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Review

Improving City Vitality through Urban Heat Reduction with Green Infrastructure and Design Solutions: A Systematic Literature Review

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Abstract: Cities are prone to excess heat, manifesting as urban heat islands (UHIs). UHIs impose a heat penalty upon urban inhabitants that jeopardizes human health and amplifies the escalating effects of background temperature rises and heatwaves, presenting barriers to participation in city life that diminish interaction and activity. This review paper investigates how green infrastructure, passive design and urban planning strategies—herein termed as green infrastructure and design solutions (GIDS)—can be used to cool the urban environment and improve city vitality. A systematic literature review has been undertaken connecting UHIs, city vitality and GIDS to find evidence of how qualities and conditions fundamental to the vitality of the city are diminished by heat, and ways in which these qualities and conditions may be improved through GIDS. This review reveals that comfortable thermal conditions underpin public health and foster activity—a prerequisite for a vital city—and that reducing environmental barriers to participation in urban life enhances physical and mental health as well as activity. This review finds that GIDS manage urban energy flows to reduce the development of excess urban heat and thus improve the environmental quality of urban spaces. Furthermore, it finds that the most equitable approach to urban cooling is one that reduces the intensity of the meso-scale UHI that affects all urban inhabitants. Subsequently, a cooler urban fabric based on GIDS is proposed. A cohesive approach to the widespread adoption of GIDS shows potential to produce a cooler urban fabric that is human-centered in its function and aesthetic to enhance participation in public life and stimulate life on the streets. Four spatial scales are presented in which a combination of GIDS may be collectively implemented to reduce the meso-scale UHI, including the urban, intra-urban, building and body scales. This approach considers the interacting nature of GIDS applied within contrasting urban landscapes, and aims to produce cooler urban conditions, better walking environments, and ecosystem co-benefits to stimulate participation in physical activity and public life to underpin public health, productivity and livelihoods, thereby inducing city vitality.

Keywords: urban heat island effect; city vitality; green infrastructure; urban planning; systematic literature review

1. Introduction

Hot cities and urban spaces present challenging environmental conditions for the people who live in them and use them. A combination of excessive surface and ambient temperatures, a lack of shade, ventilation and cooling breezes, and the persistence of heat creates conditions that jeopardize human health and well-being [1–3]. Cities are prone to excess heat—manifesting as urban heat islands (UHIs)—due to their material composition and urban morphologies within their topographic and climatic settings [4,5]. In hot conditions, people's physical needs cannot be met in many city spaces, and poor usability prevails, deterring public attendance, and adversely affecting activity intensity. In this way, excess heat removes people from the streets, diminishing city vitality. Pointedly, urban heat also exacerbates the impacts of deadly heatwaves and the impacts of climate change, placing additional stressors upon cities and their residents [6].

Of interest to urban heat is that buildings and infrastructure shape urbanization itself [7]. The built environment of cities, its roads, public places, buildings and homes, influences the choices and behaviours of its people, including the ways they travel, socialize and interact [8]. This is important from an activity perspective, as it influences the type, location, and intensity of activities undertaken, as well as from an emissions perspective, as waste heat caused by anthropogenic emissions such as transport and electricity use for air conditioners contributes to urban heat.

Vitality is defined and understood as life and liveliness, energy, vigour, and activity [9]. An active street presence makes cities vivid and living places [10], a sign of vitality that brings life and health to cities. Vitality then requires people in public places, and a diversity of people and diversity of uses for those places, which underpins the social and economic functions of the city [11]. Many urbanists, authors and scholars who discuss the stimulation of city vitality reinforce that pedestrian-scale activity in public spaces is a fundamental condition of vitality and that vitality is lost where public spaces are dominated by cars [8,10,12].

Green infrastructure (GI) integrates nature into cities through utilizing landscape elements structured within the urban landscape. Examples include urban forests, green roofs and walls, permeable surfaces, parks and wetlands, and sustainable urban drainage systems [13]. These principles are central to biophilic city planning and design, which integrates nature and the natural world into the urban environment to bring natural daylight, fresh ventilation and greenery into cities [14]. Nature-based solutions is another approach to urban environments encompassing actions that are supported by, inspired by or copied from nature, including ecosystem restoration, the greening of brownfields, rooftops and walls, and organic climate mitigation and adaptation measures [15]. Although differing terminologies, these concepts are forms of GI that provide ecosystem services to the city and are also known to reduce the effect of urban heat [13,16,17]. While we acknowledge that blue infrastructure is also a key component to biophilic cities, we have chosen to not extensively include this aspect in this paper to focus on the extensive body of GI literature.

Categorized herein as "design" are the design and planning principles and urban elements that assist in the reduction in urban heat. These principles and elements include consideration of the urban form and its spatial and geometric arrangement; passive design (including attention to the thermal behaviours and permeability of materials and structures); and purpose-designed urban elements that influence the microclimate, such as fountains and wind towers that are cognizant of, or have a basis in interactions with natural daylight, fresh ventilation and water [17]. Design also links urban space together, considering the relationship between the elements within the urban form on a broader scale. All of the above concepts are included within the scope of this review. Considered together, they will be termed GIDS.

There is clear scope for GIDS to moderate urban heat and deliver climate-appropriate built environments that attract people and activity to the city. Individuals should be able to participate in urban life without prevention [10], and comfortable thermal conditions provide a basis for participation. Green infrastructure provides shade and evaporative cooling services that reduce ambient and surface temperatures at the atmospheric level in which human activity takes place, whilst design strategies can be used to enhance the built environment to best manage solar radiation, wind, shading and evaporation to mitigate urban heat [5,18]. Together, GIDS can increase thermal comfort and create spaces that are inviting for human occupation, thereby attracting activity [12,18]. Whilst we acknowledge the important role blue infrastructure has to contribute to resilient and comfortable cities, this review paper will focus on green infrastructure to adequately examine the relevant literature. The requirement to reduce urban heat is increasingly being recognized, with local government groups such as C40 responding with steps towards climate resilience and heat mitigation in order to reduce health risks, increase quality of life, improve thermal comfort, and lower building energy use and pollution [19].

There have been many descriptive studies of UHIs, their contributing factors, and the effectiveness of green infrastructure mitigation strategies at the building scale, the city scale and the regional scale [1]. Architectural, planning and design practices and devices that affect and control heat are also well studied [18]. Many studies exist on the impacts of heat on human health, thermal comfort, and activity [3,6], and literature relating to the positive effects of natural environments towards human health and well-being is also extensive [15]. However, a relative lack of literature exists linking direct public health outcomes to the environmental conditions induced by nature in the urban setting [15], and clear links between a cool urban environment and city vitality have not been identified in the literature. This review then asks: how can green infrastructure and design solutions be used to cool the urban environment and improve city vitality? A systematic literature review has been undertaken to analyse and review scholarly literature on the connected research themes of green infrastructure and design, a cool urban environment and city vitality to determine how a reduction in heat in the urban environment using green infrastructure and design solutions can mitigate heat to stimulate life and activity within cities. Context is provided around the review themes before the methodology and organization of literature is explained, and findings are presented. Findings relating to the implementation basis for GIDS are rationalized into a structure for urban cooling using a nested spatial scale—urban (or meso-scale), intra-urban, building and body scales—which is further discussed in the context of city vitality. While this goes one step further than just a review paper, we feel that summarizing the themes found in the literature into this structure adds value to the literature on this topic.

2. Methodology

The systematic literature review (SLR) approach is advantageous to the distillation of large or even overwhelming volumes of information to answer specific questions and follow a replicable protocol of procedure with a scientific approach, without omitting key ideas or introducing bias [20]. The SLR procedure is outlined through the following steps:

1. Focus the review question;
2. Develop a search strategy and search terms;
3. Perform the literature search;
4. Review, synthesize and report.

2.1. Focus the Review Question

Scoping searches revealed a large volume of literature regarding UHIs, green infrastructure and design, with the causes and solutions for UHIs being well documented [18]. Also shown is that in affected cities, UHIs create significant public health problems [21]. However, it has proven difficult to find clear links highlighting how heat mitigation through green infrastructure and design solutions contribute towards a city's vitality, revealing a place for further research. This review then poses the question: how can green infrastructure and design solutions be used to cool the urban environment and improve city vitality?

In searching for linkages, this review aims to understand the environmental needs of humans and the impacts of the urban environment on these needs.

2.2. Develop of a Search Strategy and Search Terms

Key terms for use in the final search strings were informed through review of titles and abstracts from scoping searches. Eight different word groups were determined, resulting in eight search strings for combination into a complete search term and tested in the ProQuest database. The key terms included in the various word groups are arranged in a concept grid shown in Table 1.

Table 1. Concept grid: key themes, key words tested for inclusion, and final search strings chosen as search terms.

	Key Themes	Facet of Key Theme (Word Group)	Key Words and Related Terms Tested
Primary concepts	City vitality and cool urban environment	Location	Urban, city, suburban, suburb, atmosphere, meso
	Cool urban environment	Problem	Heat, hot, thermal, island, microclimate, exposure, exposed, climate, warming
	Green infrastructure and design solutions	Related professional fields	Architecture, design, building, planning, construction, landscape, infrastructure, developer
	City vitality	Conditions and indicators	Walk, walkability, pedestrian, interaction, variety, recreation, comfort, liveability, liveable, stress, movement, vitality, life, opportunity, well-being, energy, vibrancy, vibrant, street life, trade, vendors, transaction, use, behavior, attraction, attractive
Secondary concept	Green infrastructure and design solutions	Description of functions or properties	Temperature, sky view, green plot, cover, coverage, shade, canopy, green-blue infrastructure, grey infrastructure, biophilic, green, nature
	Green infrastructure and design solutions and cool urban environment	Desired outcome	Cool, circulate, move
	Green infrastructure and design solutions and city vitality	Built environment	Road, street, highway, freeway, car park, pavement, sidewalk, walk way, town square, plaza, terrace, building, roof, wall, surface
	City vitality	Who is involved	People, public, community, culture, civilization, public, district, society

The final two search terms used were:

Search in topic or abstract:

(urban OR city) AND (Heat OR thermal OR warm*) AND (architecture OR planning OR design) AND (vitality OR walk*OR liveab*OR vibran*OR activity OR interaction OR streetlife OR life OR use OR pedestrian OR behavio*OR attracti*OR variety OR diversity)

AND

Search all fields:

(cover*OR shade OR landscape OR canopy OR biophilic OR permeab*OR albedo OR living OR stormwater OR porous OR geometry OR wind OR green OR nature) AND (cool OR circulate) AND (Road OR car park OR pavement OR sidewalk OR building OR roof OR wall OR infrastructure OR street OR surface) AND (People OR public OR community OR society OR culture OR human)

2.3. Literature Search and Synthesis

The final search term was entered into three databases (ProQuest, Scopus and Web of Science) using filters to return a total of 369 results. To minimize bias, no language filters or publication date filters were included. Filters were applied to all databases to limit results to peer reviewed articles. Exclusion filters were included on the Web of Science database to exclude literature from less-relatable fields, generating a more manageable volume of literature for further assessment.

All results were exported from the databases into Endnote and screened for relevance. The PRISMA diagram in Figure 1 shows the screening process. In short listing, articles of a highly technical nature, such as environmental monitoring methodologies, and related testing, measurement, sensing and mapping were excluded. Articles that did not relate strongly to the key themes were also excluded, such as mechanical cooling, power generation, and farming. Articles that did relate well to the key themes, particularly those that clearly combined the themes, were short listed for inclusion. A total of 68 articles are included in this SLR (Appendix A).

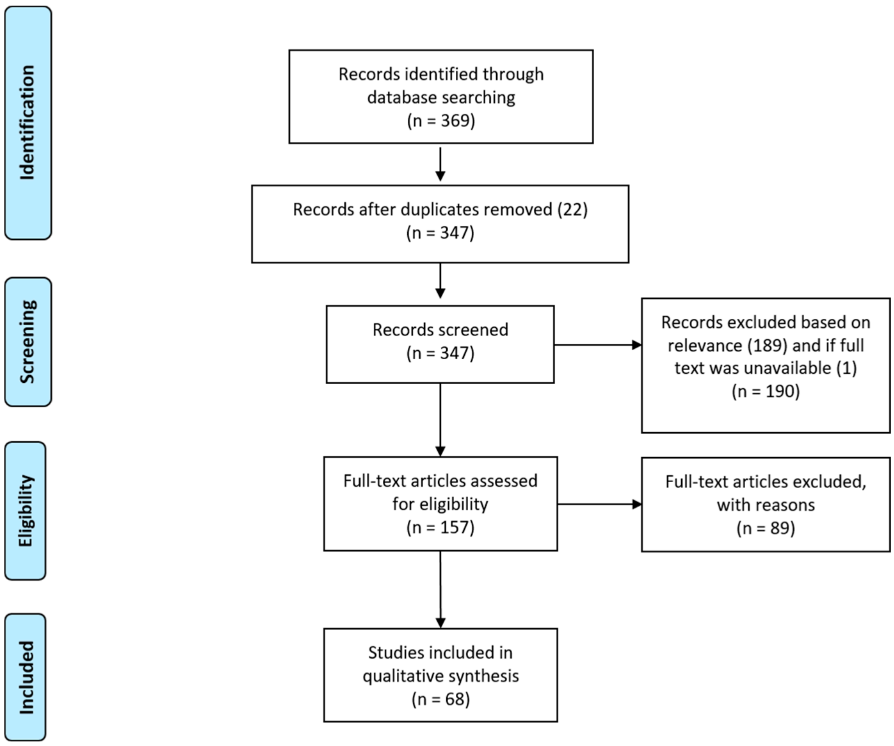

Figure 1. PRISMA flow diagram of the systematic literature review (SLR) process based on the PRISMA flow diagram available from [22].

3. Results and Discussion

3.1. Literature Analysis

The final SLR includes 68 articles across 3 key themes and 7 sub-categories, as shown in Figure 2. The themes are city vitality, cool urban environments, and green infrastructure and design. This includes the effects of heat on human health, thermal comfort, activity, use of public space, productivity and economies; the distribution of heat impacts across global urban populations and the solution space for heat mitigation; and the mechanisms by which GIDS reduce urban heat, as well as the effectiveness of these strategies in cooling urban environments.

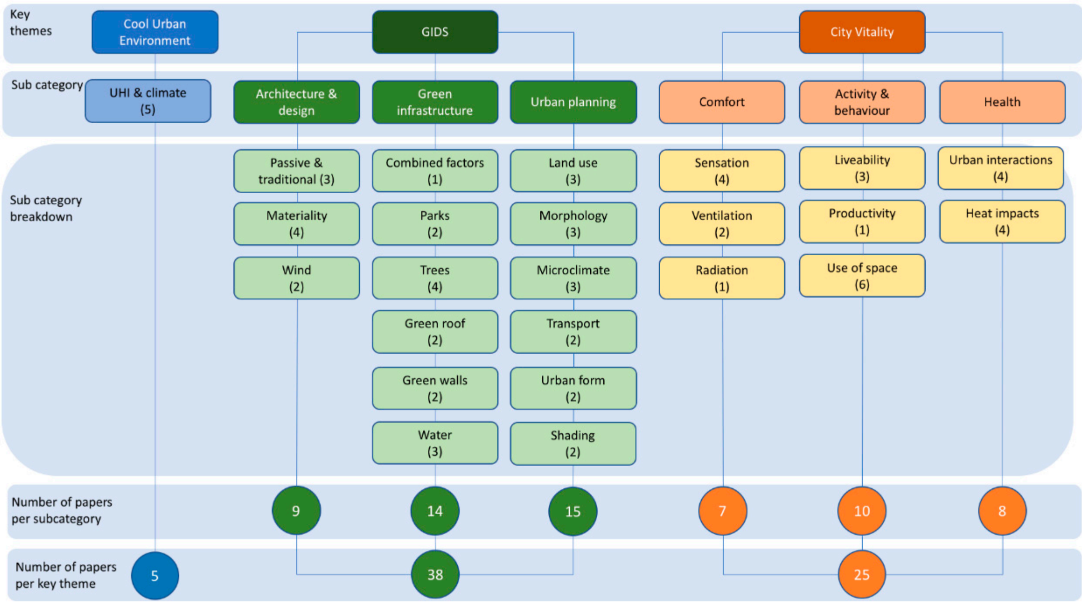

Figure 2. SLR abstract review: number of papers included across key themes and sub-categories.

Articles were analysed for year of publication, country of origin, the inclusion and location of case studies (or region-specific information), and corresponding climate zones and human development index rankings. These results are recorded in Appendix A. Despite no limitation or bias towards the year of publication in the database searches, no papers published prior to 2006 were included in the final results, and 54 of 68 articles (80%) were published between 2013 and 2020. The 68 articles originate from 24 countries, with 56% of articles originating from four countries alone: China (21%, with an additional 3% of articles originating from Hong Kong, a Chinese special administrative region), Canada (12%), Australia (10%) and the USA (10%). The remaining 44% of articles originate from 19 other countries. In analysing the proportion of articles representing the five main climate classes according to their Köppen-Geiger climate classification [23], it can be seen that the majority of articles present findings from temperate and continental (cold) climates (36 and 12 cases respectively), with few articles relating to the warmer dry and tropical climates (7 and 2 cases respectively), and no articles relating to the polar regions.

The following sections discuss the key concepts and themes identified in the articles including a current assessment of the urban environment, the human experiences of cities focusing on city vitality aspects, a comment on scenarios to avoid, and approaches to managing the urban energy balance. Finally, the mechanisms by which GIDS reduce urban heat are presented, as well as the effectiveness of these strategies in cooling urban environments.

3.2. The Current Urban Environment

A range of natural and engineered landscapes and their connected microclimates are found across urban areas, in which many energetic exchanges take place, including those with humans. The overall fabric and morphology of the urban environment forces a positive thermal anomaly, manifesting as a meso-scale UHI [4]. UHIs vary in magnitude and spatial distribution across the urban area, but on the meso-scale, urban areas are generally approximately 5–9 °C [19] warmer than their rural surrounds. Herein, the impacts of urban heat are not equally shared. This is a significant heat penalty to impose upon urban inhabitants, especially in consideration of background temperature rises driven by climate change [24]. As a consequence of these combined phenomena, the frequency, intensity and duration of extreme heat events in urban areas will increase into the future [2,25], with devastating outcomes for human health, well-being, and equity, whilst potentially deeming some areas uninhabitable [6]. This is a highly dangerous prospect for cities, but one has been heralded by the mortality rates of past heatwave events [2,26] and modelling of future climate scenarios [24].

The substitution of nature with grey infrastructure and impervious surfaces results in the loss of ecosystem regulating services that provide shade and consume solar irradiation to cool the environment [27], as well as the loss of ecosystem co-benefits such as support for biodiversity, pollution reduction, avoided stormwater processing, avoided heating, cooling and emissions, and carbon sequestration services [17,28]. The blueprint for modern urbanism also produces environmental exposures and patterns of living that are neglectful of the universal health needs of humans [17], resulting in a proliferation of non-communicable diseases [15]. Overexposure to urban and transport planning factors such as pollution, noise, heat, and a lack of green spaces and physical activity contributes to negative health outcomes and premature death [29].

The effects of exposure to extreme heat are influenced by environmental factors and personal vulnerabilities [30]. Local conditions create the most direct hazards [6], where poor environmental design can also exacerbate the health impacts of climate change [3]. Place of residence then impacts upon health outcomes [31]. This is evident in housing condition, where a higher risk of heat-related death presents due to a lack of thermal insulation, where bedrooms are heat exposed [26], and where housing is located in urban hot spots [32].

Analysis of demo-spatial dynamics and urban planning reveals the entrenchment of heat inequalities and a lack of preparedness for temperature rises in poorer urban areas [33,34]. Heat vulnerability increases as poorer groups have limited financial adaptive capacity and are more likely to work in heat-exposed and labour-intensive jobs [34,35]. They are also more likely to reside in sub-standard and less climate-resilient housing [31,32,35], and the economic burden of purchasing and operating air conditioning precludes its viability as an adaptation option [31,33,35]. Poor households are most likely to be located in what are described by Bélanger et al. (p.2, [36]) as "geographic pockets of urban poverty," characterized by little green space, high traffic density and pollution, and expanses of asphalt, resulting in disproportionately higher temperatures and increased vulnerability to heat-related illness and death [31–33,35–37].

Modern cities support and rely upon cars, at the expense of human needs [8,12,38]. The resultant sprawl, along with the separation of land uses—a hangover from the industrial revolution—severs neighbourhoods and habitats, removing people from contact with nature that is essential for health and well-being. Furthermore, it removes people from contact with each other, propagating isolation and loneliness as people are ensnared by patterns of segregated living that do little for their physical health, mental health, community and sustainability [39].

Urban planning can produce quality environments that reinforce environmental and sociobehavioural pathways to good health through the provision of cool, connected, and accessible infrastructures, and active, inclusive communities [3]. Within these environments, the provisioning and regulating services provided by nature contribute towards health improvements [2,15]. The delivery of naturally cooler urban spaces can lead to increased physical activity and enhanced social behaviours which reduce physical and mental health disorders, including but not limited to those associated with heat [3,15,40]. Hence the reinforcement of nature in the urban setting, such as street trees, corridors and pocket parks is especially important within space-constrained urban landscapes [29].

3.3. The Human Experience of Cities

As humans require a level of health, energy and amenity to encourage and enable activity, thermal comfort, adaptive behaviours, public health and use of space must be considered in the cultivation of a vital city. The city's economic activity and ecosystem services are also impacted by current urban environments. Although air-conditioned indoor environments presents a genuine adaptation option for those with socioeconomic means to avoid the worst of the heat present in cities, it contributes to the exacerbation of heat and pollution, and presents another dilemma for cities—encapsulation of the home [35]. Retreating into private space and reducing interactivity with the community does little to contribute to the liveliness of the city [11].

3.3.1. Thermal Comfort

Objective climatic conditions alone cannot predict thermal comfort [33], and thermal sensation will differ between people at the same site [41]. Thermal comfort is a psychological state of satisfaction with the thermal environment, for which subjective perceptions of comfort differ based on factors including expectations and past experiences [30,42], activity level, time and length of exposure [30], companionship, purpose of visitation, and medical history [41], gender [33,41], and destination use [43].

Humans demonstrate a degree of thermal adaptability to their surroundings and may acclimatize within a limited range [30,35]. For example, humans exhibit a greater tolerance to high temperatures in tropical cities [33]; people are able to tolerate hotter temperatures in summer seasons [42]; and a greater tolerance to variability within the thermal environment is found where there is a known lack of environmental control, such as in an outdoor setting [41]. Despite a degree of thermal adaptability for hot conditions, humans are more able to adapt to cold conditions than hot conditions, both behaviourally and psychologically [30].

According to each city's latitude, different amounts of global radiation are required to achieve thermal comfort [27], and meteorological parameters affect thermal comfort differently between climate zones. In hot and arid environments, thermal comfort is dominated by ambient and surface temperatures and solar irradiation [44] as mechanisms of heat loss through evaporation and convection aided by wind are less possible [44,45]. However, natural ventilation is the strongest passive strategy for increasing thermal comfort in high humidity conditions such as in tropical climate zones [33].There is no single sensitivity threshold for wind speed preferences, as this differs with seasons and sites [46]. Accommodation in the subtropical environment requires few energy inputs to achieve thermal comfort [47].

3.3.2. Health Impacts

The human capacity to acclimatize is not so great as to safely tolerate extreme temperature intensities and durations. Humans are limited in their ability to physiologically tolerate heat, and above a certain threshold this capacity rapidly diminishes, resulting in a loss of productivity [34], heat-related illness and even death [3,6,48]. Better public health reduces vulnerability, increases resilience to heat-related illness [6,32], and is influenced by urban factors [29]. Physical fitness is a strong determinant of tolerance to heat [36], as most heat-related health issues are due to the exacerbation of pre-existing medical conditions [48]. Physical activity is important to upholding public health, as it aids the management of chronic diseases, assists acclimatization and promotes overall health and well-being [48]. However, widely adopted land use planning and transport infrastructures not only induce urban heat, but reduce levels of physical activity whilst tearing at the social fabric, undermining sociobehavioural reinforcements of public health.

The health and environmental impacts of climate change are projected to cost in the realm of trillions of USD annually by 2030 [6], in part due to the stressors that heatwaves place on public health systems. Experience from Australia shows heatwaves have caused significant increases in all-cause mortality, ambulance emergency caseloads, home visits by general medical practitioners and emergency department presentations, and modelling for the period 2031–2080 compared with the period 1971–2010 predicts a 471% increase in mortality across the country's three largest cities [48]. In countries with ageing demographics, the compounding effect of climate change and age will result in greater numbers of vulnerable people exposed to extreme heat into the future [44]. Tropical and subtropical areas are disproportionately impacted by background temperature increases, and these areas are also highly populated and rapidly urbanizing, with inhabitants particularly vulnerable to heat stress and heat exhaustion, undermining development progress [6].

3.3.3. Adaptive Behaviours

Adaptive behaviours help to maintain the human energy balance and achieve thermal comfort, and these may require societal and personal behaviour changes [26,48]. As the body's thermoregulation system works hard to cool down, efforts must also be made to avoid the production of metabolic heat that causes additional stress, meaning less activity can be undertaken as the body's resources must be conserved for cooling [30]. Before reaching physiological limits, psychological factors also influence thermal comfort, and this thermal adaptability influences activity behaviours and choices [42].

Heat adaptation strategies can bring health improvements either directly, or as a co-benefit of implementation [3]. These include the opening of windows in the cooler hours of the day [31], the use of fans where dry heat gain and dehydration are not a risk [48], adjusting working and activity patterns [34,48], re-scheduling of outdoor events where hot weather is forecast [48], wearing cool clothing and staying shaded [26,48], frequent showering or bathing [26], applying cool stimulus [35,48], re-locating to a cooler area or visiting a cooler place, and the use of air conditioning [32,48]. However, frequent use of air conditioning may reduce acclimatization, and give rise to encapsulation of the home in which dependencies are formed on societal systems such as electricity production and distribution networks as well as their connected systems to provide thermal comfort, which may themselves be vulnerable to extreme weather events, further increasing heat vulnerabilities [6,35].

People will instinctively use their past experiences to judge thermal conditions and will plan their activity to suit the conditions they expect to encounter, revealing thermally adaptive behaviours [42]. People will re-locate when their psychological experiences and expectations do not connect with the way in which they are perceiving heat [42]. This indicates that places that can be relied upon for comfortable thermal conditions are attractive for human occupation and activity.

However, heat cannot always be avoided, especially by the poor and vulnerable. Ambient temperatures and the intensity of the heat island have a strong bearing on inside temperatures, where many elderly, sick and immobile people remain [26,31]. High mortality rates are linked to immobility and the aging population, those who are unable to undertake cooling behaviours and those who reside in sub-standard housing [26]. Vulnerable citizens are then more reliant on quality environmental conditions to uphold a quality of life and a livelihood, as their adaptation capacity and living standards are lower than others.

Adaptation options are often limited by socioeconomic status and available technical means, which widens entrenched urban and global inequalities. Where the effects of heat persist, people become less healthy and productive and more impaired [34]. The people least likely to afford or access climate-resilient workplaces, accommodation, and air conditioning, have poorer general health and are most likely or undertake heat-exposed work and activities, especially in countries with lower levels of development. In unrelenting heat, these workers are also not afforded the same biophysical recovery opportunities, further impairing livelihoods and productivity [34].

3.3.4. Activity, Behaviour and Use of Space

Thermal comfort and good health exert strong influence on behavioural patterns, choices and activities [46]. Quality urban environments underpin public health measures and enhance thermal comfort to stimulate and encourage activity. Liveable and healthy cities are described as green, vibrant, compact, safe, accessible, and environmentally just, whilst delivering community, a sense of place, and quality of life [2,29]. These qualities connect to produce the environmental conditions for increased activity. For example, the social and cultural values of urban spaces may be enhanced through enabling outdoor activities [43], and well-designed outdoor spaces can improve microclimate and regulate pollution [40,41,49] to further enhance activity and improve living conditions [41]. Humans are social beings—small talk makes us happier, and making connections with others reduces loneliness [39]. People need activity, interactions, experiences, and social supports to maintain physical and mental health [17], which requires quality public places to enable these functions. Attempts to internalize these functions, as with the building of exclusive amenity, induces loneliness [39].

An optimized thermal environment enhances the quality of any space to provide a better user experience [43,50]. Further benefits include improved self-motivation; greater physical activity, activity intensity and exercise; and higher attendance [30]. In contrast, thermal discomfort has been shown to reduce activity levels, decrease both athletic and work performance, and increase heat stress and unwanted behaviours [30]. Even perceptions of thermal stress may determine an area unsuitable for staying [51]. Increased use of space then results from appropriate microclimatic design that decreases the negative aspects of exposure [30]. For example, urban greenery has been demonstrated to provide thermal comfort and protection against thermal stress in restaurant settings, making them suitable for staying and enabling greater patronage during warmer months [41].

Huang et al. [42] find that people use space in accordance with their perceptions and preferences for thermal comfort, relying on past experiences and expectations rather than purely physiological and meteorological factors to inform their site usage [42]. Their study of spatial use behaviour confirms that people dislike high exposure to solar radiation, hence people in sunny locations are more likely to be engaged in dynamic behaviours such as standing, walking and passing through, resulting in shorter stay durations [42]. Furthermore, areas providing shade and canopy cover are more popular for engagement in leisure activities, and also result in a longer stay duration and the ability to adopt static activities such as sitting, eating, talking, reading [42]. In hot seasons static behaviours result in a reduced metabolic rate, resulting in greater comfort [42].

Kang-Ting and Yu-Hao [52] find that people also use space in line with cultural and environmental attitudes. They find that for noise-producing activities such as karaoke, dancing and exercise undertaken in Taiwanese parks, attendances are greatest for dynamic activities in the cooler morning hours and in the tree-shaded areas, where slightly cool–neutral conditions are found; and activity intensity decreases as ambient temperatures and exposure to solar radiation rises [52].

Increased walking rates are linked to better walking environments [40], for which cooler walking environments with less sidewalk obstructions create more attractive walking conditions [40,53]. However, walkable neighbourhoods, characterized by increased density, streets and sidewalks, often impose a heat penalty through their strong use of engineered materials [54]. The encouragement of active and public transit modes in Vienna has been linked to greater physical activity and lower mortality rates than comparable European cities [29]. Here, greater walkability is reflected in the allocation of urban space, with only 14% of land dedicated to cars and traffic [29].

3.3.5. Economic Activity

Providing thermally comfortable conditions that attend to the basic physiological needs of visitors helps to attract customers, improve living conditions, and increase the development of precincts, and this is important to the commercial success of businesses such as those in the hospitality and tourism sectors [33,51]. Tourists, especially in tropical cities, may be exposed to uncomfortable conditions that discourage activity [30,33], hence climate smart urban planning will support the viability of business operations that include outdoor interactions [33]. Thermally comfortable outdoor spaces also enhance business opportunities. Vít and Kopp [51] find that accommodating additional customers in bars and restaurants by extending seating into outdoor areas expands business capacity, and using an understanding of location to provide thermally comfortable conditions attracts customers. However, increased activity also affects microclimate conditions. The microclimate of pedestrianized zones can be affected by crowding, which can be amplified where street performance and economic activity attracts users to pedestrianized areas [55].

Productivity loss attributed to heat is a market impact of climate change, and one that feeds directly into the national income and the income of individuals [34]. Heat driven by climate change is a macroeconomic concern, particularly severe in low income countries that have higher baseline temperatures, jeopardizing poverty reduction and sustainable development progress [34]. Workplace heat is projected to drive half of the economic costs at a global level due to labour productivity losses [6].

Workers' effectiveness can be degraded by heat above a temperature threshold of between 25 and 30 °C, and the resultant productivity losses continue to increase, with productivity only maintained within a narrow temperature range before critical temperatures are breached, risking serious health impacts [34]. Workers' response to heat depends on meteorological factors as well as clothing, acclimatization and work intensity [34]. Outside of work hours, workers may be further affected by overnight temperatures that reduce their biophysical recovery capacity and thereby impair productivity [34]. Outdoor or high-intensity sectors such as agriculture are at higher risk of productivity loss and subsequent economic impacts [34]. Shifting economic activity to less exposed sectors such as industry and services can minimize economic impacts [34].

Productivity losses can be avoided through temperature and exposure-reducing adaptation measures, which incur direct financial costs, such as capital investments and ongoing maintenance [34]. However, this expenditure also delivers a range of economic co-benefits [34]. Co-benefits to adaptation, along with indirect costs, are considered across environmental, health and socioeconomic pillars, including emissions, policy interactions, effect on the natural environment, and social issues such as jobs, health, and education [34]. As an example, adjustments to the built form are a direct cost that provides a shift in base temperatures [6,34], whilst air conditioning can flexibly respond to temperature peaks [34]. However, the associated emissions and waste heat production of air conditioning are an example of indirect adaptation costs [34]. Also of note is that poorer populations are less likely to work in air-conditioned places and the health and productivity impacts for these people are expected to increase with climate change [35]. However, all cities must maintain a diversity of labour [56], so the impacts of heat impairments are wide reaching across each city. It is then in the interests of the whole city that heat inequalities are eliminated.

3.3.6. The Value of Ecosystem Services

Ecosystem services provide economic and health value to cities. Hot weather and sunlight interact with pollutants from transport, energy, and industry to diminish air quality, producing negative health and economic effects [2,40,48]. This is experienced in Beijing, where the number of dusty and hazy days attributed to the UHI are growing, for which there is also an attributed rise in morbidities [40]. Furthermore, pollution imposed an estimated economic cost across China of 1–6% of GDP in 2004 [40]. Ecosystem services provided by urban forests and vegetation are shown to effectively reduce the effects of such pollutants, and provide additional value to cities through air purification, heat reduction, carbon sequestration, energy savings and storm water retention [28,40]. The key pollutants that trees filter and remove include CO_2, NO_2, SO_2, PM_{10}, and $PM_{2.5}$ [28], and this ecosystem service is provided on a highly cost-effective basis that greatly exceeds initial costs and maintenance [40]. On a per capita basis, megacities have a median tree cover density of 39 m^2 [28]. This delivers pollution reduction, avoided stormwater processing, avoided heating, cooling and emissions, and carbon sequestration services, valued at $32/capita (0.12% of GDP) for megacities in 2014 [28]. Where trees are removed for urbanization, a reduction in these services is found, and conversely, an increase in ecosystem services can be gained where urban forests are expanded [28]. In the case of Tokyo, it is estimated that the conversion of all available tree cover areas to actual tree canopy would deliver benefits at double the existing value, to $1 billion per year [28].

3.4. A Structured Approach to Urban Cooling with GIDS

This section presents the SLR results rationalized into a structure for urban cooling using a nested spatial scale—urban (or meso-scale), intra-urban, building and body scales (Figure 3)—to capture the implementation basis for GIDS. A degree of urban cooling may be achieved at any level moving up the scale, but in reducing heat inequality and mitigating heat across the entire urban area, no single GIDS element stands alone. Hence, this approach maps the basis for a collective response towards a heat-responsive urban fabric to maximise meso-scale urban cooling.

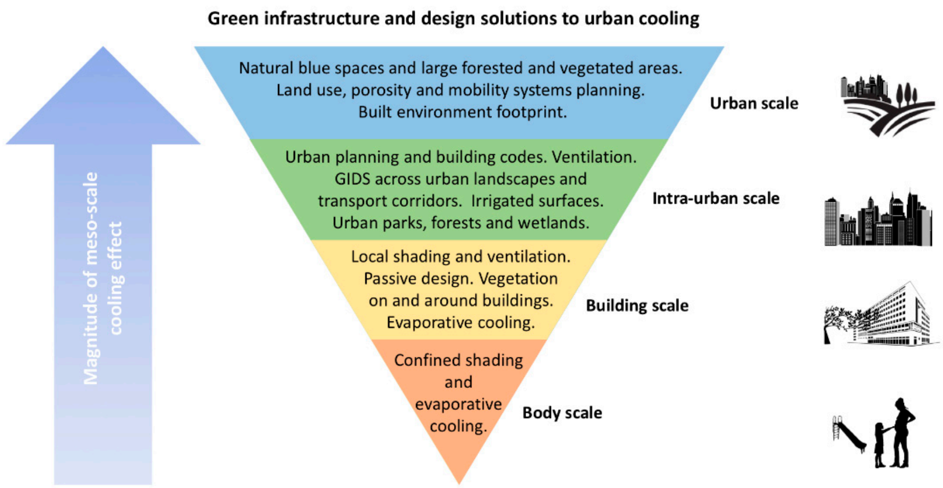

Figure 3. Application of GIDS within the urban fabric (figure by author).

3.4.1. The Urban Scale

The urban scale must consider regional and global influences to determine a climatically appropriate structural basis of the entire urban space, whilst taking an overarching view of its many incorporated intra-urban spaces and their energetic interactions. The urban scale must then comprehend the localized impacts of climate change, and accommodate the local climate zone and topography to determine climatically appropriate cooling solutions within biophysical, climatic, economic and technical capacities.

The urban scale addresses land-cover type and use across the entire urban space, which affect the strongest urban cooling outcomes [37,57]. When comparing the surface temperatures for various land use land covers, Ersoy [58] finds agricultural areas and open spaces with low levels of vegetation to exhibit the most variable temperature effects, whilst water features and forested areas are the coolest, and built up areas, roads and railways the hottest [58]. Temperature traverses of Portland, Oregon reinforce this finding, as forested areas are up to 10 °C cooler than downtown, with cool islands in the surrounding forest park, a UHI downturn in the suburban areas and the strongest UHI in the downtown area, with canopy cover being the most important factor influencing heat [59].

The configuration of greenspace has bearing on the effectiveness of cooling, as less fragmented spaces with a non-lineal nature provide increased cooling effects [37,58]. Larger patch areas with greater edge perimeter and more complex shapes exhibit greater cooling results, and as the distance between these patches decreases, their cooling potential increases [58].

Blue spaces, which include wetlands, rivers, lakes, oceans, ponds and constructed spaces, exhibit stronger cooling effects than any other land cover type [58,60], and wetlands provide the strongest cooling effects of all [60]. However, blue spaces also produce higher humidity, which may be unwelcome in some climates, along with increased risk of vector-borne infectious diseases [60]. Cooling is induced as water evaporation consumes thermal energy from the air, and the effects are spread via convection [60].

Key to cooling at the urban scale is the preservation of forested areas and large and complex blue-green spaces, providing downwind cooling due to advection [37,58]. This implicates land-use zoning and the compactness and morphology of the city in urban scale planning, as it sets the boundaries that the built environment may consume, and in that sense, apportions an energy budget towards the remainder of the heat-inducing urban fabric.

An increase in building cover and reduction in the proportion of vegetated open space—or low porosity—exerts a strong positive influence on heat [57], with a 10% increase in building cover ratio able to increase summer temperatures by up to 0.36 °C [27]. The preservation of porosity is then an important factor in the expansion of cities, hence vertical expansion, which allows for population growth and the preservation of green space, is a good expansion solution [57], and the resulting compactness further assists connectivity and walkability [2].

Porosity can also be preserved by re-assessing the provision of city infrastructure. Limiting allocated surface areas for roads and railways through restricted road width or use of underground space conserves surface area for cooling vegetation or additional pedestrian or bicycle space [31,40,61]. Simultaneously, anthropogenic heat production, which is encouraged in built-up areas through the overprovision of traffic infrastructure, can be reduced [40]. Air masses above major arterial roads in Portland, Oregon measure up to 2 °C warmer on weekdays compared to weekends when traffic density is reportedly 19% less [59]. Wang and Zacharias [40] show that selective road narrowing and re-configuration in Beijing would not disrupt traffic flow, and would allow for tree planting, potentially cooling local ambient temperatures by 1 °C. If widely adopted, this approach could further increase natural cooling, thereby reducing the city's cooling energy demands which significantly increase for every 1 °C above 26 °C, generating waste heat and pollution [40]. Limiting traffic can reduce anthropogenic emissions [62], and the design of compact cities contribute to these reductions by delivering transit services and infrastructure more efficiently [2,49].

3.4.2. The Intra-Urban Scale

The intra-urban scale includes built environments such as neighbourhoods, precincts, corridors, downtown, industrial zones, and urban parks, which are bound together by transport systems, in addition to conserved natural spaces such as forests, wetlands, and greenbelts. Independently, these environments may present as hot or cool islands across the entire urban space. Planning at the intra-urban scale targets cooling strategies for implementation within the built environment of contrasting urban landscapes, which also involves implementation at the building scale. This relies upon building and planning codes that determine the morphology and character of the area, such as the height of buildings or permissibility of green roofs. For example, cooling solutions for highly built-out industrial areas may include additional vegetation, high-albedo surfaces and green roofs, whilst suburban locations may respond with additional trees and heightening the albedo of roads and paved surfaces [37].

Green roofs can produce cool enclaves, and provide surface cooling through insulation, shading and evapotranspiration mechanisms, with irrigated roofs able to offer greater effects [63,64]. At roof level, studies show potential cooling effects of between 0.1 and 5 °C for extensive green roofs [63,64] and 0.2 and 2.1 °C for intensive green roofs (IGR) [63]. Modelling by Peng and Jim [63] shows that the size, number and orientation of roofs and the distances between them affect surrounding cool enclaves and that IGRs can improve ambient temperatures at the pedestrian level by 0.5–1.7 °C due to cool air mixing from the roof top down to the pedestrian level.

Makido et al. [37] find roof albedo a more effective cooling strategy, with the caveat that albedo cannot provide the additional services of habitat provision, storm water retention and pollution control that green roofs provide [37]. Furthermore, although increasing urban reflectance through the widespread installation of high-albedo roofs has been shown to effectively reduce ambient temperature levels, it can also result in an increase in ozone and $PM_{2.5}$ concentrations [65]. High-albedo materials can also cause radiation trapping effects within urban canyons [53], thereby increasing the temperature of walls and buildings to augment their cooling loads, as well as increasing heat stress [44,62], and inducing UV radiation and surface glare [62].

The low albedo of many impervious ground surface coverings, such as asphalt, cobblestone and concrete, is strongly associated with mean radiant temperature (MRT; the measure of the area-weighted mean temperature of all the surfaces surrounding a point, including surface radiation and sky radiation. MRT is the strongest influencing factor on thermal comfort indices, such as the universal thermal climate index (UTCI) and the physiological equivalent temperature (PET)) and thus linked to excess urban heat [66], whilst the low albedo of pervious natural elements is counteracted by other attributes including heat storage and evaporation capacity [31,66]. Replacing impervious cover with pervious cover has been modelled to reduce MRT by 1.0–1.5 °C per tenth of the local land cover converted [44]. A difference of 11.6 °C between pervious and impervious areas was measured in Amsterdam, where van der Hoeven and Wandl [31] also find that raising albedo from 0.3 to 0.5 delivers an average land surface temperature decrease of 4.0–4.5 °C. Painted asphalt presents a solution to raising albedo, as its higher solar reflectance value makes it cooler than traditional asphalt [66].

Interactions between vegetation, shading, and hydrology are influential. The stimulation of evaporative cooling using irrigation and misting systems presents powerful opportunities for microclimate cooling as well as manipulation of the urban energy balance city wide [45]. Irrigation may include the watering of surfaces such as grasses, soils and pavements, and does not require permanent changes to the environment [67]. Studies show that unirrigated grass does not effectively reduce ambient day time temperatures [67], whilst well-irrigated grass substantially reduces surface temperatures [27] and lowers lateral upward heat fluxes, to reduce MRT and produce a micro-oasis effect [44]. Phoenix, Arizona provides an example of a well-irrigated desert city, transformed into a day time cool island through increased latent heat loss [45]. However, humidity increases as water is transferred to the air, so care should be taken not to breach acceptable humidity levels, especially in humid climate zones [62,68], where there are limitations to the effectiveness of irrigation for cooling [67].

Surface coverings such as permeable and water holding pavements may be widely adopted to provide evaporative cooling effects after rain or irrigation [69]. Permeable pavements enable water infiltration to aid latent heat loss [69], whilst the application of a fine sheet of water across an impermeable pavement is also effective in reducing surface temperatures and heat stress [62,66]. However, water-holding pavements provide more sustained cooling effects [69]. Nakayama and Hashimoto [69] find water holding blocks deliver surface temperature reductions 10 °C greater than permeable pavements, with effects continuing for 5 days, and co-benefits including control of stormwater, which reduces first-flush pollutant loads [69].

Various methods of air-borne water ejection such as fountains, springs and nozzles complement shading and ventilation measures to deliver effective cooling strategies [51]. Gómez et al. [70] find that fountains, in interplay with breezes, are an effective urban cooling element, with bigger and more vaporous jets producing a better effect. Misting solutions can reduce ambient temperatures along with air conditioning cooling loads on surrounding buildings, even in humid conditions [62,71]. Trials of overhead misting rigs by Ulpiani et al. [71] reveal temperature decreases inside the two nebulized trial areas of 6 and 8 °C, a relative humidity increase of 7% in both, and the corresponding universal thermal climate index (UTCI) reductions of 8.2 and 7.9 °C [71].

Shade is critical to urban cooling, as it reduces openness to the sky, consequently reducing the absorption of shortwave radiation by the human body to affect thermal comfort [30,44,50,72], whilst strongly impacting the surface temperature of surface coverings [31,66] and reducing long wave radiation from the ground [44,73]. Shade may be provided by natural means such as trees, or artificial means, such as urban canyons [45], buildings, umbrellas and shade sails [30,72].

Trees provide significant shading and evaporative cooling services, and their placement within parks, urban canyons, and around roads should be managed to maximise shading, allow the dispersion of pollutants, and maintain ventilation [30,40,44,49,74]. The limitations of the urban environment must be considered in choice of tree species, along with climate, location and growth space [28,73,75].

The effect of trees on thermal comfort has been measured in various settings across numerous studies. Treed street canyons have been shown to produce a mean reduction in MRT and physiological equivalent temperature (PET) of 7.0 and 4.6 °C, respectively, compared to treeless canyons [30], and ambient temperature reductions within treed canyons have been measured at 3–4 °C, although cooling reduced as the depth of the canyon increased [76]. Roadside trees can produce cooler land surface temperatures in traffic spaces than their surrounds [31], and also reduce heat stress from extremely strong/strong to moderate levels, exhibiting PET reductions of 20–25% (10.6 °C) and MRT reductions of 35% (18.7 °C) [75]. In hot, dry conditions, trees reduced MRT by up to 33.4 °C by day [44]. However, a trade-off is the radiation trapping effect of reduced sky view factor (SVF), which increases

MRT by up to 5 °C by night [44]. In a park setting, a PET difference of 13.1 °C was recorded between tree-shaded and non-shaded sites at noon [52].

Parks provide cooling effects, often termed "urban cool islands," and "park cool islands," as a function of shade and evapotranspiration [74,77]. Park cooling is then strongly linked to trees, with tree height, canopy and foliage density and area important influencing factors for cooling [74,78]. Wide canopy trees have the greatest effect of human thermal comfort [78], and conversely, grassed parks that are sparsely treed and provide little shade, can be hotter than their surrounding built-up areas by day, imparting a negative effect on thermal comfort [78]. Trees also increase park humidity, and Potchter et al. [78] find that parks are effectively "humidity islands" through all hours of the day, as they are more humid than their built-up surroundings in the study's Mediterranean climate zone.

The magnitude of potential park cooling exhibits a large temperature range of between 1 and 7 °C referenced to surrounding areas [77], whilst cooling distances range from 100 to 600 m, but may reach up to 1000 m for a very large park. Cooling distance may be extended with the integration of natural landscapes in built-up areas [77]. Whilst park size influences cooling effect, the efficiency of the cooling effect itself does not increase with park size, and so small parks remain effective in providing urban cooling [77].

Yang et al. [49] modelled several approaches to urban renewal that show a combination of linear parks with ponds, roadside trees, forest, and grass to be a more effective strategy for reducing air temperature than green infrastructure alone [49]. Constructed blue-green spaces may be key features of intra-urban areas such suburban developments, and these should be oriented to maximise the dispersion of cooling effects from prevailing winds, aided by optimized street geometry [60,67]. Wind speed, turbulence and direction are then important for spreading the cooling effects, and urban morphology, including width and orientation of waterbodies and streets influences cooling range [60,67]. Better cooling is found downwind of blue spaces, and orienting constructed wetlands and lakes perpendicular to air flow aids downwind dispersion by capturing cross breezes [67], with studies indicating that cooling ranges to vary from 10 to 400 m from the water's edge [60,67].

Buildings can intercept solar radiation to provide shading at the pedestrian level [45,79]. This is influenced by aspect ratio, which describes the building height to street width (H/W) [80], along with street orientation and angle of the sun throughout the day [45,81]. The effect of aspect ratio on solar penetration in the urban canyon is evident in Johansson's [81] finding that MRT stabilized in a deep canyon between 25 and 28 °C, whilst a comparable shallow canyon exhibited large diurnal MRT swings of between 16 and 63 °C, in which resultant ambient conditions were 6–10 °C warmer throughout most of the day [81].

The position and angle of the sun throughout the day influence solar exposure for different street orientations [45]. In narrow canyons, Pearlmutter et al. [45] show that N–S-aligned streets provide the best pedestrian shading, which also provides the best thermal conditions in a hot, dry climate, whilst E–W canyons hold little chance of enhanced thermal comfort due to a high exposure to incident short-wave radiation in the hotter parts of the day [45]. However, in other urban settings, an E–W street orientation is desirable, such as when prioritizing the N–S orientation of individual building lots to increase solar potential [80].

The storage and delayed release of intercepted solar energy in the built form can be designed to shield pedestrians and temporally alter the UHI [45]. Nocturnal UHIs are influenced by radiation trapping effects within urban canyons, whereby a high H/W ratio and a lower SVF result in the blocking of outgoing longwave radiation, fueling UHI development [27,81]. However, urban geometry modifications that might reduce night-time UHIs do not preclude development of a daytime UHI. In a city such as Hong Kong, increasing the SVF ratio by 10% would increase the daytime UHI more than it decreases the nocturnal UHI [27].

The duration of high air temperatures can be reduced with higher wind speeds and greater urban ventilation [53]. Within the urban canyon, building geometry effects wind flow and temperature distribution, which can be manipulated by non-uniform building heights [27], greater porosity, and the creation of space for wind corridors to promote ventilation [53,80]. Humidity and wind speed stabilize in narrow and deep cut canyons [81], but where open spaces are introduced, surrounding tall buildings induce stronger wind speeds through funneling effects, affecting pedestrian microclimate conditions and reducing ambient temperatures [40,46]. Wind studies reveal that the placement of a few high-rise towers within a canyon yields a 90% increase in wind flow from the parallel direction, a 1 °C decrease in temperature, and a ten-fold increase in wind speed in the perpendicular flow scenario [27]. Simulations indicate a 35% increase in wind speed and an associated 0.7 °C cooling effect is possible though an ideal canyon H/W ratio [27].

Small obstacles such as trees are an important factor affecting wind at the pedestrian scale, with arrangement and spacing exerting influence [74]. In a scale model study, Cheung and Jim [50] find that four trees reduce wind speed in a shallow urban canyon by 17–49% more than one tree. Trees can become an unwanted barrier to wind, slowing wind speed and obstructing downstream airflow, stopping hot air from being removed and replaced by cool air, and causing temperature rises in downstream areas [74].

3.4.3. The Building Scale

The third scale is the building scale, which creates locally generated cooling effects in the immediate environment, and implements many of the afore-mentioned strategies at the building scale to enhance microclimate and reduce energy use.

Preventing the penetration of heat into buildings is critical to internal thermal comfort [31], hence passive design principles are key to improved internal microclimate and reduced cooling energy loads. Configuration of thermal mass, insulation, building material properties and orientation may all be designed to moderate the effects of solar exposure [60,67,79].

Shading of solar-exposed building surfaces may be achieved through use of shade trees, green roofs and green walls, which also provide external microclimate improvements [63,64,80,82,83].

Green walls or vertical gardens may be established on the sides of building using methods such as planted substrates [82] or wire rope training systems [83]. Plantings intercept solar radiation to reduce the surface temperature of vertical building surfaces, deliver cooling both inside and outside buildings [82,83]. Planted substrates provide reductions in the near air temperature behind green wall panels of 14–21 °C [82], and vertical wire rope training systems with climbing plants and 1 m air gaps show exterior surface daytime cooling ranges from 0.52 to 3.59 °C and night-time cooling from 0.03 to 0.78 °C [83]. Furthermore, where air-conditioning inlets are positioned in the cool air gap behind the climbers, a 26% cooling energy saving may be attained [83]. The cooling of vertical surfaces adjacent to sidewalks produces microclimate improvements for pedestrians [44], and vegetation aids the purification of air [82].

Ventilation may be optimized with shaded windows [84], high ceilings, and fans [47], and capturing breezes across irrigated gardens, fountains or ponds brings cool air into adjacent spaces [79].

As wind and shade work together in a complementary relationship, Hsieh et al. [74] recommend that shade tree plantings should not be so dense as to hamper ventilation at the height range in which human activity is undertaken. However, another study shows a minimal effect of 0.1 m/s wind speed reduction from trees in the high density urban environment [73] and another notes that a reduction in wind speed due to the trees does not outweigh their benefits according to other cooling parameters, as further contribution to microclimate comes from tree transpiration [75].

3.4.4. The Body Scale

The finest scale is the body scale, which targets cooling to confined areas so as to maintain usability of that space, or that part of an urban system. Examples include the misting of an entry way, or natural or artificial shading over urban furniture, such as at transit stops, to reduce surface temperatures and avoid burns [85]. Materials with high thermal conductivity such as metals and plastics may surpass safe temperature thresholds if unshaded and transfer heat quickly to the skin, increasing the likelihood of burns [85]. This includes "AstroTurf", which can be hotter than asphalt when sun exposed [66]. J.K. Vanos et al. [85] find that shade reduces a range of sun-exposed playground surfaces by an average of 24.3 °C, making them safe for use, whilst Vít and Kopp [51] find a combination of shading methods, including technical (including awnings, fixed structures and screens), building shade and vegetation, provide an effective means of shielding customers from excessive heat in outdoor eating areas.

These solutions have the smallest effect on the meso-scale climate. However, cooling solutions on all scales collectively contribute to urban cooling and contribute towards an overall heat-responsive urban fabric.

4. Conclusions

This review examined the drivers of urban heat and the effect of excess heat on urban life. This review investigated the form of the urban environment and asked: how can green infrastructure and design solutions be used to cool the urban environment and improve city vitality? Using the SLR methodology, 68 articles were reviewed across three themes: a cool urban environment, city vitality, and green infrastructure and design. Findings from the articles provide evidence of connections between heat, GIDS and human needs. They confirm that a deficit of nature in urban areas induces heat, manifesting as a UHI, that contributes to environmental conditions that are repressive and dangerous to humans. UHIs amplify baseline temperature increases driven by climate change to increase the incidence of extreme heat intensity and duration within cities. Excess heat impacts the human energy balance, physiologically limiting the amount and type of activity that humans can safely or comfortably undertake. As a result, heat mortality and a range of heat-related morbidities ensue.

Designing cooling strategies with GIDS contemplates urban thermodynamics, but must also consider liveability and the social and economic conditions of the city that produce a thriving urban environment. Maintaining a human-centered focus to urban cooling assists the development of attractive spaces to encourage use and activity, for which thermal comfort influences the type of activity and behaviour undertaken in public life [46]. A thermally comfortable environment enables greater physical activity [30,42], which is further connected to improved public health [48], whilst improved public health maintains productivity [34], reduces the draw on health infrastructure [48], and supports livelihoods such that urban inhabitants may participate in public life without prevention. Greater activity through good urban planning is then a public health measure and a mechanism of preventative medicine [30].

GIDS can produce functional, thermally comfortable and attractive environments that deliver the co-benefits of ecosystem services, such as access to nature, which enhances sociobehavioural pathways to health, such as walking [46]. GIDS deliver good walking environments through cooler ambient temperatures, shading and better pedestrian amenity, such as wider and less obstructed sidewalks. Attracting people to the streets and public places with better walking opportunities also enhances economic activity and activity intensity [33]. Through such activation, there is greater energy brought to a place [39]. Furthermore, the arrangement of compact, walkable neighbourhoods fosters a sense of place [39]. Place is a key to the competitiveness of cities—it provides a sense of identity and attracts talent, and people consider great places as those of natural beauty, that effortlessly provide lively cultural and urban experiences [86]. All of these qualities and functions are consistent with vital cities, and all of these qualities can be supported and enhanced with the human-centered focus of GIDS.

Conversely, people do not want transport, traffic, and nothing to do [86]. The forced human relationship with the car is upheld by the transport planning of many cities, and the resultant dispersed settlement patterns, which also set in place heat-inducing infrastructures that occupy large tracts of land and encourage the outward extension of the city, further consuming natural spaces [8]. The resultant dispersed settlement patterns contribute to a decline in our connection to others, setting up the conditions for loneliness [39]. These patterns are typical of many cities. The drop in traffic through the COVID-19 pandemic has highlighted the amount of space allocated to cars that is much better used to support safe public activity [87].

If cities are to be built and public spaces re-thought after COVID-19, there is opportunity to re-assess the thermal performance and attractiveness of urban spaces, and to re-think approaches to cities that establish community [56]. As humans are limited in their capacity to tolerate heat, a heat-responsive urban fabric may function as a protective canopy or a human shield, as opposed to an urban fabric that turns heat onto its inhabitants and subjects them to exposures that force changes to activities and behaviours or the exhaustion of their body’s thermoregulation resources for basic survival. A heat-responsive urban fabric will be of particular benefit throughout heatwaves and where baseline temperatures are high, as there will be minimal urban heat penalty to amplify heat. As the climate crisis grows, every opportunity to protect the health and well-being of global citizens should be grasped, and all outcomes that enhance the social fabric, improve equity, and maintain livelihoods, peace and social order are valuable contributions. GIDS can make a particularly strong contribution towards all of these goals.

It is theorized that collectively, GIDS implemented on each of these scales interacts and contributes towards an overall heat-responsive urban fabric. However, case studies to examine this further are needed. This review found that the effects of urban heat are not equally shared. Poorer populations, who also exhibit lower levels of general health, are also the most vulnerable and exposed to excess heat [6,33]. Yet whilst rapidly urbanizing low and medium human development index (HDI) countries have large populations at high risk of heat exposure, there are few insights particular to those urban contexts revealed within this review. Furthermore, many of these cities are located in tropical and dry climate zones which are also under-represented in this review.

Further research into the direct public health outcomes of the environmental conditions induced by nature in the urban setting is also suggested, in addition to the seasonal benefits, opportunities, risks and hazards of GIDS implementation, which will guide urban planning to maximise health benefits. Finally, future research opportunities exist to examine links between sustainable development and HDI to heat management through GIDS, and to develop pragmatic and culturally appropriate approaches to climate resilient city forms and heat-responsive urban fabrics within emerging cities and in climate zones that are under-represented in climate research.

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Appendix A

Table A1. Literature included for review, including country of origin, location of connected case study or region presented in the article, climate zone, HDI and thematic breakdown.

Author	Title	Year	Periodical Title	Article Type #	Country of Origin	Case Study or Regional Location	Climate Zone †	HDI Ranking *	Thematic Breakdown		
									Theme	Sub-Cat	Breakdown
Bélanger, Diane; Abdous, Belkacem; Valois, Pierre; Gosselin, Pierre; Elhadji, A. Laouan Sidi	A multilevel analysis to explain self-reported adverse health effects and adaptation to urban heat: a cross-sectional survey in the deprived areas of 9 Canadian cities [36]	2016	*BMC Public Health*	CSR	Canada	Canada	Dfb *	13	Vitality	Activity	Use of space
Broadbent, A. M.; Coutts, A. M.; Tapper, N. J.; Demuzere, M.; Beringer, J.	The microscale cooling effects of water sensitive urban design and irrigation in a suburban environment [67]	2018	*Theoretical and Applied Climatology*	CSR	Australia	Adelaide	Csa	6	GIDS	Green infrastructure	Water
Brown, Helen; Proust, Katrina; Newell, Barry; Spickett, Jeffery; Capon, Tony; Bartholomew, Lisa	Cool Communities—Urban Density, Trees, and Health [2]	2018	*International Journal of Environmental Research and Public Health*	CSR	Australia	Perth	Csa	6	Vitality	Health	Urban interaction
Cheng, June J.; Berry, Peter	Health co-benefits and risks of public health adaptation strategies to climate change: a review of current literature [3]	2013	*International Journal of Public Health*	Review	Canada	–	–	13	Vitality	Health	Heat impacts
Cheng, X. Y.; Wei, B. S.; Chen, G. J.; Li, J. X.; Song, C. H.	Influence of Park Size and Its Surrounding Urban Landscape Patterns on the Park Cooling Effect [77]	2015	*Journal of Urban Planning and Development*	CSR	China	Shanghai	Cfa	85	GIDS	Green infrastructure	Parks
Cheung, P. K.; Jim, C. Y.	Comparing the cooling effects of a tree and a concrete shelter using PET and UTCI [50]	2018	*Building and Environment*	CSR	China	Hong Kong	Cwa	4	GIDS	Architecture and design	Materiality
Choi, Yeri; Lee, Sugie; Moon, Hyunbin	Urban Physical Environments and the Duration of High Air Temperature: Focusing on Solar Radiation Trapping Effects [53]	2018	*Sustainability*	CSR	Korea	Seoul	Dwa	22	GIDS	Urban planning	Morphology
Correa, E.; Ruiz, M. A.; Canton, A.; Lesino, G.	Thermal comfort in forested urban canyons of low building density. An assessment for the city of Mendoza, Argentina [68]	2012	*Building and Environment*	CSR	Argentina	Mendoza	BWk	48	GIDS	Urban planning	Morphology

Table A1. *Cont.*

Author	Title	Year	Periodical Title	Article Type #	Country of Origin	Case Study or Regional Location	Climate Zone †	HDI Ranking *	Thematic Breakdown		
									Theme	Sub-Cat	Breakdown
Day, E.; Fankhauser, S.; Kingsmill, N.; Costa, H.; Mavrogianni, A.	Upholding labour productivity under climate change: an assessment of adaptation options [34]	2019	*Climate Policy*	Emperical	UK	–	–	15	Vitality	Activity	Productivity
Deilami, Kaveh; Kamruzzaman, Md; Hayes, John Francis	Correlation or Causality between Land Cover Patterns and the Urban Heat Island Effect? Evidence from Brisbane, Australia [57]	2016	*Remote Sensing*	CSR	Australia	Brisbane	Cfa	6	Cool Environ	UHI and climate	–
Endreny, T.; Santagata, R.; Perna, A.; De Stefano, C.; Rallo, R. F.; Ulgiati, S.	Implementing and managing urban forests: A much needed conservation strategy to increase ecosystem services and urban well-being [28]	2017	*Ecological Modelling*	CSR	USA	London, UK	Cfb	15	Vitality	Health	Urban interaction
Epstein, S. A.; Lee, S. M.; Katzenstein, A. S.; Carreras-Sospedra, M.; Zhang, X.; Farina, S. C.; Vahmani, P.; Fine, P. M.; Ban-Weiss, G.	Air-quality implications of widespread adoption of cool roofs on ozone and particulate matter in southern California [65]	2017	*Proceedings of the National Academy of Sciences of the United States of America*	CSR	USA	Southern California	Csa	15	GIDS	Architecture and design	Materiality
Ersoy, Ebru	Landscape Patterns and Urban Cooling Islands	2019	*Fresenius Environmental Bulletin*	CSR	Turkey	Samsun, Turkey	Cfa	59	GIDS	Urban planning	Land use
Gómez, Francisco; Valcuende, Manuel; Matzarakis, Andreas; Cárcel, Javier	Design of natural elements in open spaces of cities with a Mediterranean climate, conditions for comfort and urban ecology [70]	2018	*Environmental Science and Pollution Research International*	CSR	Spain	Valencia	Bsk	25	Vitality	Comfort	Sensation
Grace, A. O'Brien; Ross, Nancy A.; Strachan, Ian B.	The heat penalty of walkable neighbourhoods [54]	2019	*International Journal of Biometeorology*	CSR	Canada	Montréal	Dfb	13	Vitality	Activity	Use of space
Hart, Melissa A.; Sailor, David J.	Quantifying the influence of land-use and surface characteristics on spatial variability in the urban heat island [59]	2009	*Theoretical and Applied Climatology*	CSR	Hong Kong	Portland, USA	Csb	4	GIDS	Urban planning	Land use
Hejazi, M.	Persian architecture: Conformity with nature in hot-dry regions [79]	2006	*International Journal of Design & Nature*	CSR	Iran	Iran	Bsh *	65	GIDS	Architecture and design	Traditional
Hsieh, C. M.; Jan, F. C.; Zhang, L.	A simplified assessment of how tree allocation, wind environment, and shading affect human comfort [74]	2016	*Urban Forestry and Urban Greening*	CSR	China	Taiwan	Cfa	85	GIDS	Green infrastructure	Trees
Huang, K. T.; Lin, T. P.; Lien, H. C.	Investigating thermal comfort and user behaviors in outdoor spaces: A seasonal and spatial perspective [42]	2015	*Advances in Meteorology*	CSR	China	Taiwan	Cfa	85	Vitality	Activity	Use of space

Table A1. *Cont.*

Author	Title	Year	Periodical Title	Article Type #	Country of Origin	Case Study or Regional Location	Climate Zone †	HDI Ranking *	Thematic Breakdown		
									Theme	Sub-Cat	Breakdown
Jankovic, Vladimir; Hebbert, Michael	Hidden climate change - urban meteorology and the scales of real weather [88]	2012	*Climatic Change*	Emperical	UK	–	–	15	Cool Environ	UHI and climate	–
Jin, He; Liu, Xue Wen	The Development of Green Architectural Heritage Cave Civilization [61]	2013	*Applied Mechanics and Materials*	CSR	China	Loess Plateau	Dwb	85	GIDS	Architecture and design	Traditional
Johansson, E.	Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco [81]	2006	*Building and Environment*	CSR	Sweden	Fez, Morocco	Csa	121	GIDS	Urban planning	Morphology
Kang-Ting, Tsai; Yu-Hao, Lin	Identification of urban park activity intensity at different thermal environments and visible sky by using sound levels [52]	2018	*International Journal of Biometeorology*	CSR	China	Taiwan	Cfa	85	Vitality	Activity	Liveability
Kennedy, Rosemary; Buys, Laurie; Miller, Evonne	Residents' Experiences of Privacy and Comfort in Multi-Storey Apartment Dwellings in Subtropical Brisbane [47]	2015	*Sustainability*	CSR	Australia	Brisbane	Cfa	6	Vitality	Comfort	Ventilation
Khomenko, S.; Nieuwenhuijsen, M.; Ambròs, A.; Wegener, S.; Mueller, N.	Is a liveable city a healthy city? Health impacts of urban and transport planning in Vienna, Austria [29]	2020	*Environmental Research*	CSR	Spain	Vienna, Austria	Cfb	25	Vitality	Activity	Liveability
Kjellstrom, Tord; McMichael, Anthony J.	Climate change threats to population health and well-being: the imperative of protective solutions that will last [6]	2013	*Global Health Action*	Emperical	Sweden	–	–	8	Vitality	Health	Heat impacts
Ko, Y. K.	Urban Form and Residential Energy Use: A Review of Design Principles and Research Findings [80]	2013	*Journal of Planning Literature*	Review	USA	–	–	15	GIDS	Urban planning	Urban form
Kong, L.; Lau, K. K. L.; Yuan, C.; Chen, Y.; Xu, Y.; Ren, C.; Ng, E.	Regulation of outdoor thermal comfort by trees in Hong Kong [73]	2017	*Sustainable Cities and Society*	CSR	China	Hong Kong	Cwa	4	GIDS	Green infrastructure	Trees
Lee, Ivan; Voogt, James A.; Gillespie, Terry J.	Analysis and Comparison of Shading Strategies to Increase Human Thermal Comfort in Urban Areas [72]	2018	*Atmosphere*	CSR	Canada	London, Canada	Dfb	13	GIDS	Urban planning	Shading
Lee, L. S. H.; Jim, C. Y.	Subtropical summer thermal effects of wirerope climber green walls with different air-gap depths [83]	2017	*Building and Environment*	CSR	China	Hong Kong	Cwa	4	GIDS	Green infrastructure	Green wall
Lin, Pingying; Gou, Zhonghua; Stephen Siu-Yu, Lau; Qin, Hao	The Impact of Urban Design Descriptors on Outdoor Thermal Environment: A Literature Review [27]	2017	*Energies*	Review	China	–	–	85	GIDS	Urban planning	Microclimate

Table A1. *Cont.*

Author	Title	Year	Periodical Title	Article Type #	Country of Origin	Case Study or Regional Location	Climate Zone †	HDI Ranking *	Thematic Breakdown		
									Theme	Sub-Cat	Breakdown
Lundgren-Kownacki, K.; Hornyanszky, E. D.; Chu, T. A.; Olsson, J. A.; Becker, P.	Challenges of using air conditioning in an increasingly hot climate [35]	2018	*International Journal of Biometeorology*	Review	Sweden	_	_	8	Vitality	Activity	Liveability
MacIvor, J. S.; Margolis, L.; Perotto, M.; Drake, J. A. P.	Air temperature cooling by extensive green roofs in Toronto Canada [64]	2016	*Ecological Engineering*	CSR	Canada	Toronto	Dfb	13	GIDS	Green infrastructure	Green roof
Makido, Yasuyo; Hellman, Dana; Shandas, Vivek	Nature-Based Designs to Mitigate Urban Heat: The Efficacy of Green Infrastructure Treatments in Portland, Oregon [37]	2019	*Atmosphere*	CSR	USA	Portland	Csb	15	GIDS	Green infrastructure	Combined
Middel, A.; Krayenhoff, E. S.	Micrometeorological determinants of pedestrian thermal exposure during record-breaking heat in Tempe, Arizona: Introducing the MaRTy observational platform [44]	2019	*Science of the Total Environment*	CSR	USA	Tempe, Arizona	BWh	15	Vitality	Comfort	Radiation
Nakayama, T.; Hashimoto, S.	Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis [69]	2011	*Environmental Pollution*	CSR	Japan	Tokyo	Cfa	19	GIDS	Architecture and design	Materiality
Nouri, A. Santos	A Framework of Thermal Sensitive Urban Design Benchmarks: Potentiating the Longevity of Auckland's Public Realm [62]	2015	*Buildings*	CSR	Portugal	Auckland	Cfb	14	GIDS	Urban planning	Urban form
Pantavou, K.; Theoharatos, G.; Santamouris, M.; Asimakopoulos, D.	Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI [41]	2013	*Building and Environment*	CSR	Greece	Athens	Csa	32	Vitality	Comfort	Sensation
Pearlmutter, D.; Berliner, P.; Shaviv, E.	Urban climatology in arid regions: current research in the Negev desert [45]	2007	*International Journal of Climatology*	CSR	Israel	Dimona	Bsh	22	GIDS	Urban planning	Microclimate
Peng, Lilliana L. H.; Jim, C. Y.	Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation [63]	2013	*Energies*	CSR	China	Hong Kong	Cwa	4	GIDS	Green infrastructure	Green roof
Potchter, O.; Cohen, P.; Bitan, A.	Climatic behavior of various urban parks during hot and humid summer in the Mediterranean city of Tel Aviv, Israel [78]	2006	*International Journal of Climatology*	CSR	Israel	Tel Aviv	Csa	22	GIDS	Green infrastructure	Parks
Rossi, F.; Anderini, E.; Castellani, B.; Nicolini, A.; Morini, E.	Integrated improvement of occupants' comfort in urban areas during outdoor events [43]	2015	*Building and Environment*	CSR	Italy	Citta di Castello	Cfb	29	Vitality	Activity	Use of space

Table A1. *Cont.*

									Thematic Breakdown		
Author	**Title**	**Year**	**Periodical Title**	**Article Type #**	**Country of Origin**	**Case Study or Regional Location**	**Climate Zone †**	**HDI Ranking ***	**Theme**	**Sub-Cat**	**Breakdown**
Sadoughi, A.; Kibert, C.; Sadeghi, F. M.; Jafari, S.	Thermal performance analysis of a traditional passive cooling system in Dezful, Iran [88]	2019	*Tunnelling and Underground Space Technology*	CSR	Iran	Dezful	Bsh	65	GIDS	Architecture and design	Traditional
Shashua-Bar, L.; Potchter, O.; Bitan, A.; Boltansky, D.; Yaakov, Y.	Microclimate modelling of street tree species effects within the varied urban morphology in the Mediterranean city of Tel Aviv, Israel [76]	2010	*International Journal of Climatology*	CSR	Israel	Tel Aviv	Csa	22	GIDS	Urban planning	Shading
Shooshtarian, S.; Rajagopalan, P.	Daytime thermal performance of different urban surfaces: a case study in educational institution precinct of Melbourne [66]	2018	*Architectural Science Review*	CSR	Australia	Melbourne	Cfb	6	GIDS	Architecture and design	Materiality
Shooshtarian, S.; Rajagopalan, P.	Perception of Wind in Open Spaces [46]	2019	*Climate*	CSR	Australia	Melbourne	Cfb	6	Vitality	Comfort	Radiation
Smargiassi, A.; Goldberg, M. S.; Plante, C.; Fournier, M.; Baudouin, Y.; Kosatsky, T.	Variation of daily warm season mortality as a function of micro-urban heat islands [32]	2009	*Journal of Epidemiology and Community Health*	CSR	Canada	Montreal	Dfb	13	Vitality	Health	Heat impacts
Soutullo, S.; Olmedo, R.; Sanchez, M. N.; Heras, M. R.	Thermal conditioning for urban outdoor spaces through the use of evaporative wind towers [89]	2011	*Building and Environment*	CSR	Spain	Madrid	Csa	25	GIDS	Architecture and design	Wind
Su, Weizhong; Zhang, Yong; Yang, Yingbao; Ye, Gaobin	Examining the Impact of Greenspace Patterns on Land Surface Temperature by Coupling LiDAR Data with a CFD Model [90]	2014	*Sustainability*	CSR	China	Jiangsu	Cfa	85	GIDS	Urban planning	Land use
Su, Ying Ming; Tsai, Yi Ping	Ecological Aesthetic of Wind Environment about the Circular Earth Building in Fujian, China [91]	2013	*Applied Mechanics and Materials*	CSR	China	Fuji	Cwa	85	GIDS	Architecture and design	Wind
Szawernoga, Katarzyna; Pęczkowski, Grzegorz	Experimental tests of thermal properties pertaining to vertical plant systems in the climate of lower Silesia. [82]	2018	*Acta Scientiarum Polonorum. Formatio Circumiectus*	CSR	Poland	Silesia	Dfb	32	GIDS	Green infrastructure	Green wall
Szkordilisz, Flóra; Kiss, Marton	Potential of Vegetation in Improving Indoor Thermal Comfort and Natural Ventilation [84]	2016	*Applied Mechanics and Materials*	CSR	Hungary	Szeged	Dfb	43	GIDS	Green infrastructure	Trees
Tait, Peter W.; Allan, Sujata; Katelaris, Anthea L.	Preventing heat-related disease in general practice [48]	2018	*Australian Journal of General Practice*	CSR	Australia	Australia	Cfb	6	Vitality	Health	Urban interaction

Table A1. *Cont.*

Author	Title	Year	Periodical Title	Article Type #	Country of Origin	Case Study or Regional Location	Climate Zone †	HDI Ranking *	Thematic Breakdown		
									Theme	Sub-Cat	Breakdown
Ulpiani, G.; Di Giuseppe, E.; Di Perna, C.; D'Orazio, M.; Zinzi, M.	Thermal comfort improvement in urban spaces with water spray systems: Field measurements and survey [71]	2019	*Building and Environment*	CSR	Italy	Ancona and Rome	Cfa/Csa	29	GIDS	Green infrastructure	Water
van den Bosch, M.; Ode Sang, Å	Urban natural environments as nature-based solutions for improved public health—A systematic review of reviews [15]	2017	*Environmental Research*	Review	Canada	–	–	13	Vitality	Health	Urban interaction
van der Hoeven, Frank; Wandl, Alexander	Amsterwarm; Mapping the landuse, health and energy-efficiency implications of the Amsterdam urban heat island	2015	*Building Services Engineering Research & Technology*	CSR	Netherlands	Amsterdam	Cfb	10	Cool Environ	UHI and climate	–
Vandentorren, S.; Bretin, P.; Zeghnoun, A.; Mandereau-Bruno, L.; Croisier, A.; Cochet, C.; Riberon, J.; Siberan, I.; Declercq, B.; Ledrans, M.	August 2003 heat wave in France: Risk factors for death of elderly people living at home [26]	2006	*European Journal of Public Health*	CSR	France	Paris	Cfb	26	Vitality	Health	Heat impacts
Vanos, J. K.; Middel, A.; McKercher, G. R.; Kuras, E. R.; Ruddell, B. L.	Hot playgrounds and children's health: A multiscale analysis of surface temperatures in Arizona, USA [86]	2016	*Landscape and Urban Planning*	CSR	USA	Phoenix, Arizona	BWh	15	Vitality	Activity	Use of space
Vanos, Jennifer K.; Warland, Jon S.; Gillespie, Terry J.; Kenny, Natasha A.	Review of the physiology of human thermal comfort while exercising in urban landscapes and implications for bioclimatic design [30]	2010	*International Journal of Biometeorology*	Review	Canada	–	–	13	Vitality	Activity	Use of space
Villadiego, K.; Velay-Dabat, M. A.	Outdoor thermal comfort in a hot and humid climate of Colombia: A field study in Barranquilla [33]	2014	*Building and Environment*	CSR	France	Barranquilla, Colombia	Aw	26	Vitality	Comfort	Sensation
Vít, Václav; Kopp, Jan	Typology of Outdoor Seating Areas of Restaurants Based on Factors Influencing Their Thermal Comfort. A Case Study of Pilsen City Centre, Czechia [51]	2019	*Journal of Settlements and Spatial Planning*	CSR	Czechia	Pilsen City Centre	Cfb	26	Vitality	Comfort	Sensation
Volker, S.; Baumeister, H.; Classen, T.; Hornberg, C.; Kistemann, T.	Evidence for the temperature-mitigating capacity of urban blue space—A health geographic perspective.	2013	*Erdkunde*	Review	Germany	–	–	4	GIDS	Green infrastructure	Water
Walter Leal, Filho; Leyre Echevarria, Icaza; Emanche, Victoria Omeche; Abul Quasem, Al-Amin	An Evidence-Based Review of Impacts, Strategies and Tools to Mitigate Urban Heat Islands [1]	2017	*International Journal of Environmental Research and Public Health*	Review	Germany	–	–	4	Cool Environ	UHI and climate	–
Wang, Y.; Zacharias, J.	Landscape modification for ambient environmental improvement in central business districts—A case from Beijing [40]	2015	*Urban Forestry and Urban Greening*	CSR	China	Beijing	Dwa	85	GIDS	Urban planning	Transport
Wong, Paulina P. Y.	A Microclimate Study of Traffic and Pedestrianization Scenarios in a Densely Populated Urban City [55]	2020	*Advances in Meteorology*	CSR	Hong Kong	Hong Kong	Cwa	4	GIDS	Urban planning	Microclimate
Yang, L.; Zhang, L.; Stettler, M. E. J.; Sukitpaneenit, M.; Xiao, D.; van Dam, K. H.	Supporting an integrated transportation infrastructure and public space design: A coupled simulation method for evaluating traffic pollution and microclimate [49]	2020	*Sustainable Cities and Society*	CSR	China	Beijing	Dwa	85	GIDS	Urban planning	Transport
Zaki, S. A.; Toh, H. J.; Yakub, F.; Saudi, A. S. M.; Ardila-Rey, J. A.; Muhammad-Sukki, F.	Effects of roadside trees and road orientation on thermal environment in a tropical City [75]	2020	*Sustainability (Switzerland)*	CSR	Malaysia	Kuala Lumpur	Af	61	GIDS	Green infrastructure	Trees
Zhang, Da-Lin; Shou, Yi-Xuan; Dickerson, Russell R.; Chen, Fei	Impact of Upstream Urbanization on the Urban Heat Island Effects along the Washington-Baltimore Corridor [92]	2011	*Journal of Applied Meteorology and Climatology*	CSR	USA	Washington-Baltimore	Dfa/Cfa	15	Cool Environ	UHI and climate	–

CSR = Articles based on case studies or regions, with geographically connected content. † Köppen-Geiger Climate Classification. Where geographic connection spans multiple climate zones the most populous region is represented. * United Nations Human Development Index ranking. Corresponds to case study location, or country of origin where no case study relates.

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