obtained by

means of the Sentinel day and night products for the inland

and coastal Andalusian cities during the period under study

are shown in Fig. 3. As can be seen, the daytime LSTs of

the inland cities are higher than the LSTs of the coastal cit-

ies, whether under normal environmental conditions or in

periods of heat wave. The nighttime LSTs of inland cities

are seen to be lower than those of coastal cities, both under

normal environmental conditions and during heat waves.

Fig. 3 LST Sentinel Day (a) and night (b) by city type and during the period under study

Table 4 LST results with

Sentinel day and Sentinel night

urban and rural areas

Zones Inland cities 41.13 41.87 43.06 43.42 23.37 22.31 24.19 22.40

Differences 0.74 0.36 1.06 1.79

Coastal cities 34.15 35.05 37.68 39.31 24.50 23.33 27.34 24.94

Differences 0.90 1.63 1.17 2.40

Daytime normal

conditions

Temperatures: ºC

Daytime heat waves Nighttime normal

conditions

Nighttime heat

waves

Urban Rural Urban Rural Urban Rural Urban Rural

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As can be seen in Table 4, during the mornings the

LST values of urban areas are lower than the values of

rural areas. Numerous academic studies (Saaroni et al.

2018; Wu et al. 2019; Yang et al. 2020a) indicate that

the reasons for the higher LST in rural areas is motivated

by the higher long wave radiation received by rural areas

compared to urban ones, owing to the shade generated

by buildings and trees and the cooling rates produced

in urban green areas. The increases in diurnal LST in

inland cities under heat wave conditions with respect

to the same areas in normal conditions were 1.93 °C

and 1.55 °C for urban and rural areas, respectively. In

contrast, the nocturnal temperature differences respec-

tively amounted to 3.15 °C and 2.54 °C. The diurnal

LST increase in coastal cities in heat wave conditions

with respect to the same areas in normal conditions

was 3.53 °C for urban and 4.26 °C for rural areas. The

nocturnal increases gave values of 1.13 °C and 1.02 °C,

respectively.

In view of the above results, it can be said that periods

of heat wave entail increases in the day and night LSTs

for both urban and rural areas, in the coastal as well as

the inland cities of Andalusia. Still, the increase is greater

during the morning in the coastal cities, and in the after-

noon in the inland cities (Table 4). During the morning, the

coastal cities present average values that are 3.90 °C higher

when compared to the periods of normal environmental

conditions; the increase in LST produced in the inland cit-

ies is, in contrast, only 1.74 °C. Contrariwise, at night, the

coastal cities present mean values 1.08 °C higher than the

values for periods of normal environmental conditions, as

opposed to the increase in LST produced in the inland cit-

ies of 2.85 °C.

3.3 SUHI Amplified Under Heat Waves

The statistics of the diurnal SUHI obtained with day and

night Sentinel products for the inland and coastal cities dur-

ing the study period are shown in Fig. 4.

As Table 5 shows, the cities of Andalusia present nega-

tive mean values for the diurnal SUHI that intensify in heat

wave conditions, most notably in coastal cities. Similarly,

the night SUHIs present positive mean values, intensified

under heat wave conditions. However, their intensification

is greater in inland cities than in coastal cities. The nega-

tive values indicate that during the morning, temperatures

in rural areas are higher than temperatures in urban areas,

producing the phenomenon known as urban cooling island

(Saaroni et al. 2018; Wu et al. 2019; Yang et al. 2019). In

the early morning hours, solar radiation is greater in rural

areas because in the city, shade is generated by buildings,

trees, and the heterogeneous system of impermeable walls

with great thermal absorption and heat capacity. The sources

of shade in the city prevent long wave solar radiation from

heating the waterproof walls of urban areas and giving off

Table 5 SUHI results with Sentinel day and night, urban and rural

areas

Cities Daytime

normal con-

ditions

Daytime

heat

waves

Nighttime

normal condi-

tions

Nighttime

heat waves

Inland cities − 1.33 − 1.56 0.95 1.47

Differences 0.23 0.52

Coastal cities − 0.80 − 2.24 1.06 1.11

Differences 1.44 0.05

Temperatures: °C

Fig. 4 SUHI Sentinel Day (a) and night (b) by city type during the period under study

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high doses of heat, altering the LST of the area (Li and

Meng 2018; Lemus et al. 2020; Logan et al. 2020; Yang

et al. 2020b). The areas where the rural stations are located

are farmlands with less than 10% of impervious surfaces and

a mean NDVI that ranges between 0.2 and 0.5.

Figures 5 and 6 illustrate the diurnal and nocturnal SUHI

values under heat wave conditions (blue line) and under nor-

mal environmental conditions (brown line). In general, the

blue lines are found above the brown lines, indicating that

the temperatures in heat wave periods are higher than the

values under normal conditions. These increases occur in

both inland and coastal cities. Yet the increases are greater

during the day in coastal cities, and at night in inland cities.

Figure 7 shows the mean SUHI during the period under

study obtained with Sentinel day for coastal cities under nor-

mal environmental conditions and under heat wave condi-

tions. The intensity and extension of the SUHI are seen to be

greater in the images obtained during the heat wave.

Figure 8 shows the mean SUHI during the period under

study obtained with Sentinel night for inland cities under

both normal environmental conditions and heat wave condi-

tions. Both the intensity and the extension of the SUHI are

greater in the images obtained during the heat wave.

3.4 Statistical Analysis

3.4.1 Satellite Temperature Validation

To validate the satellite data obtained, it is important to

obtain the linear adjustment coefficients R2, correlation coef-

ficient (CC), standard deviation (SD), the mean bias error

(MBE) and the root mean square error (RMSE), each indi-

cated in Table 6. The results of R2 are considered adequate

since they present values above 0.94. This circumstance

indicates good concordance between the values analyzed,

being above 94% and considered statistically significant.

Because these values denote a good agreement between

the environmental temperature values and the LST obtained

from the satellite, they lend validity to the results obtained.

Fig. 5 Average SUHI in inland cities under normal conditions and under heat wave, according to Sentinel day and night

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Fig. 6 Average SUHI in coastal cities under normal conditions and under heat wave, according to Sentinel day and night

Next, the statistical analysis of the variables that could

influence the SUHI obtained with Sentinel day and night

was carried out using the Data Panel method. The variables

were: solar radiation, wind speed, and wind direction. It was

first necessary to determine whether calculation should be

carried out using fixed or random effects. The Hausman test

was implemented to this end, its results marking the need to

use the panel of robust random effects for the data obtained

in the first and in the second phase of analysis. To develop

the Data Panel, the Generalized Least Method (GLM) was

used, with Eq. 3.

3.4.2 Interaction between SUHI and LST

The results of the statistical analysis of the LST and SUHI

data obtained by Sentinel day and night in the study periods

are given in Table 7.

The results of the statistical analysis of the SUHI data

obtained through Sentinel day and night images point

to a statistically significant relationship of 95% with the

independent variable LST. The values obtained for R2

and the F statistic of the SUHI data are shown in Table 8.

The data show good agreement between the dependent

and independent variables according to the method used,

with a level of adjustment lower than 90% significance, as

Prob > chi2

> 0.000.

3.5 Solar Radiation Contributions to the SUHI

The AEMET has certified points for the measurement of

direct and diffuse solar radiation at rural meteorologi-

cal stations. Direct solar radiation is obtained by means

of a Kipp-Zonen Pyrheliometer, while for diffuse solar

radiation a Kipp-Zonen Pyranometer is used, periodically

calibrated against international standards. The solar radia-

tion of the rural stations of the AEMET were analyzed

for the purposes of our study to grasp its influence on the

variability of SUHI intensity in the cities of Andalusia.

The data obtained reflect that total daily radiation is some

1.2 times higher in heat wave periods than under normal

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Fig. 7 Mean SUHI during

period under study for coastal

cities in a normal environmental

conditions, and b heat wave

conditions

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Fig. 8 Mean SUHI during

period under study for inland

cities in a normal environmen-

tal conditions and b heat wave

conditions

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Table 6 Data panel results for Sentinel: relationships between SUHI

and LST

Satellite CC R2 SD MBE RMSE

Sentinel day 0.9970 0.95 8.57 − 4.10 2.92

Sentinel night 0.9902 0.97 6.36 − 3.85 3.18

CC correlation coefficient, R: linear adjustment, SD standard devia-

tion, MBE mean bias error, RMSE root mean square error

conditions. This ratio is reduced to 1.05 times in the LST

and SUHI data collection chart based on Sentinel day, and

up to 1.08 times higher in charts corresponding to Sentinel

night. The atmospheric pressure during the periods of heat

wave was 1.3 times higher than under normal conditions.

These results suggest that Andalusia tends to have higher

atmospheric pressures associated with less cloud cover

during heat wave days, which allows more solar radiation

to reach the earth's surface, as brought out in other studies

(De Boeck et al. 2010; Li et al. 2015; Jiang et al. 2019).

The results of the statistical analysis of the SUHI data

obtained by Sentinel day and night in periods of normal

conditions and in heat waves with regard to solar radiation

are indicated in Table 9.

The results of the statistical analysis of the SUHI data

obtained through Sentinel day images point to a statistically

significant relationship above 99% with the independent

variable solar radiation, both under normal atmospheric

conditions and in heat wave periods. The results of the sta-

tistical analysis of the SUHI data obtained through Sentinel

night images indicate a statistically significant relationship

of 99% with the independent variable solar radiation during

periods of normal atmospheric conditions, and above 99%

during heat waves. The cities are located in latitudes where

the sunset during the summer period is after the time of the

Sentinel night.

The values obtained for R2 and the F statistic of the SUHI

data for Sentinel day and night are shown in Table 10. The

data are seen to show good agreement between the depend-

ent and independent variables according to the method

Table 7 Data panel results for

Sentinel: relationships between

SUHI and LST

Satellite Sentinel day Sentinel night

Variables β ρ SD β ρ SD

LST − 0.0904 0.031 0.0419 − 0.0954 0.035 0.4538

β Constant, SD standard deviation, ρ P value

Table 8 R2 and F SUHI

statistical analysis for Sentinel:

relationships with LST

Satellite Sentinel day Sentinel night

Variables R2 F Prob > chi2 R2 F Prob > chi2

LST 0.55 4.66 0.0031 0.69 4.42 0.0035

R2 linear adjustment, F F statistic

Table 9 Data panel results for

Sentinel: relationships with

solar radiation

Satellite Normal conditions Heat waves

β ρ SD β ρ SD

Sentinel day 0.0739 < 0.001 0.01844 0.0834 < 0.001 0.00234

Sentinel night 0.0062 0.002 0.00203 0.0075 < 0.001 0.00058

β Constant, SD standard deviation, ρ P value

Table 10 R2 and F SUHI

statistical analysis for Sentinel:

relationships with solar

radiation

Satellite Sentinel day Sentinel night

R2 F Prob > chi2 R2 F Prob > chi2

Normal conditions 0.71 16.06 0.0004 0.72 9.42 0.0009

Heat waves 0.72 18.50 0.0001 0.75 166.39 0.0000

R2 Linear adjustment, F F statistic

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used, with an adjustment level of 99% significance, since

Prob > chi2

< 0.000. The R2 and F values are slightly higher

for heat wave conditions than for normal environmental con-

ditions, which denotes that the relationship between SUHI

and solar radiation is stronger during heat waves.

3.5.1 Wind Speed and Direction Contributions to the SUHI

The wind speed and wind direction data from the rural sta-

tions of the AEMET were analyzed to discern their influence

on the variable intensity of the SUHI in the cities of Anda-

lusia. The direction under normal conditions is from sea to

inland (northward), while during heat wave environmental

conditions, the predominant wind direction is from land to

sea (southward). This means that during the day, in heat wave

conditions, the cool breeze from the sea—which is usual in

normal environmental conditions—does not reach cities, so

that the LST and SUHI increase. The change in wind direc-

tion therefore has a strong impact on the ambient temperature.

Our data reflect a mean daytime wind speed during data

collection using Sentinel day was approximately 1.16 times

higher during periods of normal conditions than during heat

waves. This proportion increases slightly, to 1.18 times,

using Sentinel night.

Tables 11 and 12 offer the results of statistical analysis of

the SUHI data obtained with Sentinel day and night in nor-

mal conditions versus periods of heat wave in terms of wind

speed and direction. The analysis of SUHI data obtained

Table 11 Data panel results

Sentinel day: relationship with

wind speed and direction

with Sentinel day and night images gives no statistically sig-

nificant relationship among the variables analyzed for peri-

ods of normal conditions. In contrast, with Sentinel day and

under heat wave conditions there is a statistically significant

relationship above 99% with the variable wind direction,

slightly reduced to just 99% by Sentinel night.

The values obtained for R2 and the F statistic of the SUHI

data from Sentinel 3A and 3B are shown in Table 13.

The data gathered in periods of normal conditions do not

show good agreement between the dependent variable and

the independent variables according to the method used,

with a level of adjustment lower than 90% significance, as

Prob > chi2

> 0.000. On the contrary, for periods of heat wave,

method used indicates good agreement between the depend-

ent variable and the independent variables, with an adjust-

ment level greater than 99% significance, Prob > chi2

< 0.000.

The R2 and F values are slightly higher in heat wave condi-

tions than in normal environmental conditions, which denotes

that the relationship between SUHI and wind speed and

direction is stronger during heat wave periods.

3.5.2 Increase in the Surface Affected by SUHI During Heat

Wave Period

During heat waves, there is not only an increase in the LST

and an intensification of the SUHI of the analyzed cities,

but larger urban areas are reportedly affected by the SUHI

as well. The average increase in these terms during the heat

Satellite Sentinel day, normal conditions Sentinel day, heat waves

β p SD β p SD

Wind speed 0.0381 0.636 0.08068 − 0.0562 0.316 0.05614

Wind direction − 0.0015 0.497 0.00231 − 0.0053 < 0.001 0.00146

β Constant, SD Standard deviation, p P value

p value is indicated in italics

Table 12 Data panel results

Sentinel night: relationship with

wind speed and direction

Satellite Sentinel night, normal conditions Sentinel night, heat waves

β p SD β p SD

Wind speed − 0.0651 0.049 0.03315 − 0.0234 0.936 0.2913

Wind direction 0.0028 0.244 0.00246 − 0.0057 0.005 0.0021

β Constant, SD standard deviation, p P value

p value is indicated in italics

Table 13 R2 and F SUHI for

Sentinel: relationship with wind

speed and direction

Satellite Sentinel day Sentinel night

R2 F Prob > chi2 R2 F Prob > chi2

Normal conditions 0.65 3.72 0.1555 0.71 4.30 0.1167

Heat waves 0.69 13.44 0.0009 0.75 8.90 0.0007

R2 Linear fitting coefficient, F F statistic

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Fig. 9 Surface area increases

under normal conditions and

under heat waves, and increase

in urban area by cities

wave periods studied was 15.66% for the urban areas of the

cities of Andalusia.

A substantially greater increase is observed in coastal cit-

ies (22.67%) than in inland cities (8.65%). Figure 9 shows

the affected urban area under normal environmental condi-

tions, under heat wave conditions, and the increase in the

urban area of each city. It should be noted that, in general,

inland cities have larger urban areas affected by SUHI under

normal conditions (85.23%) than coastal cities (56.76%).

This circumstance is possibly motivated by the direction of

the wind, from the sea and towards the land (northward),

which minimizes the LST in the latter cities. Under heat

wave conditions, inland cities also present greater total

urban areas affected (93.88%) than coastal cities (79.43%),

although the highest growth of SUHI occurs in coastal cities.

The change in wind direction (southward) can be considered

the reason for this finding.

4 Discussion

The results presented here, for Sentinel day and night prod-

ucts used to obtain the LST and the SUHI in the cities of

Andalusia, present adequate yields that are consistent with

each other and similar to those provided by similar investiga-

tions (Li et al. 2011; Tan and Li 2015; Sobrino et al. 2016;

Prikaziuk and van der Tol 2019; Yang et al. 2019, 2020b;

Chiang and Ivan 2020; Hu et al. 2020; Venter et al. 2020).

The data obtained with Sentinel day, both for inland

cities and coastal cities, give mean LSTs in rural areas that

are higher than the mean LSTs in urban areas, both in peri-

ods of normal environmental conditions and in periods of

heat wave. Unlike Sentinel day, Sentinel night data report

1 3 that both inland cities and coastal cities have mean LSTs

in rural areas that are lower than the mean LSTs of urban

areas, whether under normal conditions or in heat waves.

There are numerous academic studies that corroborate this

situation between urban and rural temperatures in the early

hours of the morning and at night, motivated by the solar

radiation received (Zakšek et al. 2005; Keramitsoglou

et al. 2011; Li et al. 2011; Feizizadeh and Blaschke 2013;

Li and Bou-Zeid 2013; Mallick et al. 2013; Founda and

Santamouris 2017; Tsou et al. 2017; Barbieri et al. 2018;

Li and Meng 2018; Saaroni et al. 2018; Karakuş, 2019; Wu

et al. 2019; Yang et al. 2019, 2020a, b; Lemus et al. 2020).

The mean values of SUHI obtained through Seninel day

images for inland and coastal cities were negative. This

finding, likewise evoked by other authors, would be deter-

minant of an urban cooling island (Saaroni et al. 2018; Wu

et al. 2019; Yang et al. 2020a). In turn, the mean SUHI

data obtained by Sentinel night for inland and coastal cit-

ies were positive—indicative of an urban heat island, a

phenomenon previously studied (Li et al. 2011; Shwarz

et al. 2011; Lai et al. 2018; Luo and Lau 2018; Zhao et al.

2018; Tewari et al. 2019; Anjos et al. 2020; Huang et al.

2020; Santamouris, 2020). In light of our data, it can be

said that during periods of heat waves there is an intensi-

fication of the SUHI obtained by Sentinel day and night,

both in inland cities and in coastal cities. However, this

intensification is greater with Sentinel day in coastal cit-

ies, and with Sentinel night in inland cities. Numerous

academic studies corroborate the intensification of the

SUHI at night (Gregor et al. 2007; Basara et al. 2010;

House and Santamouris 2011; Founda et al. 2015; Jiang

et al. 2019;) and during the day (House and Santamouris

2011; Founda and Santamouris 2017; Ao et al. 2019; Jiang

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et al. 2019; Qiu et al. 2020; Santamouris 2020) in periods

of heat wave.

The data on total daily solar radiation obtained attest to

a 1.2-times increase in periods of heat wave with respect

to normal conditions, corroborated by statistical analysis.

A number of academic studies confirm this association

between solar radiation and SUHI (De Boeck et al. 2010; Li

et al. 2015; Li and Bou-Zeid 2013; Jiang et al. 2019), serving

to validate the data obtained in our investigation.

The wind speed and direction data gathered in our

study denote important changes in the cities of Andalusia

between periods of normal environmental conditions and

periods of heat wave, corroborated by statistical analysis.

The relationship between SUHI and wind speed and direc-

tion are stronger during heat wave periods. Numerous stud-

ies describe such an intensification of the SUHI in the early

hours of the morning and at night (Ackerman and Knox

2012; Li and Bou-Zeid 2013; Li et al. 2015; Ramamurthy

and Bou-Zeid 2017; Jiang et al. 2019; An et al. 2020), thus

validating the data obtained in this investigation.

According to our data, an average urban area in southern

Spain would be affected by the SUHI phenomenon under

normal environmental conditions to the extent of 85.23% in

inland cities and 56.76% in coastal cities. The average urban

surface affected by the SUHI phenomenon under heat wave

conditions would be 15.66% greater, when compared to peri-

ods of normal environmental conditions. Still, this increase

is uneven: 22.67% for coastal cities and 8.65% for inland

cities. Research by other authors (Lemonsu et al. 2015; Ward

et al. 2016; Carvalho et al. 2017; Jiang et al. 2019) present-

ing similar values comes to support the results obtained here.

5 Conclusions

In this work, the LST and SUHI were studied by analyz-

ing Sentinel day and night images of the eight capitals of

Andalusia (southern Spain) both in periods of normal envi-

ronmental conditions and in periods of heat wave, during the

years 2019 and 2020. A statistically significant relationship

between the two variables is evidenced.

Our results detect mean LSTs based on Sentinel day and

night in inland cities—both under normal environmental

conditions and in periods of heat wave—that are higher than

the mean LSTs of coastal cities. In turn, the average LSTs

obtained with Sentinel day and night products for both urban

and rural areas are intensified under heat wave environmen-

tal conditions, the increase being greater with Sentinel day

in coastal cities, and with Sentinel night in inland cities.

The mean SUHI obtained with Sentinel day during the

entire study period for the capitals of the Andalusian prov-

inces showed negative values, whereas the mean SUHI

obtained with Sentinel night showed positive values. This

suggests that urban areas are at lower temperatures in the

morning than neighboring rural areas, a phenomenon known

as urban cooling island. Then, during the evening, the urban

areas are at higher temperatures than the adjacent rural areas,

producing an urban heat island. During heat wave periods,

an intensification of the SUHI obtained with Sentinel day

and night is detected for both inland cities and coastal cities,

but it is greater for coastal cities with Sentinel day, and for

inland cities with Sentinel night.

Within the scope of the environmental factors studied,

our results attest to a positive and statistically significant

relationship between SUHI and solar radiation, and between

SUHI and the direction of the wind, intensified in periods of

heat wave as compared to periods of normal environmental

conditions. Wind speed turns out to be a positive and statisti-

cally significant variable, but only in periods of normal con-

ditions and according to the data from Sentinel night images.

Our results detect that the surface of the urban area

affected by the SUHI phenomenon under normal environ-

mental conditions is greater for inland cities than for coastal

cities. Notwithstanding, under heat wave conditions, the

intensified SUHI entails a larger surface area, this phenom-

enon being greater for coastal cities than for inland cities.

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Ethics approval The author indicates that all the ethical principles

governing the publication of a research article in a journal have been

followed.

Consent to participate The author agrees to participate in the review

process and subsequent publication in the event of such an event.

Consent for publication If the article is accepted, the author consents

to the publication and transfer of the information to the journal.

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